Multivariable Calculus Self-Learning Module

Exercises

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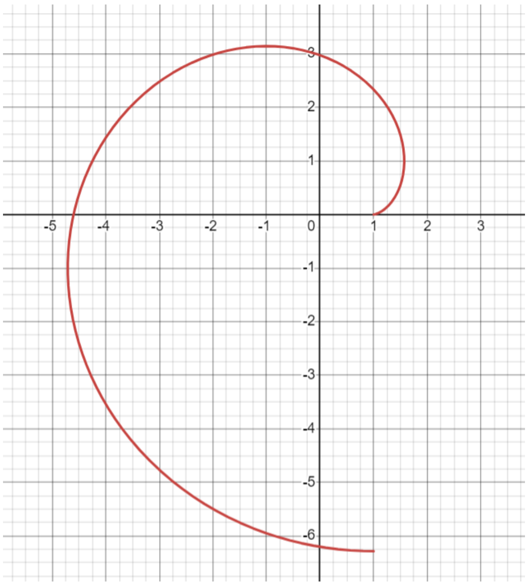
1 Exercise

Calculate the length of curve C, where C is the curve:

$$t \mapsto (\cos(t) + t\sin(t),\, \sin(t) - t\cos(t))$$

for $0 \leq t \leq 2\pi$.



1.1 Hint

There is a formula for calculating the length of the curve. You must know this one! The formula is of the form:

$$\int_{\dots}^{\dots} |\dots|\, dt$$

1.2 Hint

The formula for the length is:

$$\int_0^{2\pi} |f'(t)|\, dt$$

1.3 Hint

$$\begin{aligned} f'(t) &= \frac{d}{dt}(\cos(t) + t\sin(t),\, \sin(t) - t\cos(t)) \\ &= (-\sin(t) + \sin(t) + t\cos(t),\, \cos(t) - \cos(t) + t\sin(t)) \\ &= (t\cos(t),\, t\sin(t)) \end{aligned}$$

So

$$\begin{aligned} |f'(t)| &= \sqrt{t^2\cos^2(t) + t^2\sin^2(t)} \\ &= \sqrt{t^2} \\ &= |t| \end{aligned}$$

1.4 Solution

Since $t \geq 0$, we have $|t| = t$, so:

$$
\begin{aligned}
\int_0^{2\pi} |f'(t)|\, dt &= \int_0^{2\pi} t\, dt \\
&= \left[\frac{t^2}{2}\right]_0^{2\pi} \\
&= 2\pi^2
\end{aligned}
$$

2 Exercise

Consider the curve C given by $f(x, y) = 0$, where

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

Determine the point on C at which $x + y$ is maximal.

2.1 Hint

We want to maximize $g(x, y) = x + y$ subject to the constraint $f(x, y) = 0$. Use Lagrange.

2.2 Hint

Solve the equation $\nabla g = \lambda \nabla f$.

2.3 Solution

$$\nabla g(x, y) = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$\nabla f(x, y) = \begin{pmatrix} 2(x - y) + 4 \\ -2(x - y) + 4 \end{pmatrix}$$

So

$$\begin{pmatrix} 1 \\ 1 \end{pmatrix} = \lambda \begin{pmatrix} 2(x - y) + 4 \\ -2(x - y) + 4 \end{pmatrix}$$

Note that $\lambda = 0$ gives

$$\begin{pmatrix} 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

which is a contradiction, so $\lambda \neq 0$ and we get the system:

$$\begin{cases} 2(x - y) + 4 = \dfrac{1}{\lambda} \\ \\ -2(x - y) + 4 = \dfrac{1}{\lambda} \end{cases}$$

Subtracting the two equations gives:

$$2(x - y) + 4 + 2(x - y) - 4 = \frac{1}{\lambda} - \frac{1}{\lambda} \iff 4(x - y) = 0 \iff x = y$$

Since we are looking for the point that maximizes $x + y$ on C, we substitute $y = x$ in $f(x, y) = 0$:

$$(x - x)^2 + 4(x + x) - 4 = 0 \iff 8x = 4 \iff x = \frac{1}{2}$$

So

$$(x, y) = \left(\frac{1}{2}, \frac{1}{2}\right)$$

and the maximum is

$$g\left(\frac{1}{2}, \frac{1}{2}\right) = 1.$$

3 Exercise

Consider the function

$$f(x,y,z) = \frac{1}{x} + \frac{1}{8y} + \frac{1}{27z}.$$

Find the point on the unit sphere (i.e. the sphere centered at $(0,0,0)$ of radius 1) at which f is maximal and the point at which it is minimal. Calculate also these maximum and minimum values.

