MTHSC 206 Section 15.6 – Directional Derivatives and the Gradient Vector

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Definition

We define the directional derivative of the function $f(x, y)$ at the point (x_0, y_0) in the direction of the unit vector $u = (a, b)$ (u should be thought of as a vector in the xy-plane) as

$$D_u f(x_0, y_0) = \lim_{h \to 0} \frac{f(x_0 + ah, y_0 + by) - f(x_0, y_0)}{h}.$$

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Theorem

If $f(x, y)$ is differentiable, then

$$D_u f(x, y) = f_x(x, y)a + f_y(x, y)b.$$

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We can also write $g(h) = f(x, y)$ where $x = x_0 + ah$ and $y = y_0 + bh$.

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Thus,

$$D_u f(x_0, y_0) = g'(0) = f_x(x_0, y_0)a + f_y(x_0, y_0)b.$$

Note

If the vector u is at an angle θ with the x-axis then we can write $u = (\cos(\theta), \sin(\theta))$. Thus

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

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Example

Find the directional derivative $D_u f(x, y)$ of the function $f(x, y) = x^2 + xy + y^2$ in the direction of the unit vector which is at an angle of $\theta = \frac{\pi}{3}$ to the x-axis.

Note

The directional derivative of f in the direction of u can be written as

$$D_u f(x,y) = (f_x(x,y), f_y(x,y)) \cdot u.$$

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We define the gradient of a function $f(x,y)$ as

$$\nabla f = (f_x(x,y), f_y(x,y)) = f_x(x,y)i + f_y(x,y)j.$$

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Fact

If u is a unit vector and $f(x, y)$ is a function of 2 variables then

$$D_u f(x, y) = \nabla f \cdot u.$$

EXAMPLE

Consider the function $f(x, y) = e^{xy}$. Compute the gradient of f. Compute the directional derivative of f in the direction of $u = (\sqrt{3}/2, 1/2)$.

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The directional derivative of $f(x, y, z)$ at (x_0, y_0, z_0) in the direction of the unit vector $u = (a, b, c)$ is

$$D_u f(x_0, y_0, z_0) = \lim_{h \to 0} \frac{f(x_0 + ah, y_0 + bh, z_0 + ch) - f(x_0, y_0, z_0)}{h}.$$

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Fact

If $f(x, y, z)$ is differentiable then

$$D_u f(x, y, z) = f_x(x, y, z)a + f_y(x, y, z)b + f_z(x, y, z)c.$$

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Example

Suppose that $f(x, y, z) = sin(xy)e^z$. Compute ∇f. What is the directional derivative at $(\pi, 1/2, 0)$ in the direction $(\sqrt{3}/3, \sqrt{3}/3, \sqrt{3}/3)$. Can you find the direction which maximizes $D_u f$ at this point?

Theorem

Suppose that f is a differentiable function of two or three variables. The maximal value of the directional derivative $D_u f(\vec{x})$ at the point $\vec{x}$ is $|\nabla f|$ and it occurs when $u = \frac{1}{|\nabla f|}\nabla f$.

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Example

Consider the function $f(x, y, z) = e^{xyz}$. What is the directional derivative at the point $(0, 1, 0)$ in the direction of $\overrightarrow{((0, 1, 0), (1, 1, 1))}$. What is the maximum value of the directional derivative at this point? In which direction does it occur?

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Example

Again consider the function $f(x, y, z) = e^{xyz}$. What is the directional derivative at the point $(1, 1, 1)$ in the direction of $\overrightarrow{((1, 1, 1), (2, 3, 1))}$. What is the maximum value of the directional derivative at this point? In which direction does it occur?

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Then C can be parametrized by $r(t)=(x(t),y(t),z(t))$.

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Supposing all functions to be differentiable, we can use the chain rule to obtian,

$$0 = F_x x'(t) + F_y y'(t) + F_z z'(t) =$$

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Supposing all functions to be differentiable, we can use the chain rule to obtian,

$$0 = F_x x'(t) + F_y y'(t) + F_z z'(t) = \nabla F \cdot r'(t).$$

That is, $\nabla F(P)$ is orthogonal to the tangent vector at P of any curve along S passing through P.

Definition

We define the tangent plane to the level surface $F(x, y, z) = k$ at $P = (x_0, y_0, z_0)$ as the plane that passes through P and has normal vector $\nabla F(x_0, y_0, z_0)$. This plane has equation

$$F_x(x_0, y_0, z_0)(x-x_0)+F_y(x_0, y_0, z_0)(y-y_0)+F_z(x_0, y_0, z_0)(z-z_0) = 0.$$

or

$$\nabla F(x_0, y_0, z_0) \cdot \overrightarrow{(P, (x, y, z))} = 0$$

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

Note

We can think of the graph $z = f(x, y)$ of $f(x, y)$ as the level surface $F(x, y, z) = 0$ where $F(x, y, z) = f(x, y) - z$.

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In this case, $\nabla F = (f_x, f_y, -1)$
So the tangent plane to the graph of f as a level surface at P would have equation

$$f_x(x_0, y_0, z_0)(x - x_0) + f_y(x_0, y_0, z_0)(y - y_0) - (z - z_0) = 0.$$

which is consistent with our previous definition of tangent plane.

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The normal line has equation

$$\frac{x - x_0}{f_x(x_0, y_0, z_0)} = \frac{y - y_0}{f_y(x_0, y_0, z_0)} = -(z - z_0).$$

Example

Find the equations of the tangent plane and normal line at the point $(1, 1, 2)$ to the ellipsoid $\frac{x^2}{9} + \frac{y^2}{4} + z^2 = 5$.