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WIP: On Visual and Intuitive Understanding of the Concept of Partial Derivative

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Abstract

Understanding partial derivatives often poses a conceptual challenge for students, who tend to memorize formulas rather than internalize their physical meaning. This paper presents a visual and intuitive approach to teaching how a multivariable quantity changes with respect to one variable while keeping others constant. Partial derivatives are interpreted as *directional sensitivities*, slopes measured along one axis while the others remain fixed, helping students see change, not just compute it.

The paper organizes a broad range of visual and experiential examples into several categories:
(a) Daily-life experiences: slicing bread (revealing slope in one direction), riding a roller coaster (change along the track), and driving on a wavy road (height varying with both position and time).
(b) Analogies and visualizations: sand dunes, landscapes, and topographic maps showing how fixing one variable creates meaningful cross-sections.
(c) Engineering examples: heat flow across a metal plate.
(d) Computer science examples: image brightness variations used in edge detection.
(e) Scientific examples: melting ice cream and chemical concentration in a tube.
(f) Mathematical visualization: colored slices or tangent lines on 3D surfaces illustrating directional change.

Together, these examples help students visualize the transition from a traditional single-variable derivative to multiple directional derivatives, linking mathematical models with physical intuition and real-world experiences.

Following an initial qualitative assessment, a more rigorous extra-credit evaluation was conducted. Students identified partial derivatives from STEM fields and rated this teaching approach. Scores showing strong support for intuitive, visual methods that students found exciting, practical, and memorable. Engagement scores indicated that adding real physical systems could enhance learning. Ratings for reducing heavy derivations suggest a preference for intuition and visualization before mathematical detail.

This work in progress does not aim to modify textbook chapters but rather to provide a supplementary, visually grounded resource that enhances the introduction of the partial derivative concept and promotes intuitive understanding.

Key words: Calculus, partial derivative

1. Introduction

A recurring challenge in mathematics education is that the intuitive meaning behind new ideas is often minimized or lost. This issue becomes especially apparent when concepts are introduced primarily through formal definitions and symbolic procedures, with few connections to familiar, real-world experiences. Partial derivatives are no exception. Although the multivariable derivative is usually defined clearly and rigorously in textbooks, students often struggle to internalize what it truly means for a function to change with respect to one variable while the others are held constant.

This paper presents a collection of visual, intuitive, and everyday examples designed to illuminate the underlying ideas behind partial derivatives. By emphasizing graphical interpretations, physical analogies, and interactive “slice-based” thinking, we aim to make the concept more approachable prior to engaging with the full mathematical framework.

Our intention is to offer instructors flexible supplementary material that can be incorporated without replacing or competing with existing textbooks or lectures. The examples are versatile and suitable for students with diverse backgrounds. Even a single illustration or analogy may trigger an “aha” moment, helping students grasp the essence of partial derivatives in a meaningful and lasting way.

In this paper, the illustrative examples are organized into five thematic groups, each offering a different lens through which students can develop an intuitive feel for partial derivatives. The collection spans a wide range of settings, from everyday experiences to engineering and scientific applications, highlighting how “changing one variable while holding others fixed” naturally appears in many contexts.

(a) Everyday phenomena. Simple, familiar situations, such as slicing a loaf of bread to reveal how thickness changes along a single direction, moving along a roller-coaster track where elevation varies point by point, or driving along an uneven road whose profile changes with position and speed, provide intuitive entry points for understanding one-dimensional changes extracted from richer, multivariable environments.

(b) Visual analogies. Landscapes, sand formations, and contour or topographic maps demonstrate how fixing one variable produces informative cross-sections. These visual cues help students see how a surface “behaves” when examined along one coordinate direction.

(c) Engineering contexts. Classical problems, such as temperature gradients on a metal plate, show how partial derivatives capture how heat changes with respect to one spatial coordinate while other factors remain constant.

(d) Computing and information examples. Variations in image intensity used in edge-detection algorithms illustrate how computer vision systems rely on partial changes in brightness across horizontal or vertical directions.

