MATH 311

Topics in Applied Mathematics I

Lecture 31:
Differentiation in vector spaces.

The derivative

Definition. A real function f is said to be **differentiable** at a point $a \in \mathbb{R}$ if it is defined on an open interval containing a and the limit

$$\lim_{h \to 0} \frac{f(a+h) - f(a)}{h}$$

exists. The limit is denoted $f'(a)$ and called the **derivative** of f at a. An equivalent condition is

$$f(a+h) = f(a) + f'(a)h + r(h), \text{ where } \lim_{h \to 0} r(h)/h = 0.$$

If a function f is differentiable at a point a, then it is continuous at a.

Suppose that a function f is defined and differentiable on an interval I. Then the derivative of f can be regarded as a function on I.

Convergence in normed vector spaces

Suppose V is a vector space endowed with a norm $\|\cdot\|$. The norm gives rise to a distance function $\operatorname{dist}(\mathbf{x}, \mathbf{y}) = \|\mathbf{x} - \mathbf{y}\|$.

Definition. We say that a sequence of vectors $\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3, \dots$ converges to a vector $\mathbf{u}$ in the normed vector space V if $\|\mathbf{v}_k - \mathbf{u}\| \to 0$ as $k \to \infty$.

In the case $V = \mathbb{R}^n$, a sequence of vectors converges with respect to a norm if and only if it converges in each coordinate. In the case $V = \mathcal{M}_{m,n}(\mathbb{R})$, a sequence of matrices converges with respect to a norm if and only if it converges in each entry.

Similarly, in the case $\dim V < \infty$ we can choose a finite basis $\mathbf{w}_1, \mathbf{w}_2, \dots, \mathbf{w}_n$. Any vector $\mathbf{v} \in V$ can be expanded into a linear combination $\mathbf{v} = x_1\mathbf{w}_1 + x_2\mathbf{w}_2 + \cdots + x_n\mathbf{w}_n$. Then a sequence of vectors converges with respect to a norm if and only if each of the coordinates x_i converges.

Vector-valued functions

Suppose V is a vector space endowed with a norm $\|\cdot\|$.

Definition. We say that a function $\mathbf{v} : X \to V$ defined on a set $X \subset \mathbb{R}$ converges to a limit $\mathbf{u} \in V$ at a point $a \in \mathbb{R}$ if $\|\mathbf{v}(x) - \mathbf{u}\| \to 0$ as $x \to a$.

Further, we say that the function $\mathbf{v}$ is continuous at a point $c \in X$ if $\mathbf{v}(c) = \lim\limits_{x \to c} \mathbf{v}(x)$.

Finally, the function $\mathbf{v}$ is said to be differentiable at a point $a \in \mathbb{R}$ if it is defined on an open interval containing a and the limit

$$\lim_{h \to 0} \frac{1}{h}\big(f(a+h) - f(a)\big)$$

exists. The limit is denoted $\mathbf{v}'(a)$ and called the derivative of $\mathbf{v}$ at a.

Differentiability theorems

Sum Rule If functions $\mathbf{v} : X \to V$ and $\mathbf{w} : X \to V$ are differentiable at a point $a \in \mathbb{R}$, then the sum $\mathbf{v} + \mathbf{w}$ is also differentiable at a. Moreover, $(\mathbf{v} + \mathbf{w})'(a) = \mathbf{v}'(a) + \mathbf{w}'(a)$.

Homogeneous Rule If a function $\mathbf{v} : X \to V$ is differentiable at a point $a \in \mathbb{R}$, then for any $r \in \mathbb{R}$ the scalar multiple $r\mathbf{v}$ is also differentiable at a. Moreover, $(r\mathbf{v})'(a) = r\mathbf{v}'(a)$.

Difference Rule If functions $\mathbf{v} : X \to V$ and $\mathbf{w} : X \to V$ are differentiable at a point $a \in \mathbb{R}$, then the difference $\mathbf{v} - \mathbf{w}$ is also differentiable at a. Moreover, $(\mathbf{v} - \mathbf{w})'(a) = \mathbf{v}'(a) - \mathbf{w}'(a)$.

Differentiability theorems

Product Rule #1 If functions $f : X \to \mathbb{R}$ and $\mathbf{v} : X \to V$ are differentiable at a point $a \in \mathbb{R}$, then the scalar multiple $f\mathbf{v}$ is also differentiable at a. Moreover, $(f\mathbf{v})'(a) = f'(a)\mathbf{v}(a) + f(a)\mathbf{v}'(a)$.

