

SE102:Multivariable Calculus

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Definition

An **open ball** $B_\varepsilon(\mathbf{a})$ of the radius $\varepsilon > 0$ at a point $\mathbf{a} \in \mathbf{R}^n$ is the set defined by

$$B_\varepsilon(\mathbf{a}) = \{\mathbf{x} \in \mathbf{R}^n \mid \|\mathbf{x} - \mathbf{a}\| < \varepsilon\}$$

Definition

A function $f(x_1, \dots, x_n) = (y_1, \dots, y_m)$ is said to be **continuously differentiable**, or of **class \mathcal{C}^1** , at $\mathbf{a} \in \mathbf{R}^n$ if there is $\varepsilon > 0$ such that all the partial derivatives $\frac{\partial y_j}{\partial x_i}$ are continuous on an open ball $B_\varepsilon(\mathbf{a})$.

Theorem

If a function $z = f(x, y)$ is continuously differentiable at $\mathbf{a} = (x_0, y_0)$, then it is differentiable at \mathbf{a} .

Proof.

Let $B_\varepsilon(\mathbf{a})$ be an open ball on which the partial derivatives f_x, f_y are continuous. Let us choose a point $\mathbf{b} = (x, y) \in B_\varepsilon(\mathbf{a})$ and define a sequence

$$\mathbf{p}_0 = \mathbf{a}, \quad \mathbf{p}_1 = (x, y_0), \quad \mathbf{p}_2 = \mathbf{b}$$

Without loss of generality, we will assume that $x_0 \leq x$ and $y_0 \leq y$. Define a function $\phi_1(t) = f(t, y_0)$ on $[x_0, x]$. Note that $\phi'_1(t) = f_x(t, y_0)$. By the mean value theorem on one-variable function, there is $t_1 \in [x_0, x]$ such that

$$\phi'_1(t_0)(x - x_0) = f(x, y_0) - f(x_0, y_0)$$

Proof.

Likewise, let us define $\phi_2(t) = f(x, t)$ on $[y_0, y]$, then there exists $t_2 \in [y_0, y]$ satisfying

$$\phi_2'(t_2)(y - y_0) = f(x, y) - f(x, y_0)$$

Then,

$$\begin{aligned} f(\mathbf{b}) - f(\mathbf{a}) - f_x(\mathbf{a})(x - x_0) - f_y(\mathbf{a})(y - y_0) \\ &= (\phi_1'(t_1) - f_x(\mathbf{a}))(x - x_0) + (\phi_2'(t_2) - f_y(\mathbf{a}))(y - y_0) \\ &= (f_x(t_1, y_0) - f_x(\mathbf{a}))(x - x_0) + (f_y(x, t_2) - f_y(\mathbf{a}))(y - y_0) \end{aligned}$$

Note that as $\mathbf{b} \rightarrow \mathbf{a}$, we have $t_1 \rightarrow x_0$ and $t_2 \rightarrow y_0$, which means the above goes to 0. Since $(x - x_0)/\|\mathbf{b} - \mathbf{a}\|$ and $(y - y_0)/\|\mathbf{b} - \mathbf{a}\|$ bounded, we proved the differentiability of f at \mathbf{a} .

Definition

A function $z = f(x, y)$ is said to be of **class** \mathcal{C}^2 at $\mathbf{a} \in \mathbf{R}^2$ if there exists $\varepsilon > 0$ such that all second-order partial derivatives are continuous on an open ball $B_\varepsilon(\mathbf{a})$.

Remark

Given a function $\mathbf{f} : \mathbf{R}^n \rightarrow \mathbf{R}^m$, the derivative $\mathbf{D}\mathbf{f}$ is a function $\mathbf{D}\mathbf{f} : \mathbf{R}^n \rightarrow \mathbf{R}^{nm}$ whose coordinate functions are all the first derivatives of \mathbf{f} . The function \mathbf{f} being a class \mathcal{C}^1 means that $\mathcal{D}\{\mathbf{f}\}$ is continuous. Similarly, being a class \mathcal{C}^2 means that $\mathbf{D}\mathbf{f}$ is \mathcal{C}^1 , which equivalent to saying that $\mathbf{D}^2\mathbf{f}$ is continuous. We say the function \mathbf{f} is of class \mathcal{C}^n if $\mathbf{D}^n\mathbf{f}$ is continuous. Moreover, the function \mathbf{f} is of class \mathcal{C}^∞ if $\mathbf{D}^n\mathbf{f}$ is continuous for all $n > 0$.

