Convex Functions (II)

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Outline

- The Conjugate Function
- Quasiconvex Functions
- Log-concave and Log-convex Functions
- Convexity with Respect to Generalized Inequalities
- Summary

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Conjugate Function

- $f: \mathbf{R}^n \to \mathbf{R}$. Its conjugate function is

$$f^*(y) = \sup_{x \in \mathrm{dom}\, f} \left(y^\top x - f(x)\right)$$

  - $\mathrm{dom}\, f^* = \{y | f^*(y) < \infty\}$
  - f^* is always convex

Conjugate Function

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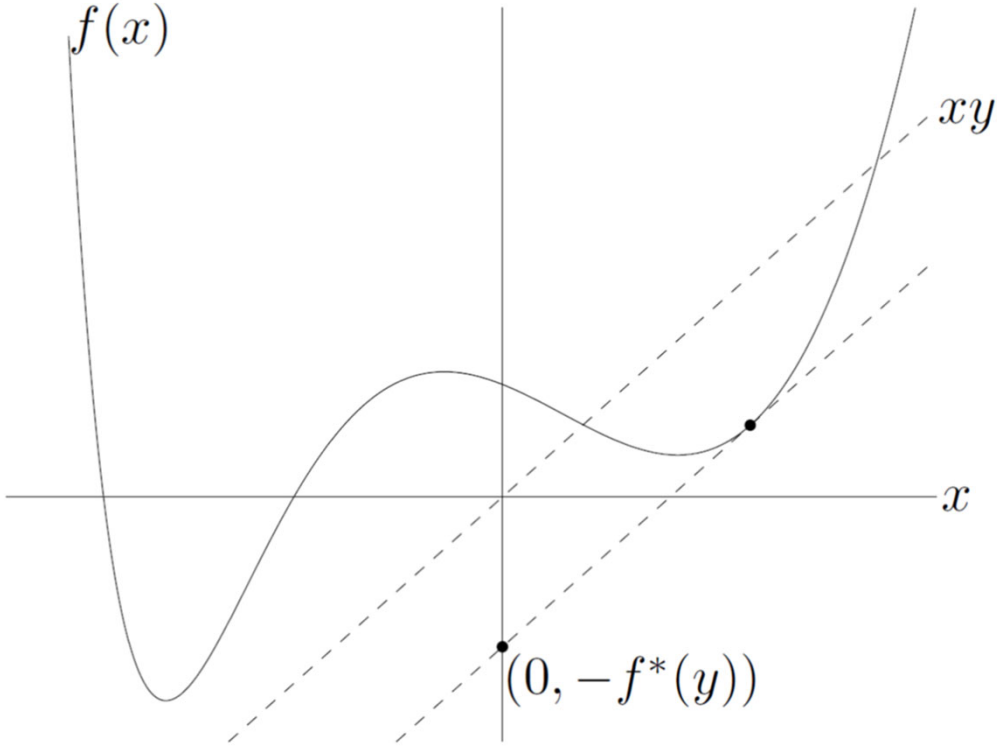

Conjugate examples

Affine function

- $f(x) = ax + b$
- $f^*(y) = \sup_{x \in \mathbf{R}} (yx - ax - b)$
- $\operatorname{dom} f^* = \{a\}, f^*(a) = -b$

Negative logarithm

- $f(x) = -\log x$
- $f^*(y) = \sup_{x \in \mathbf{R}_{++}} (yx + \log x)$
- $\operatorname{dom} f^* = -\mathbf{R}_{++}, f^*(y) = -\log(-y) - 1$

Conjugate examples

- Exponential
  - $f(x) = e^x$
  - $f^*(y) = \sup_{x \in \mathbf{R}} (xy - e^x)$
  - $\operatorname{dom} f^* = \mathbf{R}_+, f^*(y) = y \log y - y$
- Negative entropy
  - $f(x) = x \log x$
  - $f^*(y) = \sup_{x \in \mathbf{R}_+} (yx - x \log x)$
  - $\operatorname{dom} f^* = \mathbf{R}, f^*(y) = e^{y-1}$

Conjugate examples

Inverse

- $f(x) = 1/x, x \in \mathbf{R}_{++}$
- $f^*(y) = \sup_{x \in \mathbf{R}_{++}} (xy - 1/x)$
- $\mathrm{dom}\, f^* = -\mathbf{R}_+, f^*(y) = -2(-y)^{1/2}$