3.1 Hint

The surface of a sphere centered at (x_0, y_0, z_0) of radius R has the formula

$$(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2 = R^2$$

3.2 Hint

Let

$$g(x,y,z) = x^2 + y^2 + z^2 - 1.$$

We want to maximize $f(x,y,z)$ given the constraint $g(x,y,z) = 0$. Use Lagrange.

3.3 Hint

Solve the equation $\nabla f = \lambda \nabla g$.

3.4 Hint

$$\nabla f(x,y,z) = \begin{pmatrix} -\dfrac{1}{x^2} \\ \\ -\dfrac{1}{8y^2} \\ \\ -\dfrac{1}{27z^2} \end{pmatrix}$$

$$\nabla g(x,y,z) = \begin{pmatrix} 2x \\ 2y \\ 2z \end{pmatrix}$$

So

$$\begin{pmatrix} -\dfrac{1}{x^2} \\ \\ -\dfrac{1}{8y^2} \\ \\ -\dfrac{1}{27z^2} \end{pmatrix} = \lambda \begin{pmatrix} 2x \\ 2y \\ 2z \end{pmatrix}$$

Note that the left-hand side is always non-zero, so $\lambda \neq 0$. Hence:

$$\begin{cases} -\dfrac{1}{x^2} = 2\lambda x \\ \\ -\dfrac{1}{8y^2} = 2\lambda y \\ \\ -\dfrac{1}{27z^2} = 2\lambda z \end{cases} \iff \begin{cases} x^3 = -\dfrac{1}{2\lambda} \\ \\ y^3 = -\dfrac{1}{8\cdot 2\lambda} \\ \\ z^3 = -\dfrac{1}{27\cdot 2\lambda} \end{cases} \iff \begin{cases} x = -\sqrt[3]{\dfrac{1}{2\lambda}} \\ \\ y = -\dfrac{1}{2}\sqrt[3]{\dfrac{1}{2\lambda}} \\ \\ z = -\dfrac{1}{3}\sqrt[3]{\dfrac{1}{2\lambda}} \end{cases} \iff \begin{cases} x = -\sqrt[3]{\dfrac{1}{2\lambda}} \\ \\ y = -\dfrac{1}{2}\cdot x \\ \\ z = -\dfrac{1}{3}\cdot x \end{cases}$$

3.5 Hint

The points lie on the unit sphere, so $x^2 + y^2 + z^2 = 1$ must also hold.

3.6 Solution

$$\begin{aligned}
x^2 + \left(-\frac{1}{2} \cdot x\right)^2 + \left(-\frac{1}{3} \cdot x\right)^2 &= 1 \\
\iff x^2 \cdot \left(1 + \frac{1}{4} + \frac{1}{9}\right) &= 1 \\
\iff x^2 \cdot \frac{49}{36} &= 1 \\
\iff x^2 &= \frac{36}{49} \\
\iff x &= \pm\frac{6}{7}
\end{aligned}$$

We get two solutions:

$$\begin{aligned}
x &= \frac{6}{7} \\
y &= -\frac{1}{2} \cdot x = -\frac{3}{7} \\
z &= -\frac{1}{3} \cdot x = -\frac{2}{7}
\end{aligned}$$

and

$$\begin{aligned}
x &= -\frac{6}{7} \\
y &= -\frac{1}{2} \cdot x = \frac{3}{7} \\
z &= -\frac{1}{3} \cdot x = \frac{2}{7}
\end{aligned}$$

In order to determine which one gives the minimum and which one the maximum, we substitute in f:

$$\begin{aligned}
f\left(\frac{6}{7}, -\frac{3}{7}, -\frac{2}{7}\right) &= \frac{1}{-6/7} + \frac{1}{8 \cdot (-3/7)} + \frac{1}{27 \cdot (-2/7)} \\
&= -\frac{7}{6} - \frac{7}{24} - \frac{7}{54} \\
&= -\frac{373}{216}
\end{aligned}$$

and

$$\begin{aligned}
f\left(-\frac{6}{7}, \frac{3}{7}, \frac{2}{7}\right) &= \frac{1}{6/7} + \frac{1}{8 \cdot 3/7} + \frac{1}{27 \cdot 2/7} \\
&= \frac{7}{6} + \frac{7}{24} + \frac{7}{54} \\
&= \frac{373}{216}
\end{aligned}$$