Product Rule #2 Assume that the norm on V is induced by an inner product $\langle \cdot, \cdot \rangle$. If functions $\mathbf{v} : X \to V$ and $\mathbf{w} : X \to V$ are differentiable at a point $a \in \mathbb{R}$, then the inner product $\langle \mathbf{v}, \mathbf{w} \rangle$ is also differentiable at a. Moreover, $(\langle \mathbf{v}, \mathbf{w} \rangle)'(a) = \langle \mathbf{v}'(a), \mathbf{w}(a) \rangle + \langle \mathbf{v}(a), \mathbf{w}'(a) \rangle$.

Chain Rule If a function $f : X \to \mathbb{R}$ is differentiable at a point $a \in \mathbb{R}$ and a function $\mathbf{v} : Y \to V$ is differentiable at $f(a)$, then the composition $\mathbf{v} \circ f$ is differentiable at a. Moreover, $(\mathbf{v} \circ f)'(a) = f'(a)\mathbf{v}'(f(a))$.

Partial derivative

Consider a function $f : X \to V$ that is defined in a domain $X \subset \mathbb{R}^n$ and takes values in a normed vector space V. The function f depends on n real variables: $f = f(x_1, x_2, \dots, x_n)$.

Let us select a point $\mathbf{a} = (a_1, a_2, \dots, a_n) \in X$ and a variable x_i. Now we go to the point $\mathbf{a}$ and fix all variables except x_i. That is, we introduce a function of one variable

$$\phi(x) = f(a_1, \dots, a_{i-1}, x, a_{i+1}, \dots, a_n).$$

If the function ϕ is differentiable at a_i, then the derivative $\phi'(a_i)$ is called the **partial derivative** of f at the point $\mathbf{a}$ with respect to the variable x_i.

Notation: $\dfrac{\partial f}{\partial x_i}(\mathbf{a})$, $\dfrac{\partial}{\partial x_i} f(\mathbf{a})$, $(D_{x_i} f)(\mathbf{a})$.

Directional derivative

Consider a function $f : X \to V$ that is defined on a subset $X \subset W$ of a vector space W and takes values in a normed vector space V. For every point $\mathbf{a} \in X$ and vector $\mathbf{v} \in W$ we introduce a function of real variable $\phi(t) = f(\mathbf{a} + t\mathbf{v})$. If the function ϕ is differentiable at 0, then the derivative $\phi'(0)$ is called the **directional derivative** of f at the point $\mathbf{a}$ along the vector $\mathbf{v}$. Notation: $(D_{\mathbf{v}}f)(\mathbf{a})$.

The partial derivative is a particular case of the directional derivative, when $W = \mathbb{R}^n$ and $\mathbf{v}$ is from the standard basis.

Homogeneity $(D_{r\mathbf{v}}f)(\mathbf{a}) = r(D_{\mathbf{v}}f)(\mathbf{a})$ for all $r \in \mathbb{R}$ whenever $(D_{\mathbf{v}}f)(\mathbf{a})$ exists.

Linearity Suppose W is a normed vector space, $(D_{\mathbf{v}}f)(\mathbf{a})$ exists for all $\mathbf{v}$ and depends continuously on $\mathbf{a}$. Then $\mathbf{v} \mapsto (D_{\mathbf{v}}f)(\mathbf{a})$ is a linear transformation.

Limit of a function and continuity

Let V and W be normed vector spaces. Suppose $f : E \to V$ is a function defined on a set $E \subset W$.

Definition. We say that the function f **converges to a limit** $L \in V$ at a point $\mathbf{w}_0 \in W$ if for every $\varepsilon > 0$ there exists $\delta = \delta(\varepsilon) > 0$ such that for all $\mathbf{w} \in E$,

$$0 < \|\mathbf{w} - \mathbf{w}_0\| < \delta \quad \text{implies} \quad \|f(\mathbf{w}) - L\| < \varepsilon.$$

An equivalent condition is that for any sequence $\mathbf{w}_1, \mathbf{w}_2, \dots$ of vectors from E, $\lim\limits_{n\to\infty} \mathbf{w}_n = \mathbf{w}_0$ implies $\lim\limits_{n\to\infty} f(\mathbf{w}_n) = L$.

Definition. Given a set $E \subset W$, a function $f : E \to V$, and a point $\mathbf{w}_0 \in E$, the function f is **continuous at $\mathbf{w}_0$** if

$$f(\mathbf{w}_0) = \lim_{\mathbf{w}\to\mathbf{w}_0} f(\mathbf{w}).$$

We say that the function f is **continuous on** a set $E_0 \subset E$ if f is continuous at every point of E_0.

Continuity of a linear transformation

Theorem Suppose V and W are normed vector spaces and $L : W \to V$ is a linear transformation. Then the following conditions are equivalent:

(i) L is continuous everywhere on W,

(ii) L is continuous at the zero vector,

(iii) $\|L(\mathbf{w})\| \leq C\|\mathbf{w}\|$ for some $C > 0$ and all $\mathbf{w} \in W$.