(e) Scientific and mathematical illustrations. Examples such as the rate at which ice cream melts along one dimension of a container, or how chemical concentration varies along a tube, reinforce the idea of isolating directional change. Complementary mathematical visualizations, colored slices, level curves, and tangent lines on 3-D surfaces, further demonstrate how partial derivatives quantify change along specific coordinate "slices."

We always reminded the students that a partial derivative is defined as the rate of change of a multi-variable function with respect to just one of its variables, with all others held constant. This mathematical technique allows for the examination of the slope of a surface in only one direction at a time.

After observing encouraging informal feedback during early class discussions, a more structured evaluation was carried out through an extra-credit assignment. 27 Students were asked to locate examples of partial derivatives in fields such as chemistry, physics, and biology, and to comment on the overall instructional approach. Their ratings, reported on a 1–10 scale, indicated strong approval of the visual and intuitive methodology, with most items receiving scores in the 8–10 range. Students described the examples as engaging, practical, and easy to recall. They emphasized that diagrams and intuition-driven explanations were particularly helpful for grasping the underlying ideas. Engagement ratings (7–10) also suggested that introducing additional hands-on, physical demonstrations, rather than relying solely on simulations, could further enhance understanding. Many students expressed a desire to minimize lengthy algebraic derivations at the outset, preferring to build intuition and visual comprehension before moving on to detailed mathematical formulations.

This work should be viewed as part of an ongoing effort (work in progress), as additional assessment will be needed to fully determine the instructional impact of this approach. Nonetheless, prior experience at our institution indicates that students consistently value the use of visual, intuitive, and engaging examples across multiple STEM subjects.

Numerous efforts have been made to make mathematical ideas more accessible. Calculus, in particular, is often perceived as daunting and difficult when introduced primarily through traditional textbook formats [1][2][3]. Various authors have responded by experimenting with alternative forms of presentation, some using humor or playful narratives to draw readers in [4], others grounding explanations in common, relatable experiences [5], or embedding concepts within storylines that students can follow [6]. Additional works [7] and [8] emphasize visual interpretations and provide multiple examples aimed at clarifying calculus concepts through imagery. Notably, the author of [9] demonstrated that many foundational ideas in calculus can be communicated visually without relying on algebraic expressions.

Taken together, these approaches reflect a growing movement toward more creative, intuitive, and student-centered ways of teaching calculus.

2. Class examples

The paper organizes a broad range of visual and experiential examples into several categories:

(a) Daily-life experiences: slicing bread (revealing slope in one direction), riding a roller coaster (change along the track), and driving on a wavy road (height varying with both position and time).

a1. Slicing bread (fixing one variable, changing another)

Imagine a loaf of bread as a height function $h(x, y)$over a rectangular domain (refer to Figure 1). When the loaf is sliced straight through, one fixes the left–right direction (say y) and moves only along the x-direction, revealing the one-dimensional profile of the crumb. The resulting slope along that slice corresponds to the partial derivative $\partial h/ \partial x$. Turning the loaf and slicing the other way exposes the complementary slice and the partial derivative $\partial h/ \partial y$. This simple analogy provides an intuitive physical visualization of holding one variable fixed while varying another.

