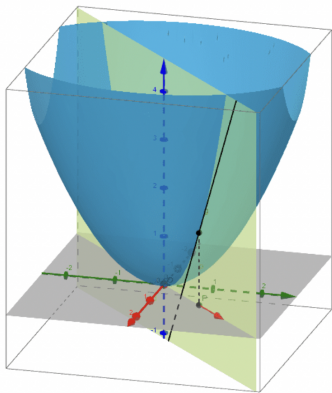


MATH 224: Vector Calculus



Class 12: March 6, 2026



Daylight Saving Time Starts

March 8, 2026

Remember to set your clocks **ahead** one hour Saturday night or Sunday morning the weekend of March 9.



- ▶ Notes on Assignment 10
- ▶ Assignment 11
- ▶ AWM Stress Buster



$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

AWM Stress Busters and Election Information



Overwhelmed with midterms? Needing a study break? Want to hang out with other students interested in math? Join AWM for a stress buster event this Friday 2:30-4:00 pm!

We will provide:

- Snacks
- Coloring pages
- Cards
- Board games
- and more!

Additionally, elections for next year's AWM board are happening soon. If you are interested please be sure to attend this meeting!

Friday 3/6 2:30-4pm
Warner 101
awm@middlebury.edu

Today

**Partial With Respect to a
Vector**

Directional Derivative

Definition: A **real-valued function** f is **differentiable at a point** \mathbf{a} means there is a 1 by n matrix \mathbf{m} such that

$$\lim_{|\mathbf{h}| \rightarrow 0} \frac{f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) - \mathbf{m}\mathbf{h}}{|\mathbf{h}|} = 0$$

Theorem 4.2.1: If f is a real-valued function differentiable at a point, then \mathbf{m} is the vector of first order partial derivatives evaluated at that point.

Theorem 4.2.2: If f has continuous first order partial derivatives at a point, then f is differentiable at that point.

Definition: A **real-valued function** f is **differentiable at a point** \mathbf{a} means there is a 1 by n matrix \mathbf{m} such that

$$\lim_{\mathbf{h} \rightarrow 0} \frac{f(\mathbf{a} + \mathbf{h}) - f(\mathbf{a}) - \mathbf{m}\mathbf{h}}{|\mathbf{h}|} = 0$$

An equivalent definition is

$$\lim_{\mathbf{x} \rightarrow \mathbf{a}} \frac{f(\mathbf{x}) - f(\mathbf{a}) - \nabla f(\mathbf{a}) \cdot (\mathbf{x} - \mathbf{a})}{|\mathbf{x} - \mathbf{a}|} = 0$$

If $f : \mathbb{R}^2 \rightarrow \mathbb{R}^1$ is differentiable at \mathbf{a} , then

$$f(\mathbf{x}) \approx f(\mathbf{a}) + \nabla f(\mathbf{a}) \cdot (\mathbf{x} - \mathbf{a})$$

If $f : \mathbb{R}^2 \rightarrow \mathbb{R}^1$ is differentiable at \mathbf{a} , then

$$f(\mathbf{x}) \approx f(\mathbf{a}) + (f_x(\mathbf{a}), f_y(\mathbf{a})) \cdot (\mathbf{x} - \mathbf{a})$$

Right hand Side is Equation of a Plane

Partial With Respect to a Vector

Let $f(x, y) = x^2y$ and $\mathbf{a} = (3, 9)$ so $f(3, 9) = 81$.

Find the partial derivative of f at $(3, 9)$ if we approach $(3, 9)$ along arbitrary vector $\mathbf{v} = (v_1, v_2)$.

$$\text{We want } f_{\mathbf{v}}(\mathbf{a}) = \lim_{t \rightarrow 0} \frac{f(\mathbf{a} + t\mathbf{v}) - f(\mathbf{a})}{t}$$

$$\begin{aligned} f_{\mathbf{v}}(\mathbf{a}) &= \lim_{t \rightarrow 0} \frac{f(3 + tv_1, 9 + tv_2) - f(3, 9)}{t} \\ &= \lim_{t \rightarrow 0} \frac{(3 + tv_1)^2(9 + tv_2) - (3^2)(9)}{t} \\ &= \lim_{t \rightarrow 0} \frac{(3^2 + 6tv_1 + t^2v_1^2)(9 + tv_2) - (3^2 \cdot 9)}{t} \\ &= \lim_{t \rightarrow 0} \frac{(3^2)(9) + 3^2tv_2 + 6tv_1(9) + 6t^2v_1v_2 + t^2v_1^2(9) + t^3v_1^2v_2 - (3^2 \cdot 9)}{t} \\ &= \lim_{t \rightarrow 0} (3^2v_2 + 54v_1 + 6tv_1v_2 + tv_1^2(9) + t^2v_1^2v_2) \\ &= 9v_2 + 54v_1 = 54v_1 + 9v_2 \end{aligned}$$

Let $f(x, y) = x^2y$ and $\mathbf{a} = (3, 9)$ so $f(3, 9) = 81$.
Find the partial derivative of f at $(3, 9)$ if we approach $(3, 9)$ along
arbitrary vector $\mathbf{v} = (v_1, v_2)$.

$$f_{\mathbf{v}}(\mathbf{a}) = 54v_1 + 9v_2 = (54, 9) \cdot (v_1, v_2)$$

Note

$$f_x(x, y) = 2xy \text{ and } f_y(x, y) = x^2 \text{ so } f_x(3, 9) = 54, f_y(3, 9) = 9$$

Thus

$$f_{\mathbf{v}}(\mathbf{a}) = \nabla f(\mathbf{a}) \cdot \mathbf{v}$$

(In This Case At Least)

Theorem: If $f : \mathbb{R}^n \rightarrow \mathbb{R}^1$ is differentiable at \mathbf{a} , then

$$f_{\mathbf{v}}(\mathbf{a}) = \nabla f(\mathbf{a}) \cdot \mathbf{v}$$

Proof of Theorem:

(Case 1): $\mathbf{v} = \mathbf{0}$: Both sides are 0.