Strictly convex quadratic function

- $f(x) = \frac{1}{2} x^\top Q x, Q \in \mathbf{S}^n_{++}$
- $f^*(y) = \sup_{x \in \mathbf{R}^n} (y^\top x - \frac{1}{2} x^\top Q x)$
- $\mathrm{dom}\, f^* = \mathbf{R}^n, f^*(y) = \frac{1}{2} y^\top Q^{-1} y$

Conjugate examples

Log-determinant

- $f(X) = \log\det X^{-1}, X \in \mathbf{S}_{++}^n$
- $f^*(Y) = \sup_{X \in \mathbf{S}_{++}^n} (\operatorname{tr}(XY) + \log\det X)$
- $\operatorname{dom} f^* = -\mathbf{S}_{++}^n, f^*(Y) = \log\det(-Y)^{-1} - n$

Indicator function

- $I_S(x) = 0, \operatorname{dom} I_S = S, S \subseteq \mathbf{R}^n$ is not necessarily convex
- $I_S^*(y) = \sup_{x \in S} y^\top x$
- $I_S^*(y)$ is the support function of the set S

Conjugate examples

Support function of a set

- $C \subseteq \mathbf{R}^n, C \neq \emptyset$
- $S_C(x) = \sup\{x^\top y | y \in C\}$
- $\operatorname{dom} S_C = \{x | \sup_{y \in C} x^\top y < \infty\}$

Indicator function

- $I_S(x) = 0, \operatorname{dom} I_S = S, S \subseteq \mathbf{R}^n$ is not necessarily convex
- $I_S^*(y) = \sup_{x \in S} y^\top x$
- $I_S^*(y)$ is the support function of the set S

Conjugate examples

Norm

- $f(x) = \|x\|, x \in \mathbf{R}^n$, with dual norm $\|\cdot\|_*$
- $f^*(y) = \sup_{x \in \mathbf{R}^n} (x^\top y - \|x\|)$
- $\mathrm{dom}\, f^* = \{y | \|y\|_* \leq 1\}, f^*(y) = 0$

Norm squared

- $f(x) = \frac{1}{2}\|x\|^2, x \in \mathbf{R}^n$, with dual norm $\|\cdot\|_*$
- $f^*(y) = \sup_{x \in \mathbf{R}^n} (x^\top y - \frac{1}{2}\|x\|^2)$
- $\mathrm{dom}\, f^* = \mathbf{R}^n, f^*(y) = \frac{1}{2}\|y\|_*^2$

Basic properties

Fenchel's inequality

- $\forall x \in \operatorname{dom} f, y \in \operatorname{dom} f^*,\ f(x) + f^*(y) \geq x^\top y$
- $f^*(y) = \sup_{x \in \mathbf{R}^n} (x^\top y - f(x))$
- $f(x) = \frac{1}{2} x^\top Q x, Q \in \mathbf{S}^n_{++}$

  $\Rightarrow x^\top y \leq \frac{1}{2} x^\top Q x + \frac{1}{2} y^\top Q^{-1} y$

Conjugate of the conjugate

- f is convex and closed $\Rightarrow f^{**} = f$

Basic properties

Differentiable functions

- f is convex and differentiable, $\operatorname{dom} f = \mathbf{R}^n$
- $f^*(y) = \sup_{x \in \mathbf{R}^n} (x^\top y - f(x))$
- $x^* = \operatorname{argmax}\big(x^\top y - f(x)\big) \Rightarrow \nabla f(x^*) = y$
- $f^*(y) = x^{*\top} \nabla f(x^*) - f(x^*) = x^{*\top} y - f(x^*)$
  - ✓ $x^* = \nabla^{-1} f(y)$

Basic properties

Scaling with affine transformation

- $a > 0, b \in \mathbf{R}, g(x) = af(x) + b$
  $\Rightarrow g^*(y) = af^*\left(\frac{y}{a}\right) - b$
- $A \in \mathbf{R}^{n\times n}$ is nonsingular, $b \in \mathbf{R}^n, g(x) = f(Ax + b) \Rightarrow g^*(y) = f^*(A^{-\mathsf{T}}y) - b^{\mathsf{T}}A^{-\mathsf{T}}y, \operatorname{dom} g^* = A^{\mathsf{T}}\operatorname{dom} f^*$

