

Inequalities

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1 Inequalities

I Triangle Inequality (三角不等式)

$$|a| + |b| \geq |a + b|$$

Proof.

$$(|a| + |b|)^2 - |a + b|^2 = 2(|a||b| - ab) \geq 0$$

□

$$|a - b| \geq ||a| - |b||$$

Proof.

$$(|a - b|)^2 - (|a| - |b|)^2 = 2(|a||b| - ab) \geq 0$$

□

$$|\mathbf{a}| + |\mathbf{b}| \geq |\mathbf{a} + \mathbf{b}|$$

Proof.

$$(|\mathbf{a}| + |\mathbf{b}|)^2 - |\mathbf{a} + \mathbf{b}|^2 = 2(|\mathbf{a}||\mathbf{b}| - \mathbf{a} \cdot \mathbf{b}) \geq 0$$

□

$$|\mathbf{a} - \mathbf{b}| \geq ||\mathbf{a}| - |\mathbf{b}||$$

Proof.

$$|\mathbf{a} - \mathbf{b}|^2 - (|\mathbf{a}| - |\mathbf{b}|)^2 = 2(|\mathbf{a}||\mathbf{b}| - \mathbf{a} \cdot \mathbf{b}) \geq 0$$

□

II Jensen's Inequality (詹森不等式)

Let (Ω, μ) be a probability space, $g : \Omega \rightarrow \mathbb{R}$ be a real-valued μ -integrable function, and $\varphi : \mathbb{R} \rightarrow \mathbb{R}$ be a convex function. Then, Jensen's inequality states:

$$\int_{\Omega} \varphi \circ g(\omega) \, d\mu(\omega) \geq \varphi \left(\int_{\Omega} g(\omega) \, d\mu(\omega) \right)$$

Proof.

Since φ is convex, at each real number x , we have a non-empty set of subderivatives, which may be thought of as lines touching the graph of φ at x , but which are below the graph of φ at all points.

We define:

$$x_0 := \int_{\Omega} g \, d\mu.$$

Because of the existence of subderivatives for convex functions, we may choose a and b such that $ax + b \leq \varphi(x)$ for all real x and $ax_0 + b = \varphi(x_0)$.

But then we have that for almost all $\omega \in \Omega$:

$$\varphi(g(\omega)) \geq ag(\omega) + b$$

Since we have a probability measure, the integral is monotone with $\mu(\Omega) = 1$ so that

$$\begin{aligned} \int_{\Omega} \varphi \circ g(\omega) d\mu(\omega) &\geq \int_{\Omega} ag(\omega) + b d\mu(\omega) \\ &= a \int_{\Omega} g d\mu + b \int_{\Omega} d\mu \\ &= ax_0 + b = \varphi(x_0) \\ &= \varphi\left(\int_{\Omega} g d\mu\right). \end{aligned}$$

□

III AM-GM Inequality (算幾不等式)

$$\frac{\sum_{i=1}^n x_i}{n} \geq \sqrt[n]{\prod_{i=1}^n x_i}$$

Proof.

Lemma: Jensen's inequality.

Applying Jensen's inequality to the logarithm function, which is concave, and the arithmetic mean:

$$\log\left(\frac{\sum_{i=1}^n x_i}{n}\right) \geq \sum_{i=1}^n \frac{1}{n} \log(x_i) = \log\left(\sqrt[n]{\prod_{i=1}^n x_i}\right)$$

Exponentiating both sides gives the desired inequality:

$$\frac{\sum_{i=1}^n x_i}{n} \geq \sqrt[n]{\prod_{i=1}^n x_i}$$

□

IV Cauchy-Schwarz Inequality (柯西-施瓦茨不等式)

For any $\mathbf{u}, \mathbf{v} \in \mathbb{C}^n$,

$$|\mathbf{u} \cdot \mathbf{v}| \leq \|\mathbf{u}\| \|\mathbf{v}\|$$

and

$$|\mathbf{u} \cdot \mathbf{v}| \leq \|\mathbf{u}\| \|\mathbf{v}\| \iff \mathbf{u}/\mathbf{v},$$

where $\mathbf{u} \cdot \mathbf{v}$ is the standard inner product defined as

$$\mathbf{u} \cdot \mathbf{v} = \sum_{i=1}^n u_i \overline{v_i},$$

with $\overline{v_i}$ denoting the complex conjugate of v_i .

Proof.

Consider the complex number $z = \mathbf{u} \cdot \mathbf{v}$.

Define the function

$$f(t) = |\mathbf{u} + t\mathbf{v}|^2$$

for some real number t . Then, we have

$$\begin{aligned} f(t) &= (\mathbf{u} + t\mathbf{v}) \cdot \overline{(\mathbf{u} + t\mathbf{v})} \\ &= (\mathbf{u} \cdot \bar{\mathbf{u}}) + t(\mathbf{u} \cdot \bar{\mathbf{v}}) + t(\mathbf{v} \cdot \bar{\mathbf{u}}) + t^2(\mathbf{v} \cdot \bar{\mathbf{v}}) \\ &= |\mathbf{u}|^2 + 2t\Re(\mathbf{u} \cdot \bar{\mathbf{v}}) + t^2|\mathbf{v}|^2. \end{aligned}$$

Since $f(t) \geq 0$ for all $t \in \mathbb{R}$, the quadratic equation in t must have a non-positive discriminant. The discriminant of this quadratic is:

$$\begin{aligned} \Delta &= (2\Re(\mathbf{u} \cdot \bar{\mathbf{v}}))^2 - 4 \times |\mathbf{v}|^2 \times |\mathbf{u}|^2 \\ &= 4(\Re(\mathbf{u} \cdot \bar{\mathbf{v}}))^2 - 4|\mathbf{u}|^2|\mathbf{v}|^2. \end{aligned}$$

We require $\Delta \leq 0$. This implies:

$$(\Re(\mathbf{u} \cdot \bar{\mathbf{v}}))^2 \leq |\mathbf{u}|^2|\mathbf{v}|^2.$$

Taking the square root of both sides and noting that $|\mathbf{u} \cdot \mathbf{v}| \geq \Re(\mathbf{u} \cdot \bar{\mathbf{v}})$:

$$|\mathbf{u} \cdot \mathbf{v}| \leq |\mathbf{u}||\mathbf{v}|.$$

Equality $|\mathbf{u} \cdot \mathbf{v}| = |\mathbf{u}||\mathbf{v}|$ holds if and only if the discriminant $\Delta = 0$. This happens when the quadratic equation has a double root or equivalently, when $\mathbf{u} + t\mathbf{v} = 0$ for some real t , implying \mathbf{u} is a scalar multiple of \mathbf{v} . Therefore, \mathbf{u} and \mathbf{v} are linearly dependent, meaning

$$\mathbf{u}/\mathbf{v}.$$

□