Theorem (Clairaut)

If $z = f(x, y)$ is of class \mathcal{C}^2 at (x_0, y_0) , then

$$f_{xy}(x_0, y_0) = f_{yx}(x_0, y_0).$$

Example

Check if the following function satisfies Clairaut's theorem at $(0, 0)$.

$$f(x, y) = \begin{cases} xy \frac{x^2 - y^2}{x^2 + y^2} & (x, y) \neq (0, 0) \\ 0 & (x, y) = (0, 0) \end{cases}$$

Proof of Clairaut's Theorem.

Let us define $\mu : B_\varepsilon(\mathbf{a}) \rightarrow \mathbf{R}$ as

$$\mu(x, y) = f(x, y) - f(x_0, y) - f(x, y_0) + f(x_0, y_0)$$

Let us define $\phi(t) = f(t, y) - f(t, y_0)$ on $[x_0, x]$. Since f is of class \mathcal{C}^1 , ϕ is differentiable on $[x_0, x]$. Note that

$$\mu(x, y) = \phi(x) - \phi(x_0).$$

By the mean value theorem, there exists $t_1 \in [x_0, x]$ satisfying

$$\mu(x, y) = \phi'(t_1)(x - x_0) = (f_x(t_1, y) - f_x(t_1, y_0))(x - x_0).$$

Since f_x is of class \mathcal{C}^1 , we can apply the mean value theorem on $\psi(h) = f_x(t_1, h)$, which means that there exists $t_2 \in [y_0, y]$ satisfying

$$f_x(t_1, y) - f_x(t_1, y_0) = \psi'(t_2)(y - y_0) = f_{xy}(t_1, t_2)(y - y_0)$$

Proof.

Thus we showed that there exists $(t_1, t_2) \in [x_0, x] \times [y_0, y]$ satisfying

$$\mu(x, y) = f_{xy}(t_1, t_2)(x - x_0)(y - y_0).$$

If we switch the role of x and y when we defined ϕ , we would obtain the similar result: there exists a point $(s_1, s_2) \in [x_0, x] \times [y_0, y]$ satisfying

$$\mu(x, y) = f_{yx}(s_1, s_2)(x - x_0)(y - y_0).$$

Let us replace $x = x_0 + h$ and $y = y_0 + h$. Since we assume that f is of class \mathcal{C}^2 , the following function converges as $(x, y) \rightarrow (x_0, y_0)$.

$$\frac{\mu(x_0 + h, y_0 + h)}{h^2} = f_{xy}(t_1, t_2) = f_{yx}(s_1, s_2)$$

Since $(t_1, t_2), (s_1, s_2) \rightarrow (x_0, y_0)$ as $(x, y) \rightarrow (x_0, y_0)$, we are done.

Definition

Suppose that $f(x, y)$ is of class \mathcal{C}^2 at (x_0, y_0) . Then the following polynomial is called the **Taylor polynomial of second degree 2** of f at (x_0, y_0) .

$$\begin{aligned} Q(x, y) = & f(x_0, y_0) + f_x(x_0, y_0)(x - x_0) \\ & + f_y(x_0, y_0)(y - y_0) + \frac{1}{2}f_{xx}(x_0, y_0)(x - x_0)^2 \\ & + f_{xy}(x_0, y_0)(x - x_0)(y - y_0) \\ & + \frac{1}{2}f_{yy}(x_0, y_0)(y - y_0)^2. \end{aligned}$$

Remark

If all n -th order partial derivatives of a function $f(x, y)$ are continuous, then

- ▶ f is differentiable, and
- ▶ the formulae of n -order partial derivatives does not depend on the order of partial derivatives.