(Case 2): $\mathbf{v} \neq \mathbf{0}$:

Note: $|\mathbf{v}| \neq 0$ so we can divide by $|\mathbf{v}|$ if necessary.

By differentiability of f at \mathbf{a} , we have

$$\lim_{\mathbf{x} \rightarrow \mathbf{a}} \frac{f(\mathbf{x}) - f(\mathbf{a}) - \nabla f(\mathbf{a}) \cdot (\mathbf{x} - \mathbf{a})}{|\mathbf{x} - \mathbf{a}|} = 0$$

Set $\mathbf{x} = \mathbf{a} + t\mathbf{v}$ so $\mathbf{x} \rightarrow \mathbf{a}$ is equivalent to $t \rightarrow 0$ and $\mathbf{x} - \mathbf{a} = t\mathbf{v}$

We have

$$\lim_{t \rightarrow 0} \frac{f(\mathbf{a} + t\mathbf{v}) - f(\mathbf{a}) - \nabla f(\mathbf{a}) \cdot t\mathbf{v}}{|t\mathbf{v}|} = 0$$

$$\lim_{t \rightarrow 0} \frac{f(\mathbf{a} + t\mathbf{v}) - f(\mathbf{a}) - \nabla f(\mathbf{a}) \cdot t\mathbf{v}}{|t\mathbf{v}|} = 0$$

Now $|t\mathbf{v}| = |t||\mathbf{v}|$

Can take $t > 0$ (Why?). So $|t\mathbf{v}| = t|\mathbf{v}|$

We can write limit as

$$\lim_{t \rightarrow 0} \left[\frac{f(\mathbf{a} + t\mathbf{v}) - f(\mathbf{a})}{t|\mathbf{v}|} - \frac{t\nabla f(\mathbf{a}) \cdot \mathbf{v}}{t|\mathbf{v}|} \right] = 0$$

Factor out t from second term and multiply both sides by the nonzero scalar $|\mathbf{v}|$ to obtain

$$\lim_{t \rightarrow 0} \left[\frac{f(\mathbf{a} + t\mathbf{v}) - f(\mathbf{a})}{t} - \nabla f(\mathbf{a}) \cdot \mathbf{v} \right] = 0$$

$$\lim_{t \rightarrow 0} \left[\frac{f(\mathbf{a} + t\mathbf{v}) - f(\mathbf{a})}{t} - \nabla f(\mathbf{a}) \cdot \mathbf{v} \right] = 0$$

implies

$$\lim_{t \rightarrow 0} \left[\frac{f(\mathbf{a} + t\mathbf{v}) - f(\mathbf{a})}{t} \right] = \nabla f(\mathbf{a}) \cdot \mathbf{v}$$

But the left hand side is, by definition $f_{\mathbf{v}}(\mathbf{a})$

Directional Derivative

Let $f(x, y) = x^2y$ and $\mathbf{a} = (3, 9)$ so $f(3, 9) = 81$.

Find the directional derivative of f at $(3, 9)$ in the direction of the vector $\mathbf{v} = (v_1, v_2)$.

$$\text{Recall } f_{\mathbf{v}}(\mathbf{a}) = \nabla f(\mathbf{a}) \cdot \mathbf{v}$$

But $\mathbf{w} = 2\mathbf{v}$ points in the same direction as \mathbf{v} .

However

$$f_{\mathbf{w}}(\mathbf{a}) = \nabla f(\mathbf{a}) \cdot \mathbf{w} = 2\nabla f(\mathbf{a}) \cdot \mathbf{v} = 2f_{\mathbf{v}}(\mathbf{a})$$

We want a rate of change that depends only on **DIRECTION**

Idea: Choose a **unit vector** \mathbf{u} in that direction that has length 1;
that is

$$\mathbf{u} = \frac{\mathbf{v}}{|\mathbf{v}|}$$

Directional Derivative

Let $f(x, y) = x^2y$ and $\mathbf{a} = (3, 9)$

Find the directional derivative of f at $(3, 9)$ in the direction of the vector $\mathbf{v} = (v_1, v_2)$.

The Directional Derivative is $\nabla f(\mathbf{a}) \cdot \frac{\mathbf{v}}{|\mathbf{v}|}$ where $|\mathbf{v}| = \sqrt{v_1^2 + v_2^2}$

Normalizing a Vector:

Example $\mathbf{v} = (3, 5)$. The $|\mathbf{v}| = \sqrt{3^2 + 5^2} = \sqrt{34}$. The unit vector is

$$\mathbf{u} = \left(\frac{3}{\sqrt{34}}, \frac{5}{\sqrt{34}} \right)$$

Rate of Change in Direction \mathbf{u} is

$$\nabla f(\mathbf{a}) \cdot \mathbf{u} = |\nabla f(\mathbf{a})| |\mathbf{u}| \cos \theta = |\nabla f(\mathbf{a})| \cos \theta$$

since $|\mathbf{u}| = 1$.

Maximum rate of change occurs when $\cos \theta = 1$; that is $\theta = 0$ so pick \mathbf{u} in the direction of the gradient.