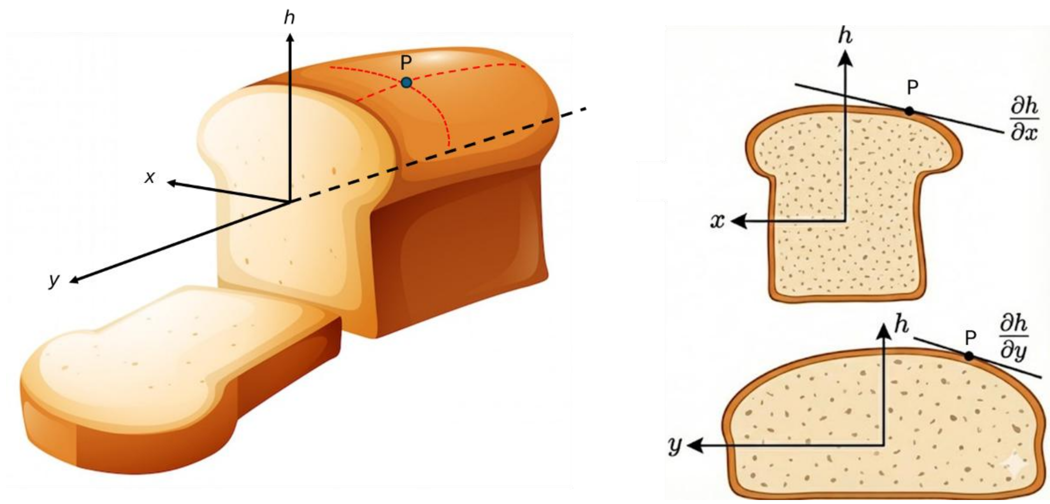

Figure 1. Directional bread slicing

a2. Riding a roller coaster

A roller coaster occupies a three-dimensional space, where its height can be viewed as a function $h(x, y)$ defined over a surface. As the cart travels forward, it follows a specific curve on that surface rather than moving freely in all directions. The instantaneous feeling of "steepness" corresponds to a directional partial derivative of h along the track, capturing how rapidly the elevation changes in the direction of motion. This example reinforces the idea that partial derivatives quantify change along one variable while keeping others fixed.

a3. Driving on a wavy road

Driving along a wavy road provides a natural way to visualize how slope depends on direction. The road's elevation can be described as a function $h(x, y)$ of horizontal position. When a driver continues straight north, the east–west coordinate remains fixed, so the experienced incline corresponds to the partial derivative of h in the northward direction. Conversely, when driving straight east, the north–south coordinate is held constant and the slope felt in that direction reflects the partial derivative with respect to eastward motion. This example reinforces that the perceived slope is not a property of the surface alone but of the direction in which one moves across it.

(b) Analogies and visualizations: sand dunes, landscapes, and topographic maps showing how fixing one variable creates meaningful cross-sections.

b1. Topographic maps (holding one variable constant)

Topographic maps illustrate partial derivatives through contour lines that represent curves of constant height (refer to Figure 2). When a hiker moves perpendicular to these contours, the elevation changes most rapidly, reflecting the direction of maximum slope and thus the largest partial derivative along that path. In contrast, moving along a contour keeps the elevation fixed while changing horizontal position, resulting in zero change in height and therefore a zero derivative in that direction. This example visually emphasizes how holding one variable constant while varying another reveals directional rates of change on a surface.

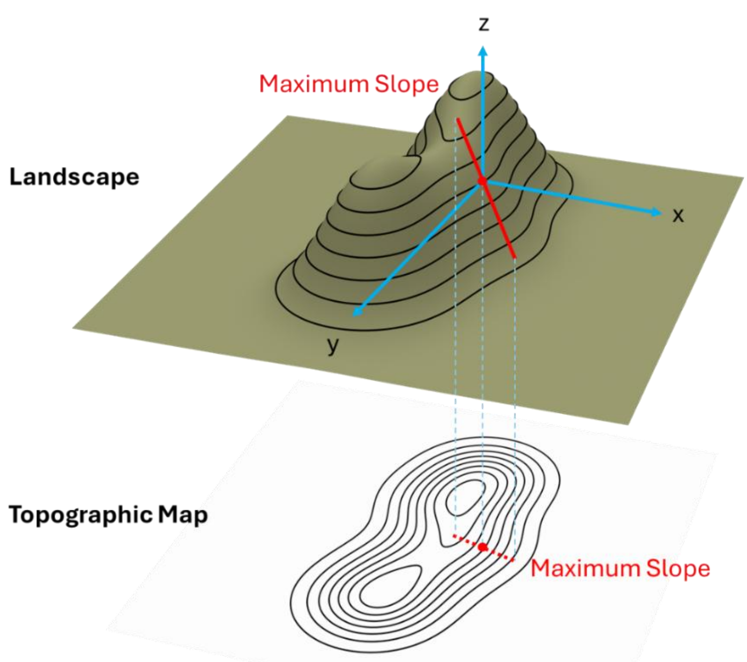

Figure 2. Directional slopes in topographic maps

b2. Sand dunes

Sand dunes can be viewed as continuous surfaces in three-dimensional space whose elevation varies with horizontal position. Walking straight north up a dune samples the change in height in one specific direction, revealing one partial derivative, while walking straight east samples another. Because dunes are often shaped by prevailing winds, they may be noticeably steeper in one direction than another, allowing a person to directly experience directional anisotropy in slope.