Sums of independent functions

- $f(u, v) = f_1(u) + f_2(v), f_1, f_2$ are convex $\Rightarrow$ $f^*(w, z) = f_1^*(w) + f_2^*(z)$

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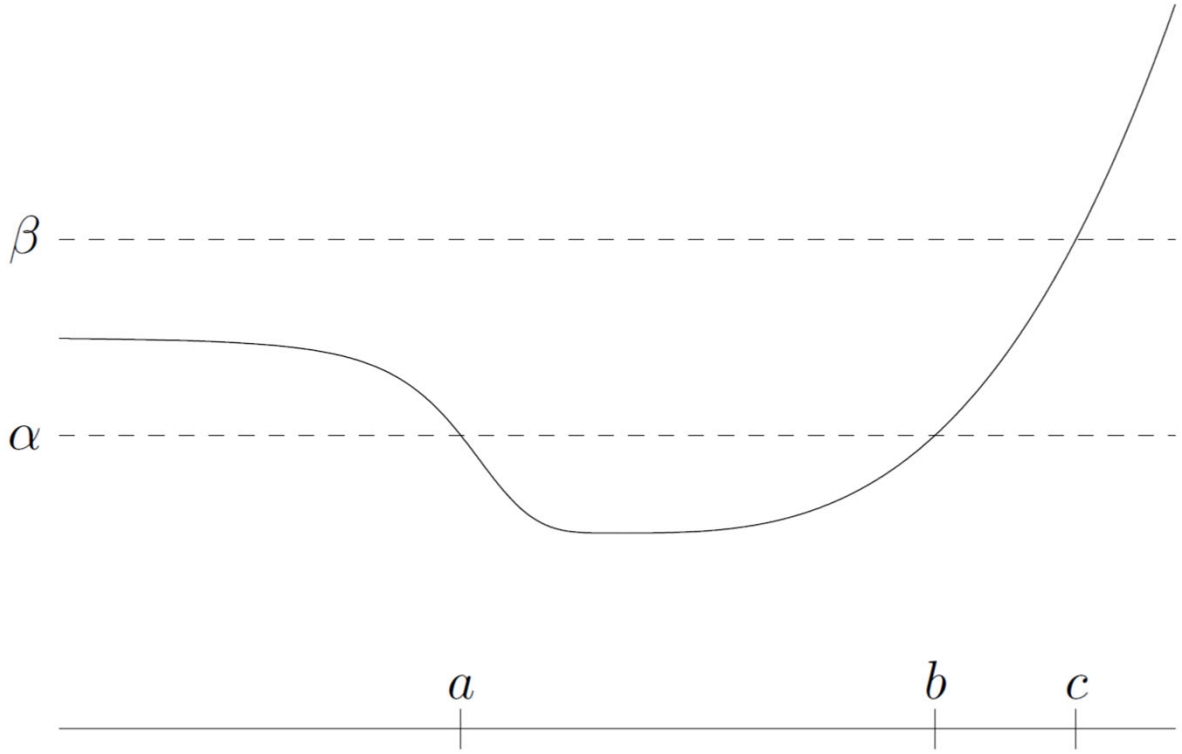
Quasiconvex functions

Quasiconvex

- $f: \mathbf{R}^n \to \mathbf{R}$
- $S_\alpha = \{x \in \operatorname{dom} f \mid f(x) \leq \alpha\}, \forall \alpha \in \mathbf{R}$ is convex



Quasiconvex functions

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- $f: \mathbf{R}^n \to \mathbf{R}$
- $S_\alpha = \{x \in \operatorname{dom} f \mid f(x) \leq \alpha\}, \forall \alpha \in \mathbf{R}$ is convex