So f achieves a maximum value of $373/216$ at

$$\left(-\frac{6}{7}, \frac{3}{7}, \frac{2}{7}\right)$$

and a minimum value of $-373/216$ at

$$\left(\frac{6}{7}, -\frac{3}{7}, -\frac{2}{7}\right).$$

4 Exercise

Consider the function

$$f(x, y) = \frac{x^2 + y^2}{xy}$$

defined on the set

$$K = \{(x, y) : 0 < x \leq 1, 0 < y \leq 1\}.$$

Determine where f assumes its minimum, and what that minimum value is.

4.1 Hint

Calculate ∇f.

4.2 Hint

$$\begin{aligned}
\frac{\partial f}{\partial x} &= \left(\frac{xy \cdot 2x - (x^2 + y^2) \cdot y}{x^2 y^2}\right) \\
&= \frac{x^2 y - y^3}{x^2 y^2} \\
&= \frac{x^2 - y^2}{x^2 y}
\end{aligned}$$

By symmetry, we have:

$$\frac{\partial f}{\partial y} = \frac{y^2 - x^2}{xy^2}$$

So

$$\nabla f(x, y) = \begin{pmatrix} \frac{\partial f}{\partial x} \\ \\ \frac{\partial f}{\partial y} \end{pmatrix} = \begin{pmatrix} \frac{x^2 - y^2}{x^2 y} \\ \\ \frac{y^2 - x^2}{xy^2} \end{pmatrix}$$

4.3 Hint

Solve $\nabla f = 0$.

4.4 Hint

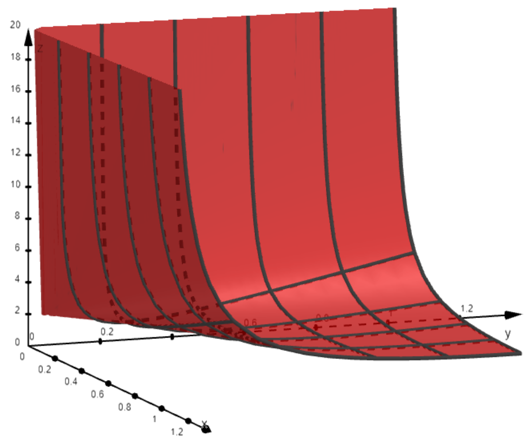
$$\begin{pmatrix} \frac{x^2 - y^2}{x^2 y} \\ \\ \frac{y^2 - x^2}{xy^2} \end{pmatrix} = 0 \iff x^2 - y^2 = 0 \iff x = \pm y$$

4.5 Solution

Note that since $x, y > 0$ on K, we cannot have $x = -y$. Substituting $y = x$ in f we get:

$$f(x, x) = \frac{x^2 + x^2}{x^2} = 2$$

So f achieves its minimum value 2 on the entire line segment $x = y$, $0 < x \leq 1, 0 < y \leq 1$.



20
18
16
14
12
10
8
6
4
2
0
z
0
0.2
1.2
y
0
0.2
0.4
0.6
0.8
1
1.2
x

5 Exercise

Consider the surface S defined by $f(x, y, z) = 0$, where

$$f(x, y, z) = x^2 + y^2 + z^2 + 3xy - z - 11$$

1. Check that $A = (1, 1, 3)$ lies on S.
2. Give an equation of the form $\alpha x + \beta y + \gamma z = \delta$ describing the tangent plane to S at point A.