b3. Landscapes

Landscapes provide a familiar example of a surface of the form $z = f(x, y)$. Cutting the terrain with a vertical plane where $x$is held constant produces a profile curve, and the slope of that curve at a given point corresponds to $\partial f / \partial y$. Similarly, holding $y$constant generates a profile whose slope reflects $\partial f / \partial x$. Comparing “north–south” versus “east–west” profiles helps illustrate how slope depends on direction and how partial derivatives capture changes along one variable while the other is fixed.

(c) Engineering examples

c1. Heat flow across a metal plate

Heat flow across a metal plate can be described by a temperature field $T(x, y)$ defined over its surface (refer to Figure 3). The partial derivative $\partial T/\partial x$ measures how temperature changes horizontally across the plate, while $\partial T/\partial y$ measures the vertical change. These gradients are directly tied to heat transport: engineers compute heat flux components using $q_x = -k\ \partial T/\partial x$ and $q_y = -k\ \partial T/\partial y$, where k denotes the thermal conductivity. This example highlights that partial derivatives are not merely abstract slopes but physical gradients that drive the flow of heat.

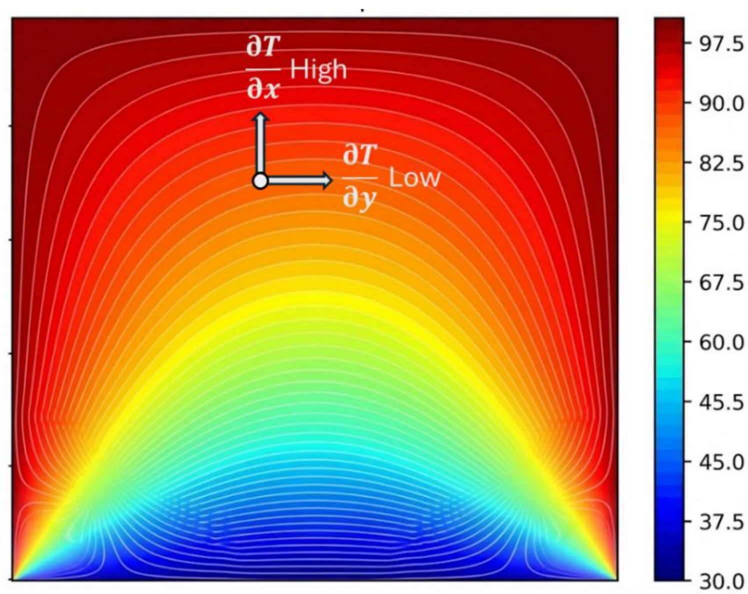

Figure 3. Directional heat changes across a metal plate

c2. Pressure distribution on an aircraft wing

The pressure field over an aircraft wing can be represented as $p(x, y)$, varying across the surface as a function of chordwise and spanwise position. The partial derivative $\partial p/\partial x$ describes how pressure changes along the chord, while $\partial p/\partial y$ captures the change along the wingspan. These gradients contribute to the distribution of aerodynamic forces, and their integration over the wing surface ultimately determines lift. This example demonstrates how partial derivatives encode spatial variations that have direct physical consequences in engineered systems.

c3. Elastic deformation in beams

Elastic deformation in wide beams or plates can be described by a deflection field $w(x, y)$ that varies in two spatial directions. Partial derivatives of w provide information about the local slope and curvature of the surface, which in turn relate to bending strain and internal stresses within the material. In this setting, partial derivatives are not merely geometric slopes but quantities that govern how a structure deforms and carries load.

(d) Computer science examples: image brightness variations used in edge detection.

d1. Image brightness for edge detection

In computer vision, a grayscale image can be modeled as a two-dimensional function $I(x, y)$ that assigns a brightness value to each point in the image plane (refer to Figure 4). Edges correspond to locations where brightness changes rapidly, and these changes are quantified through partial derivatives of I. The horizontal gradient $\partial I/\partial x$ measures intensity variation along the x-direction, while the vertical gradient $\partial I/\partial y$ measures variation along the y-direction. This identifies edge strength and serves as a fundamental operation in many edge-detection algorithms.