Example. • If $\dim W < \infty$ then any linear transformation $L : W \to V$ is continuous. Otherwise it is not so.

Continuity of a linear transformation

Examples. • Multiplication by a fixed function $L : C[a,b] \to C[a,b]$, $L(f) = gf$, where $g \in C[a,b]$.

It is continuous with respect to the uniform norm $\|f\|_\infty = \max_{a \le x \le b} |f(x)|$ and with respect to any p-norm

$$\|f\|_p = \left(\int_a^b |f(x)|^p \, dx \right)^{1/p}, \; p \ge 1.$$

Indeed, $\|gf\|_\infty \le \|g\|_\infty \|f\|_\infty$ and $\|gf\|_p \le \|g\|_\infty \|f\|_p$.

• Evaluation at a fixed point $\ell : C[a,b] \to \mathbb{R}$, $\ell(f) = f(c)$, where $c \in [a,b]$.

It is continuous with respect to the uniform norm, but not continuous with respect to the p-norms.

Continuity of a linear transformation

Examples. • Inner product with a fixed vector $\ell : V \to \mathbb{R},\ \ell(\mathbf{v}) = \langle \mathbf{v}, \mathbf{v}_0 \rangle,$ where $\mathbf{v}_0 \in V$.

It is continuous with respect to the induced norm since $|\ell(\mathbf{v})| \leq C\|\mathbf{v}\|,$ where $C = \|\mathbf{v}_0\|$.

• Differentiation $D : C^\infty[a, b] \to C^\infty[a, b]$, $D(f) = f'$.

Consider a function $f_\lambda(x) = e^{\lambda x},\ a \leq x \leq b$. We have $D(f_\lambda) = \lambda f_\lambda,$ hence $\|D(f_\lambda)\| = |\lambda|\, \|f_\lambda\|$ for any norm. Since λ can be arbitrarily large, the operator D is not continuous.

The (Frechét) differential

Suppose V and W are normed vector spaces and consider a function $F : X \to V$, where $X \subset W$.

Definition. We say that the function F is **differentiable** at a point $\mathbf{a} \in X$ if it is defined in a neighborhood of $\mathbf{a}$ and there exists a continuous linear transformation $L : W \to V$ such that

$$F(\mathbf{a}+\mathbf{v}) = F(\mathbf{a}) + L(\mathbf{v}) + R(\mathbf{v}),$$

where $\|R(\mathbf{v})\|/\|\mathbf{v}\| \to 0$ as $\|\mathbf{v}\| \to 0$. The transformation L is called the **differential** of F at $\mathbf{a}$ and denoted $(DF)(\mathbf{a})$.

Theorem If a function F is differentiable at a point $\mathbf{a}$, then the directional derivatives $(D_{\mathbf{v}}F)(\mathbf{a})$ exist for all $\mathbf{v}$ and $(D_{\mathbf{v}}F)(\mathbf{a}) = (DF)(\mathbf{a})[\mathbf{v}]$.

Fermat's Theorem If a real-valued function F is differentiable at a point $\mathbf{a}$ of local extremum, then the differential $(DF)(\mathbf{a})$ is identically zero.

Examples

- Any linear transformation $L : \mathbb{R} \to \mathbb{R}$ is a scaling $L(x) = rx$ by a scalar r. If L is the differential of a function $f : X \to \mathbb{R}$ at a point $a \in \mathbb{R}$, then $r = f'(a)$.

- Any linear transformation $L : \mathbb{R}^n \to \mathbb{R}$ is the dot product with a fixed vector, $L(\mathbf{x}) = \mathbf{x} \cdot \mathbf{v}_0$. If L is the differential of a function $f : X \to \mathbb{R}$ at a point $\mathbf{a} \in \mathbb{R}^n$, then $\mathbf{v}_0 = \nabla f(\mathbf{a})$.

- Any linear transformation $L : \mathbb{R}^n \to \mathbb{R}^m$ is a matrix transformation: $L(\mathbf{x}) = B\mathbf{x}$, where $B = (b_{ij})$ is an $m \times n$ matrix. If L is the differential of a function $\mathbf{F} : X \to \mathbb{R}^m$ at a point $\mathbf{a} \in \mathbb{R}^n$, then $b_{ij} = \dfrac{\partial F_i}{\partial x_j}(\mathbf{a})$.

The matrix B of partial derivatives is called the **Jacobian matrix** of **F** and denoted $\dfrac{\partial(F_1, \dots, F_m)}{\partial(x_1, \dots, x_n)}$.