5.1 Hint

1. Substitute $x = 1$, $y = 1$, $z = 3$ in f to get:

$$1^2 + 1^2 + 3^2 + 3 \cdot 1 \cdot 1 - 3 - 11 = 0.$$

5.2 Hint

2. There are several ways to go about this, but in most (if not all) you need to compute ∇f at the point A.

5.3 Hint

$$\nabla f(x, y, z) = \begin{pmatrix} \dfrac{\partial f}{\partial x} \\ \\ \dfrac{\partial f}{\partial y} \\ \\ \dfrac{\partial f}{\partial z} \end{pmatrix} = \begin{pmatrix} 2x + 3y \\ 3x + 2y \\ 2z - 1 \end{pmatrix}$$

So

$$\nabla f(1, 1, 3) = \begin{pmatrix} 2 \cdot 1 + 3 \cdot 1 \\ 3 \cdot 1 + 2 \cdot 1 \\ 2 \cdot 3 - 1 \end{pmatrix} = \begin{pmatrix} 5 \\ 5 \\ 5 \end{pmatrix}$$

5.4 Hint

The gradient of f at A is a vector orthogonal to the tangent plane to S at point A. How do you find an equation of a plane if you know a vector orthogonal to it and a point on it?

5.5 Solution

The tangent plane is perpendicular to the vector $\nabla f(1, 1, 3) = (5, 5, 5)$ and passes through the point $(1, 1, 3)$, so its equation is:

$$5 \cdot (x - 1) + 5 \cdot (y - 1) + 5 \cdot (z - 3) = 0 \iff 5x + 5y + 5z = 25$$

Remark: *There is also a formula given in the book as the linearization of f at $A = (x_0, y_0, z_0)$:*

$$L(x, y, z) = f(A) + f_x(A) \cdot (x - x_0) + f_y(A) \cdot (y - y_0) + f_z(A) \cdot (z - z_0)$$

(this is essentially a first order Taylor expansion). The formula will yield the exact same answer. However, applying formulas without understanding is like eating your food without chewing!

6 Exercise

Consider the plane P which contains the points $A = (1, 1, 1)$, $B = (2, 3, 9)$, $C = (3, 5, 4)$. Try to think of as many was as possible to determine the equation $\alpha x + \beta y + \gamma z = \delta$ of this plane.

6.1 Method 1

Just substitute the coordinates of the 3 points in $\alpha x + \beta y + \gamma z = \delta$ and solve for α, β, γ, δ.

6.2 Solution 1

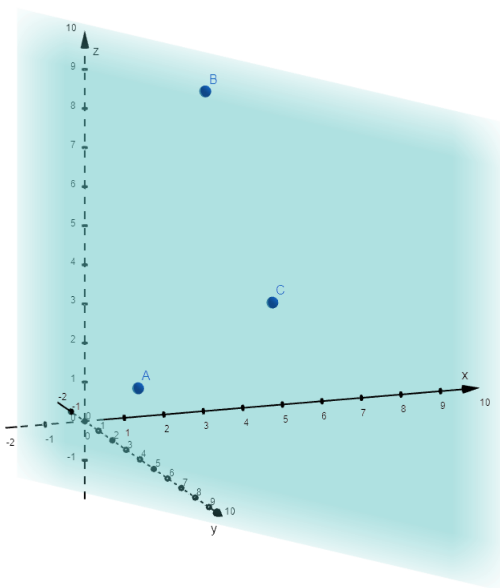
$$\begin{aligned}
&\begin{cases} \alpha + \beta + \gamma = \delta \\ 2\alpha + 3\beta + 9\gamma = \delta \quad | \quad R_2 \leftarrow R_2 - 2R_1 \\ 3\alpha + 5\beta + 4\gamma = \delta \quad | \quad R_3 \leftarrow R_3 - 3R_1 \end{cases} \\
\iff &\begin{cases} \alpha + \beta + \gamma = \delta \\ \beta + 7\gamma = -\delta \\ 2\beta + \gamma = -2\delta \quad | \quad R_3 \leftarrow R_2 - \frac{1}{2}R_3 \end{cases} \\
\iff &\begin{cases} \alpha + \beta + \gamma = \delta \\ \beta + 7\gamma = -\delta \\ \frac{13}{2}\gamma = 0 \end{cases} \\
\iff &\begin{cases} \alpha = 2\delta \\ \beta = -\delta \\ \gamma = 0 \end{cases}
\end{aligned}$$

Note that δ is a free variable here, and

$$2\delta \cdot x - \delta \cdot y + 0 \cdot z = \delta$$

defines the same plane for any $\delta \neq 0$ (for $\delta = 0$ we just get $0 = 0$ which is satisfied by any x, y, z, i.e. we don't get a plane but the entire $\mathbb{R}^3$). So we can choose for example $\delta = 1$ to get the following equation for P:

$$2x - y = 1$$



6.3 Method 2

Make the vectors $\overrightarrow{AB}$, $\overrightarrow{AC}$ and compute the vector $\overrightarrow{AB} \times \overrightarrow{AC}$. Then...