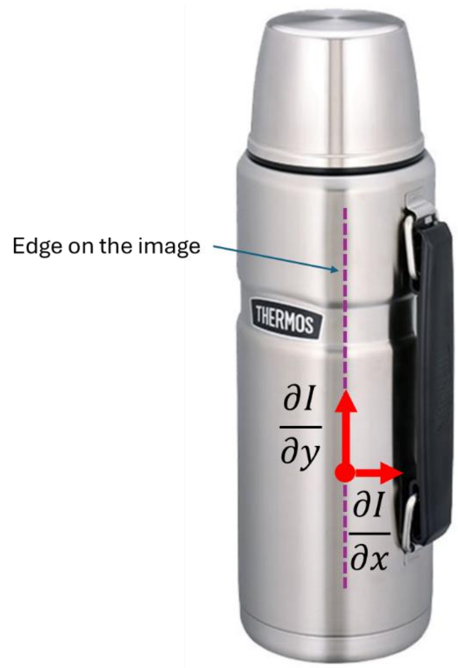

Figure 4. Directional change in image brightness

d2. Terrain modeling in games

Terrain in video games is often represented by a heightmap $h(x, y)$, a surface that assigns elevation to each point in a virtual world. Partial derivatives of this surface are used to compute the normal vector, which depends on $\partial h/\partial x$ and $\partial h/\partial y$, and determines how the terrain interacts with light. These gradients play a direct role in shading models, enabling realistic shadows, highlights, and illumination effects that make landscapes appear three-dimensional and visually coherent.

d3. Neural networks & gradients

In machine learning, a neural network is trained by minimizing a loss function $L(w_1, w_2, \ldots)$defined over its weights. Varying a single weight while keeping the others fixed produces a partial derivative such as $\partial L/\ \partial w_1$, which measures how sensitive the loss is to changes in that specific parameter. These partial derivatives form the gradient of the loss function and are fundamental to optimization procedures like gradient descent, making partial derivatives central to how neural networks learn.

(e) Scientific examples: For example, melting ice cream and chemical concentration in a tube.

e1. Weather and temperature gradients

Weather maps provide a natural setting for understanding partial derivatives, since atmospheric temperature can be viewed as a field $T(x, y, z)$ that varies with longitude, latitude, and altitude (refer to Figure 5). Partial derivatives of Tindicate how temperature changes in a particular direction: horizontally across the surface of the Earth or vertically through the atmosphere. Steep gradients appear where isotherms cluster closely together, corresponding to sharp temperature differences over short distances, while widely spaced contours indicate small gradients and more uniform conditions. This example illustrates how partial derivatives capture directional changes in physical quantities that vary continuously in space.