Remark

Let

$$\Delta \mathbf{x} = (\Delta x, \Delta y) = (x - x_0, y - y_0)$$

and denote the *gradient operator* ∇ in vector notation:

$$\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y} \right)$$

Let us define the *multiplication* of differential operators as follows:

$$\left(\frac{\partial}{\partial x} \frac{\partial}{\partial x}\right) f = \frac{\partial^2 f}{\partial x^2}, \quad \left(\frac{\partial}{\partial x} \frac{\partial}{\partial y}\right) f = \frac{\partial^2 f}{\partial x \partial y}$$

By the assumption in the definition of Taylor polynomial, we have $f_{xy}(x_0, y_0) = f_{yx}(x_0, y_0)$. Thus we can write

$$Q(x, y) = \sum_{n=0}^2 \frac{1}{n!} (\Delta \mathbf{x} \cdot \nabla)^n f(x_0, y_0)$$

We can generalize this to the k -th order Taylor polynomial.

$$P_k f(\mathbf{x}) = \sum_{n=0}^k \frac{1}{n!} (\Delta \mathbf{x} \cdot \nabla)^n f(\mathbf{x}_0)$$

This is a generalization of the Taylor polynomial for single variable function:

Theorem (Taylor)

Let $z = f(x, y)$ be a function of class \mathcal{C}^3 on a rectangular region

$$D = \{(x, y) \mid |x - x_0|, |y - y_0| \leq \epsilon\}.$$

Then for each $(x, y) \in D$, there exists a constant $0 \leq c \leq 1$ satisfying

$$f(x, y) = Q(x, y) + R_2(x, y)$$

where

$$R_2(x, y) = \frac{1}{3!}(\Delta \mathbf{x} \cdot \nabla)^3 f(\mathbf{x}_0 + c\Delta \mathbf{x})$$

Remark

This theorem is a generalization of Taylor theorem for one-variable function:

Let f be of class C^{k+1} on an interval $I = (x_0 - \epsilon, x_0 + \epsilon)$. Then for $x, c \in I$, there exists a constant ξ between x and c such that

$$f(x) = P_k(x) + \frac{f^{(k+1)}(\xi)}{(k+1)!}(x-c)^{k+1}$$

Note that the choice of c *depends* on the choice of x, x_0 . Since all the third-order partial derivatives of f are bounded, the error $|R_n(x, y)|$ decreases to zero, as $(x, y) \rightarrow (x_0, y_0)$,

Example

Find $Q_2(x, y)$ at $(0, 0)$ for

▶ $f(x, y) = xy - x^2 - 5y^2 + y - 1$

▶ $f(x, y) = \cos x \cos y$

and compare the graphs of Q_2 and f near $(1, 0)$

Definition

Let $f(x, y)$ be a function $f(x, y)$ defined on a region D .

- ▶ A point (x_0, y_0) is said to be **local maximal** (**minimal**, respectively) at $\mathbf{x}_0 = (x_0, y_0)$ if there exists a (sufficiently small) $\epsilon > 0$ such that for all $\mathbf{x} = (x, y)$ satisfying $\|\mathbf{x} - \mathbf{x}_0\| < \epsilon$, we have $f(x_0, y_0) \geq f(x, y)$ ($f(x_0, y_0) \leq f(x, y)$, respectively). A local maximal / minimal is often called an **extremal**.
- ▶ A point (x_0, y_0) is called a **critical point** if it satisfies one of the following.
 1. $f_x(x_0, y_0) = f_y(x_0, y_0) = 0$;
 2. f_x or f_y does not exist at (x_0, y_0) ;
 3. f is discontinuous at (x_0, y_0) .

A critical point which is *not* an extremal is called a **saddle point**.

Example

Find the critical points of

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

and classify them. Also, find $Q_2(x, y)$ at each critical points and compare their graphs.

