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The Cauchy-Schwarz Inequality

July 21, 2009

1 Introduction

The Cauchy-Schwarz inequality states that any time you take an inner product (i.e. dot product) of two vectors, you can't get something larger than if you just multiplied the two vectors' lengths. This is the crucial theorem underlying Bregman's Shortest Pathing.

In the simple vector we show in physics 101, the inequality is obvious, because the dot product of two vectors \mathbf{a} and \mathbf{b} is

$$\mathbf{a} \cdot \mathbf{b} = |\mathbf{a}||\mathbf{b}|\cos\theta \quad (1)$$

with θ the angle between the vectors. Because $\cos\theta \leq 1$, the dot product is less than or equal to the product of the lengths. Also, the dot product equals the product of the lengths only when the vectors point in the same direction. Here, we want to generalize this result to abstract vector spaces, working from the outside. Here we're talking about abstract vectors from now on, rather than little arrows in a plane, so I'll switch to the bra-ket notation.

2 Inner Products and Norms

Vector spaces can exist without inner products, but they're less interesting that way because we can't define orthogonality or take projections. Inner products are also closely tied to norms. If a vector space has an inner product defined, we can define the norm of a vector \mathbf{x} by

$$\|\mathbf{x}\| = \sqrt{\langle \mathbf{x}, \mathbf{x} \rangle} \quad (2)$$

Alternatively, if we have a norm but no inner product (as might be the case in a physical situation, where the norm is what you get by hitting down a meter), we can define the inner product of two vectors by

$$\langle \mathbf{x}, \mathbf{y} \rangle = \|\mathbf{x} + \mathbf{y}\|^2 - \|\mathbf{x}\|^2 - \|\mathbf{y}\|^2 \quad (3)$$

Although it isn't immediately obvious, this definition is linear in both vectors. For a complex vector space, the appropriate definition is

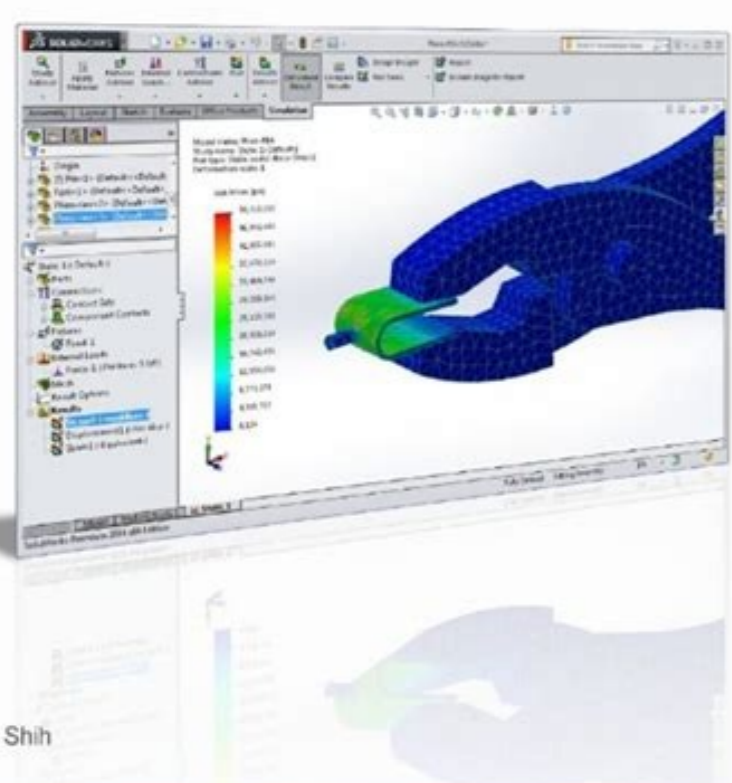
$$\langle \mathbf{x}, \mathbf{y} \rangle = \|\mathbf{x} + \mathbf{y}\|^2 - \|\mathbf{x}\|^2 - \|\mathbf{y}\|^2 - i\|\mathbf{x} + i\mathbf{y}\|^2 + \|\mathbf{x}\|^2 + \|\mathbf{y}\|^2 \quad (4)$$



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