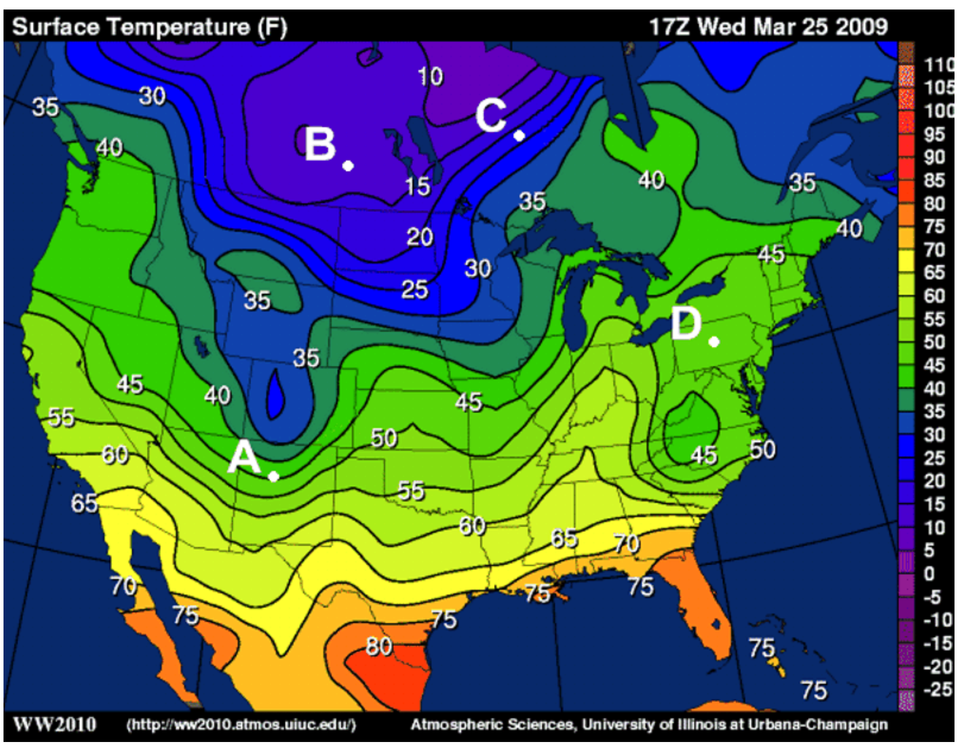

Figure 5. Weather and temperature gradients

e2. Melting ice cream

As ice cream melts, its temperature can be described by a field $T(x, y, t)$ that varies across the surface and evolves over time. The time derivative $\partial T/\partial t$ indicates how quickly the ice cream warms, while spatial derivatives such as $\partial T/\partial x$ or $\partial T/\partial y$ describe how heat spreads laterally across the surface. This example highlights the distinction between spatial and temporal partial derivatives and illustrates how a single physical process can involve both simultaneously.

e3. Chemical concentration in tube

Chemical concentration in a narrow tube can be modeled as $C(x, t)$, a function of position along the tube and of time. The spatial derivative $\partial C/\partial x$ measures how concentration varies from one point to another, while the time derivative $\partial C/\partial t$ describes how the concentration profile evolves due to diffusion or reaction processes.

e4. Population density

Population density in a geographic region can be represented as a function $P(x, y)$ giving the number of individuals per unit area at each location. The partial derivative $\partial P/\partial x$ reflects how density changes in the east–west direction, while $\partial P/\partial y$ reflects changes in the north–south direction. This provides an intuitive example of a two-dimensional spatial field in which partial derivatives quantify directional variations in an underlying distribution.

(f) Mathematical visualization:

This mathematical visualization is the way textbooks typically introduce the concept. Three-dimensional surface plots offer an intuitive picture of partial derivatives. Vertical slices through the surface at fixed x or y reveal planar curves whose tangents at a point correspond to $\partial f/\partial x$ and $\partial f/\partial y$, respectively (refer to Figure 6). These slices show how the surface tilts in different directions and form the building blocks for directional derivatives and for the gradient vector.

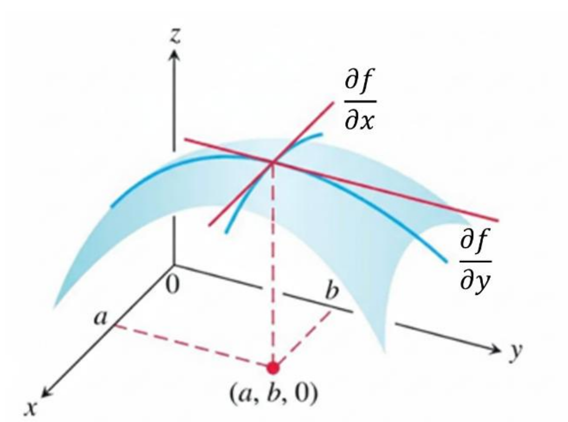

Figure 6. Mathematical visualization of partial derivatives

3. Students' assignment

Twenty-seven students were asked to develop well-explained examples, each from a different discipline such as medicine, electrical engineering, aeronautics, chemistry, physics, biology, nature, or computer science, that clearly illustrate the concepts of partial derivatives. For each example, students were instructed to provide a title, a specific description, a clear explanation of its relevance to partial derivative, and to include a figure whenever appropriate.