Remark

1. Let $f(x, y)$ is differentiable at (x_0, y_0) . Suppose that (x_0, y_0) is a critical point $f(x, y)$ of the type 1 in the definition. Then the linear approximation (x_0, y_0) is the plane $z = f(x_0, y_0)$.
2. Suppose that (x_0, y_0) is a saddle point. Then there exists a curve $c : (-\epsilon, \epsilon) \rightarrow \mathbf{R}^2$, $c(0) = (x_0, y_0)$ such that composition $F(t) = (f \circ c)(t)$ is a inflection point.

Definition

Let $R \subset \mathbf{R}^2$ be a domain of $f(x, y)$ and $(x_0, y_0) \in R$. Suppose that all second partial derivatives of $f(x, y)$ are continuous on a region R . Then

$$\Delta_f = f_{xx}(x_0, y_0)f_{yy}(x_0, y_0) - f_{xy}(x_0, y_0)^2$$

is called the **discriminant** of f .

Example

Graph the following function at $(0, 0)$ and compare their discriminants.

$$z = -x^2 - y^2, \quad z = x^2 + y^2, \quad z = x^2 - y^2$$

Theorem (Hesse)

Let (x_0, y_0) be a critical point of the type 1 of $f(x, y)$.

- ▶ *If $\Delta > 0$ and $f_{xx}(x_0, y_0) > 0$, then (x_0, y_0) is a local minimum point.*
- ▶ *If $\Delta > 0$ and $f_{xx}(x_0, y_0) < 0$, then (x_0, y_0) is a local maximum point.*
- ▶ *If $\Delta < 0$, then $f(x_0, y_0)$ is a saddle point.*
- ▶ *If $\Delta = 0$, then we cannot determine local extremity by this method.*

Remark

Let $\Delta x = x - x_0, \Delta y = y - y_0$. The degree-2 summands of $Q(x, y)$ can be written as

$$\frac{1}{2} [\Delta x \quad \Delta y] \underbrace{\begin{bmatrix} f_{xx}(x_0, y_0) & f_{xy}(x_0, y_0) \\ f_{xy}(x_0, y_0) & f_{yy}(x_0, y_0) \end{bmatrix}}_{=A} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix}$$

Note that $\Delta_f = \det A$. Using linear transformation of x, y , we can correspond the matrix A to one of three matrices below, without changing the classifications of extremals.

$$\begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}, \quad \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \begin{bmatrix} \pm 1 & 0 \\ 0 & \mp 1 \end{bmatrix}$$

Example (Least square method)

Suppose that a set of data is given by

$$(x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)$$

We want to find a line $y = mx + b$ which approximates these data. If there are values m_0, b_0 such that the sum of squares of vertical distances between data and the line $y = m_0x + b_0$ is the minimum among all possible lines, then we say that $y = m_0x + b_0$ best approximates the data. In other words, we want to find m, b such that

$$d(m, b) = \sum_{i=1}^n (y_i - (mx_i + b))^2$$

is minimum.

Consider $d(m, b)$ as two-variable function on m, b . The critical point is

$$m_0 = \frac{n \sum_{i=1}^n x_i y_i - \sum_{i=1}^n x_i \sum_{i=1}^n y_i}{n \sum_{i=1}^n x_i^2 - \left(\sum_{i=1}^n x_i \right)^2}$$

$$b_0 = \frac{\sum_{i=1}^n x_i^2 \sum_{i=1}^n y_i - \sum_{i=1}^n x_i \sum_{i=1}^n x_i y_i}{n \sum_{i=1}^n x_i^2 - \left(\sum_{i=1}^n x_i \right)^2}$$

The Hessian of $d(m, b)$ at (m_0, b_0) is
$$\begin{bmatrix} 2 \sum_{i=1}^n x_i^2 & 2 \sum_{i=1}^n x_i \\ 2 \sum_{i=1}^n x_i & 2n \end{bmatrix}$$

Since the discriminant of f is

$$\Delta_f(m_0, b_0) = 4n \sum_{i=1}^n x_i^2 - 4 \left(\sum_{i=1}^n x_i \right)^2 > 0$$

The point (m_0, b_0) is a local minimum point. (in fact a global minimum point, why?)