6.4 Solution 2

$$\overrightarrow{AB} = \overrightarrow{B} - \overrightarrow{A} = (2,3,9) - (1,1,1) = (1,2,8)$$
$$\overrightarrow{AC} = \overrightarrow{C} - \overrightarrow{A} = (3,5,4) - (1,1,1) = (2,4,3)$$

$$\begin{aligned}
\overrightarrow{AB} \times \overrightarrow{AC} &= \begin{vmatrix} 1 & 2 & 8 \\ 2 & 4 & 3 \\ e_x & e_y & e_z \end{vmatrix} \\
&= \begin{vmatrix} 2 & 8 \\ 4 & 3 \end{vmatrix} \cdot e_x - \begin{vmatrix} 1 & 8 \\ 2 & 3 \end{vmatrix} \cdot e_y + \begin{vmatrix} 1 & 2 \\ 2 & 4 \end{vmatrix} \cdot e_z \\
&= -26 \cdot e_x + 13 \cdot e_y + 0 \cdot e_z \\
&= (-26, 13, 0)
\end{aligned}$$

Now $\overrightarrow{AB} \times \overrightarrow{AC}$ is normal to P and A lies on P, so we get the following equation for P:

$$-26 \cdot (x-1) + 13 \cdot (y-1) + 0 \cdot (z-1) = 0 \iff -26x + 13y = -13$$

6.5 Method 3

Find a vector (α, β, γ) that is orthogonal to $\overrightarrow{AB}$, $\overrightarrow{AC}$ by solving the system

$$\overrightarrow{AB} \cdot (\alpha, \beta, \gamma) = 0$$
$$\overrightarrow{AC} \cdot (\alpha, \beta, \gamma) = 0$$

Then...

6.6 Solution 3

$$\begin{aligned}
&\begin{cases} (1,2,8) \cdot (\alpha, \beta, \gamma) = 0 \\ (2,4,3) \cdot (\alpha, \beta, \gamma) = 0 \end{cases} \\
\iff &\begin{cases} \alpha + 2\beta + 8\gamma = 0 \\ 2\alpha + 4\beta + 3\gamma = 0 \quad | \quad R_2 \leftarrow R_2 - 2R_1 \end{cases} \\
\iff &\begin{cases} \alpha + 2\beta + 8\gamma = 0 \\ -13\gamma = 0 \end{cases} \\
\iff &\begin{cases} \alpha = -2\beta \\ \gamma = 0 \end{cases}
\end{aligned}$$

Choose $\beta = 1$, so $(\alpha, \beta, \gamma) = (-2, 1, 0)$, and the equation for P becomes:

$$-2 \cdot x + 1 \cdot y + 0 \cdot z = \delta$$

Substitute $(1,1,1)$ in the equation to find δ:

$$\delta = -2 + 1 = -1$$

So the equation for P is:

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

7 Exercise

Find all points that are equidistant to the 3 points $A = (2, 2, 0)$, $B = (0, 3, 3)$, $C = (4, 0, 4)$.

7.1 Hint

Let $P = (x, y, z)$ be such a point. Write down equations for the distances of P from A, B, C to be equal, i.e.:

$$\left|\overrightarrow{PA}\right|^2 = \left|\overrightarrow{PB}\right|^2 = \left|\overrightarrow{PC}\right|^2$$

7.2 Hint

$$\left|\overrightarrow{PA}\right|^2 = (x-2)^2 + (y-2)^2 + (z-0)^2,$$

etc.