In addition, students were asked to evaluate this intuitive and visual method of learning. Using a 1–10 scale (10 being the highest), they rated their overall excitement level, the amount of intuition, visualization, and engagement they prefer when learning new concepts, as well as their preference for less formula derivation**.**

4. Students' examples

The sources provide a comprehensive collection of partial derivative examples, demonstrating how this concept is applied across various fields to analyze the isolated effect of one variable on a multi-variable outcome.

A partial derivative is defined as the rate of change of a multi-variable function with respect to just one of its variables, while all others are held constant.

The utility of a partial derivative, seen across these examples, is analogous to a multi-stage filter. In a complex system with many inputs, the partial derivative isolates one input at a time, allowing the observer to see *only* the change caused by that specific factor, much like isolating a single ingredient's flavor in a complex dish.

Detailed elaboration of partial derivative examples

The examples are grouped below by general subject area and numbered sequentially.

No.	Example Title	Description	Partial Derivative Meaning
Group A: Health, medicine, and biology			
1	Effect of Medication Dosage on Body Temperature	Body temperature T is a function of dosage D and hydration H.	$\partial T/\partial D$ measures how temperature changes with dosage alone, keeping hydration constant.

2	Diet and Body Weight	Body weight U depends on calories X and exercise Y.	$\partial U/\partial X$ measures weight change due to calories (exercise fixed). $\partial U/\partial Y$ measures weight change due to exercise (calories fixed).
3	Body Mass Index (BMI)	$BMI(w,h) = w / h^2$.	$\partial BMI/\partial w = 1/h^2$ shows the change in BMI for increased weight (height fixed). $\partial BMI/\partial h = -2w/h^3$ shows the change in BMI for increased height (weight fixed).
4	Sensitivity in Pharmacokinetics	Drug concentration C depends on time t and elimination rate k_e.	$\partial C/\partial k_e$ measures how sensitive the predicted concentration is to changes in k_e, with other factors fixed.
5	Plant Growth with Sunlight and Water	Plant height H depends on sunlight S and water W.	$\partial H/\partial W$ shows the growth rate as water increases, assuming sunlight stays constant.
Group B: Physics, engineering, and thermodynamics			
6	Solar Panel Power vs. Temperature and Light	Power P depends on solar irradiance G and panel temperature T.	$\partial P/\partial T$ measures how power changes with temperature alone, keeping irradiance constant.
7	Air Pressure vs. Altitude	Air pressure P depends on altitude H and temperature T.	$\partial P/\partial H$ describes how pressure decreases with height, assuming temperature remains constant.
8	Metal Plate Heating	Temperature $Z = T(X,Y) = 10 - X^2 - Y^2$ depends on coordinates X and Y.	$\partial T/\partial X$ and $\partial T/\partial Y$ measure how quickly temperature decreases as one moves away from the center along one axis while holding the other coordinate constant.
9	Cylinder Volume	Volume $V(r,h) = \pi r^2 h$.	$\partial V/\partial r = 2\pi r h$ shows how volume changes when radius changes (height fixed). $\partial V/\partial h$

			$= \pi r^2$ shows how volume changes when height changes (radius fixed).
10	Kinetic Energy	$K(m,v) = (1/2)\, m\, v^2$.	$\partial K/\partial m = (1/2)\, v^2$ shows how K changes if mass changes (velocity fixed). $\partial K/\partial v = m\, v$ shows how K changes if velocity changes (mass fixed).
11	Heat Capacity at Constant Volume	Internal energy U depends on temperature T and volume V.	$C_v = (\partial U/\partial T)$ at constant V measures how internal energy changes with temperature when volume is held fixed.
12	Pollutant Dispersion in Air	Pollutant concentration $C = C(x,y,z,t)$.	$\partial C/\partial x$ represents the spatial gradient in the x-direction; $\partial C/\partial t$ is the accumulation or depletion rate at a fixed point.
13	Viscosity and Shear Stress	Shear stress τ in a Newtonian fluid often simplifies to $\tau = \mu\, (\partial u/\partial y)$.	$\partial u/\partial y$ is the velocity gradient (rate of change of velocity u with respect to distance y), which is used to define viscosity.
Group C: Economics and technology			
14	Training an AI Model (Gradient Descent)	Loss L depends on weights $w_1, w_2, \ldots$.	Each partial derivative $\partial L/\partial w_i$ isolates that weight's contribution to the total error. All partial derivatives together form the gradient, which guides the algorithm toward minimum error.
15	Marginal Cost in Manufacturing	Total cost $C(L,K)$ depends on labor L and capital K.	$\partial C/\partial L$ is the marginal cost of labor (cost increase per extra labor hour, capital fixed). $\partial C/\partial K$ is the marginal cost of capital (cost increase per extra machine, labor fixed).