Theorem

Let (x_0, y_0, z_0) be a critical point of $f(x, y, z)$ where f_x, f_y, f_z are all zero. Let H be the 3×3 matrix defined by

$$\begin{bmatrix} f_{xx} & f_{xy} & f_{xz} \\ f_{yx} & f_{yy} & f_{yz} \\ f_{zx} & f_{zy} & f_{zz} \end{bmatrix}$$

Let d_1, d_2, d_3 be the determinants of the $1 \times 1, 2 \times 2, 3 \times 3$ sub-matrices on the left-top corner of H .

- ▶ If $d_i > 0$ for all i , then (x_0, y_0, z_0) is a local minimum point.
- ▶ if $d_1, d_3 < 0$ and $d_2 > 0$, then (x_0, y_0, z_0) is a local maximal point.
- ▶ In all other cases, (x_0, y_0, z_0) is a saddle point.

Proposition

*Let $L_c(f)$ be the level curve at $c = f(x_0, y_0)$. on the xy -plane.
Then the gradient vector $\nabla f(x_0, y_0)$ is perpendicular to the
curve $L_c(f)$ at (x_0, y_0)*

Theorem (Lagrange multiplier)

Let $g(x, y)$, $f(x, y)$ be differentiable functions. Let $L_c(g)$ be a level curve at c . Let us restrict the domain of f onto $L_c(g)$. If (x_0, y_0) is an extremal point of f and $\nabla g(x_0, y_0) \neq \mathbf{0}$, there exists λ such that

$$\nabla f(x_0, y_0) = \lambda \nabla g(x_0, y_0)$$

Example

The Lagrange multiplier finds the maxima or minima of a **target** function $f(x, y)$ under the **constraint** $g(x, y) = c$. Find the point on the circle $x^2 + y^2 = 10$ where the function $f(x, y) = 3x + y$ attains maximal or minimal.

Corollary

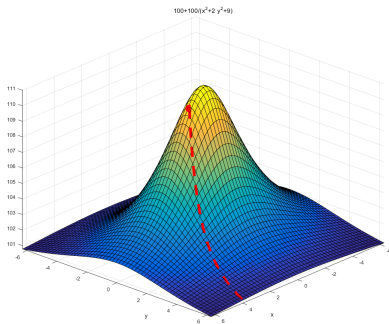
The gradient vector $\nabla f(x_0, y_0)$ has the direction where the value of function $f(x, y)$ increases the most from (x_0, y_0) .

Example

Let

$$f(x, y) = 100 + \frac{100}{x^2 + 2y^2 + 9}$$

be a function whose graph represent the contour of a mountain. Suppose that a water flow from the point $(1, 0, 110)$ down the valley in the steepest direction. Find the trajectory of the water path.



Theorem

Let $g(x, y, z)$, $f(x, y, z)$ be differentiable functions. Suppose that (x_0, y_0, z_0) is a local extremal of $f(x, y, z)$ restricted the level set $L_c(g)$. If $\nabla g(x_0, y_0) \neq \mathbf{0}$, then there exists λ such that

$$\nabla f(x_0, y_0, z_0) = \lambda \nabla g(x_0, y_0, z_0)$$

Example

Find the minimal and maximal value of $f(x, y, z) = x^3 + y^3 + z^3$ on the sphere $x^2 + y^2 + z^2 = 1$ on the first octant.

Problem

Find all critical points and classify them

1. $f(x, y) = xy + \frac{2}{x} + \frac{2}{y}$
2. $e^y(x^2 + y^2 - z^2)$

Problem

Find all local extremes of $f(x, y)$ with the give constraints.

1. $f(x, y) = 2x + y^2 + x^2, 2x^2 + y^2 = 2$
2. $f(x, y, z) = xy + yz, x^2 + y^2 = 1, yz = 1$

Problem

Find the local extremes of $f(x, y) = x^2 + xy + y^2$ on the disk $D = \{(x, y) \mid x^2 + y^2 \leq 1\}$.

Problem

Find the point on the graph $xy^2z^3 = 2$ which is the closest to the origin.