7.3 Hint

$$\begin{aligned}
&(x-2)^2 + (y-2)^2 + (z-0)^2 \\
&= (x-0)^2 + (y-3)^2 + (z-3)^2 \\
&= (x-4)^2 + (y-0)^2 + (z-4)^2 \\
\iff& \\
&x^2 + y^2 + z^2 - 4x - 4y + 8 \\
&= x^2 + y^2 + z^2 - 6y - 6z + 18 \\
&= x^2 + y^2 + z^2 - 8x - 8z + 32 \\
\iff& \\
&-4x - 4y \\
&= -6y - 6z + 10 \\
&= -8x - 8z + 24 \\
\iff& \\
&2x + 2y \\
&= 3y + 3z - 10 \\
&= 4x + 4z - 12
\end{aligned}$$

7.4 Hint

Note that in fact we have 2 equations:

$$\begin{cases} 2x + 2y = 3y + 3z - 10 \\ 2x + 2y = 4x + 4z - 12 \end{cases} \iff \begin{cases} 2x - y - 3z = -10 \\ -2x + 2y - 4z = -12 \end{cases}$$

So the solution is the intersection of 2 planes, i.e. a line! How can we find the equation of the line in parametric form?

7.5 Hint

This is now a linear algebra problem.

$$
\begin{aligned}
&\left(\begin{array}{ccc|c} 2 & -1 & -3 & -10 \\ -2 & 2 & -4 & -12 \end{array}\right) \quad | \quad R_2 \leftarrow R_2 + R_1 \\
\rightarrow &\left(\begin{array}{ccc|c} 2 & -1 & -3 & -10 \\ 0 & 1 & -7 & -22 \end{array}\right) \quad | \quad R_1 \leftarrow R_1 + R_2 \\
\rightarrow &\left(\begin{array}{ccc|c} 2 & 0 & -10 & -32 \\ 0 & 1 & -7 & -22 \end{array}\right) \quad | \quad R_1 \leftarrow \frac{1}{2} R_1 \\
\rightarrow &\left(\begin{array}{ccc|c} 1 & 0 & -5 & -16 \\ 0 & 1 & -7 & -22 \end{array}\right)
\end{aligned}
$$

So

$$
\begin{cases} x - 5z = -16 \\ y - 7z = -22 \end{cases} \iff \begin{cases} x = 5z - 16 \\ y = 7z - 22 \end{cases},
$$

where z is free. So there is a line of points equidistant from A, B, C given by the equation:

$$
(x, y, z) = (5\lambda - 16, 7\lambda - 22, \lambda)
$$

for $\lambda \in \mathbb{R}$.

8 Exercise

Consider the following 5 points:

$$A = (0,0,0), \quad B = (2,0,0), \quad C = (4,4,0), \quad D = (4,0,4), \quad E = (0,0,4)$$

Find all the points that are equidistant from A, B, C, D, E.

8.1 Hint

Let $P = (x, y, z)$ be such a point. Write down equations for the distances of P from A, B, C to be equal, i.e.:

$$\left|\overrightarrow{PA}\right|^2 = \left|\overrightarrow{PB}\right|^2 = \left|\overrightarrow{PC}\right|^2 = \left|\overrightarrow{PD}\right|^2 = \left|\overrightarrow{PE}\right|^2$$

8.2 Hint

$$\left|\overrightarrow{PB}\right|^2 = (x-2)^2 + (y-0)^2 + (z-0)^2,$$

etc.

8.3 Hint

$$\begin{aligned}
&(x-0)^2 + (y-0)^2 + (z-0)^2 \\
&= (x-2)^2 + (y-0)^2 + (z-0)^2 \\
&= (x-4)^2 + (y-4)^2 + (z-0)^2 \\
&= (x-4)^2 + (y-0)^2 + (z-4)^2 \\
&= (x-0)^2 + (y-0)^2 + (z-4)^2 \\
\iff& \\
&x^2 + y^2 + z^2 \\
&= x^2 + y^2 + z^2 - 4x + 4 \\
&= x^2 + y^2 + z^2 - 8x - 8y + 32 \\
&= x^2 + y^2 + z^2 - 8x - 8z + 32 \\
&= x^2 + y^2 + z^2 - 8z + 16 \\
\iff& \\
&0 \\
&= -4x + 4 \\
&= -8x - 8y + 32 \\
&= -8x - 8z + 32 \\
&= -8z + 16
\end{aligned}$$

8.4 Solution

We have:

$$0 = -4x + 4 \iff x = 1$$

For $x = 1$:

$$0 = -8x - 8y + 32 = -8y + 24 \iff y = 3$$

For $x = 1, y = 3$:

$$0 = -8x - 8z + 32 \iff z = 3$$

But now for $x = 1,\ y = 3,\ z = 3$:

$$-8z + 16 = 0 \implies -8 = 0,$$

contradiction! So there are no points equidistant from A, B, C, D, E.