16	Battery Life in Smartphones	Battery life L depends on brightness B and usage U.	$\partial L/\partial B$ gives how battery life changes with brightness, and $\partial L/\partial U$ gives how battery life changes with usage.
Group D: Conceptual and everyday scenarios			
17	Climbing a Hill	The hill's height $h(x,y)$ is a function of horizontal position.	$\partial h/\partial x$ measures the rate of height change when moving sideways in the x-direction, keeping the other coordinate fixed.
18	Balloon in a Room	Balloon size S depends on amount of air A and temperature T.	One partial derivative ($\partial S/\partial A$) measures size change due to air alone (temperature fixed); the other ($\partial S/\partial T$) measures size change due to heating alone (amount of air fixed).
19	Cake Baking in the Oven	Cake temperature T depends on time t and spatial position x (or (x,y,z)).	$\partial T/\partial t$ measures how a single point heats up over time (position fixed), and $\partial T/\partial x$ measures temperature variation in space at one instant (time fixed).
20	Height of Water in a Bucket	Water height H depends on flow rate F and time t.	$\partial H/\partial F$ shows how height changes when flow rate changes (time fixed), and $\partial H/\partial t$ shows how height changes as time passes (flow rate fixed).
21	Boiling Water	Time to boil T depends on stove heat H and water amount W.	$\partial T/\partial H$ gives how boiling time changes with heat (water amount fixed), and $\partial T/\partial W$ gives how boiling time changes with water amount (heat fixed).

22	Fuel Consumption while Driving	Fuel use F depends on speed S and weight (load) W.	∂F/∂S gives how fuel use changes with speed (load fixed), and ∂F/∂W gives how fuel use changes with load (speed fixed).

5. Assessment

Quantitative assessment of the learning approach

Students provided high ratings and positive feedback regarding the learning approach that uses real-life, cross-disciplinary examples and visualization to teach partial derivatives. They noted that this method made abstract ideas much easier to understand, built strong intuition, and connected theory to practice.

Assessment Category	**Summary of Student Feedback**	**Quantitative Ratings (Scale: 1–10)**
Opinion (4a)	Students found the use of cross-disciplinary, real-life examples enjoyable, memorable, and practical. This approach clears confusion and helps to understand "what it actually is", making concepts more relatable and increasing engagement.	N/A
Excitement Level (4b)	Learning through relatable, real-world examples raised the excitement level for active engagement.	9.6
More Intuition	Highly favored, as it helps students understand the meaning of the concept before worrying about symbols or equations.	9.8
More Visual Content	Visuals, such as graphs, surface plots, and conceptual diagrams, help students see how the mathematics is being applied to everyday processes.	9.3
More Engagement/Interaction	Engagement through projects and interactive examples is appreciated. Students suggested improvement by providing access to physical systems to see the effects of the mathematics they do in class, rather than just simulation.	8.0

Overall, students felt that this approach made abstract mathematical ideas much easier to understand, built strong intuition, and connected theory to practice, reducing rote memorization.

6. Conclusion

The central aim of this paper, and of the examples it presents, is to offer instructors additional resources that support both teaching and learning. Each example adopts a visual and intuitive approach designed to make the idea of a partial derivative more accessible. The examples draw on familiar, everyday experiences and rely on basic intuitive reasoning.

These materials are intended to serve as optional supplements that instructors may incorporate into their lessons as they see fit. They are not designed to replace established teaching methods or standard textbook content.

This paper should be viewed as ongoing work. The approach has been evaluated with a group of 27 students, and further assessment with a larger population is planned. We hope that these examples prove valuable to instructors when introducing the concept of partial derivative.

7. Acknowledgements

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