Quasiconcave

- $-f$ is quasiconvex $\Rightarrow f$ is quasiconcave

Quasilinear

- f is quasiconvex and quasiconcave $\Rightarrow f$ is quasilinear

Examples

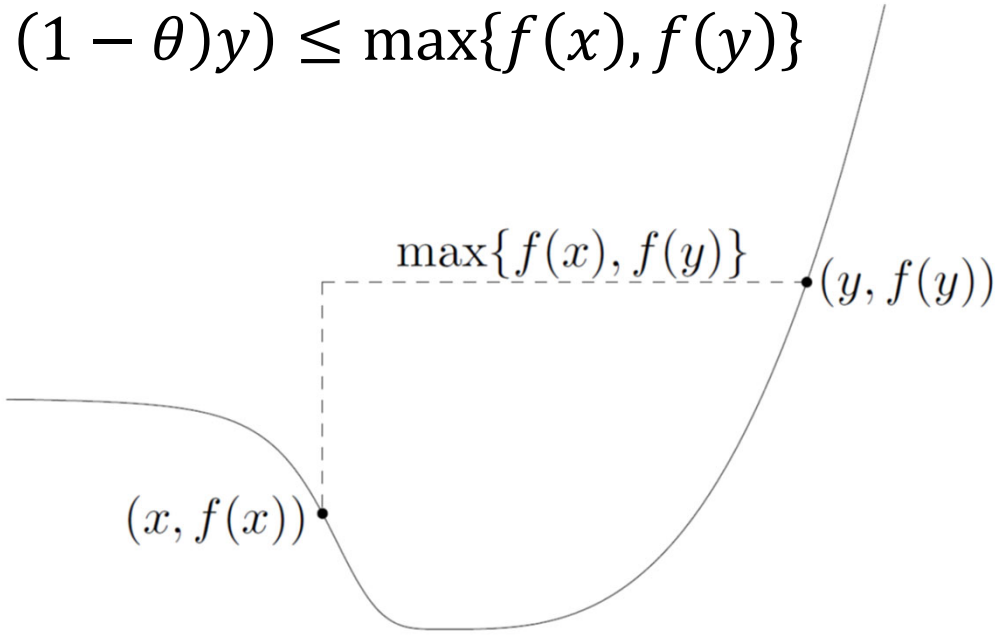
- Some example on $\mathbf{R}$
  - Logarithm: $\log x$ on $\mathbf{R}_{++}$
    - ✓ Concave, quasiconvex, quasiconcave
  - Ceiling function: $\operatorname{ceil}(x) = \inf\{z \in \mathbf{Z} \mid z \geq x\}$
    - ✓ quasiconvex, quasiconcave
- Linear-fractional function
  - $f(x) = \frac{a^{\mathsf{T}}x+b}{c^{\mathsf{T}}x+d}, \operatorname{dom} f = \{x | c^{\mathsf{T}}x + d > 0\}$
  - $\left\{x \middle| c^{\mathsf{T}}x + d > 0, \frac{a^{\mathsf{T}}x+b}{c^{\mathsf{T}}x+d} \geq \alpha\right\}$ and $\left\{x \middle| c^{\mathsf{T}}x + d > 0, \frac{a^{\mathsf{T}}x+b}{c^{\mathsf{T}}x+d} \leq \alpha\right\}$ is convex

    $\Rightarrow f$ is Quasilinear

Basic properties

- Jensen's inequality for quasiconvex functions
  - f is quasiconvex $\Leftrightarrow \mathrm{dom}\, f$ is convex and $\forall x, y \in \mathrm{dom}\, f, 0 \leq \theta \leq 1$

$$f(\theta x + (1-\theta)y) \leq \max\{f(x), f(y)\}$$



Basic properties

Condition

- f is quasiconvex $\Leftrightarrow$ its restriction to any line intersecting its domain is quasiconvex

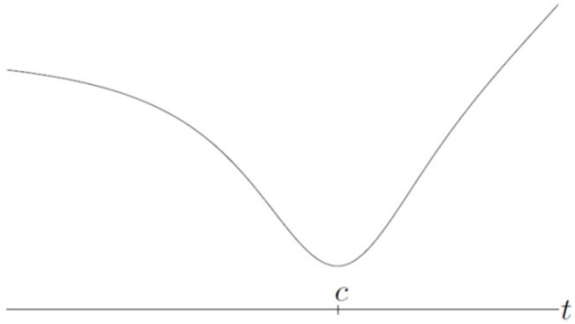
Quasiconvex functions on $\mathbf{R}$

- A continuous function $f: \mathbf{R} \to \mathbf{R}$ is quasiconvex $\Leftrightarrow$ one of the following conditions holds

✓ f is nondecreasing

✓ f is nonincreasing

✓ $\exists c \in \mathrm{dom}\, f, \forall t \in \mathrm{dom}\, f, t \leq c, f$ is nonincreasing, and $t \geq c, f$ is nondecreasing

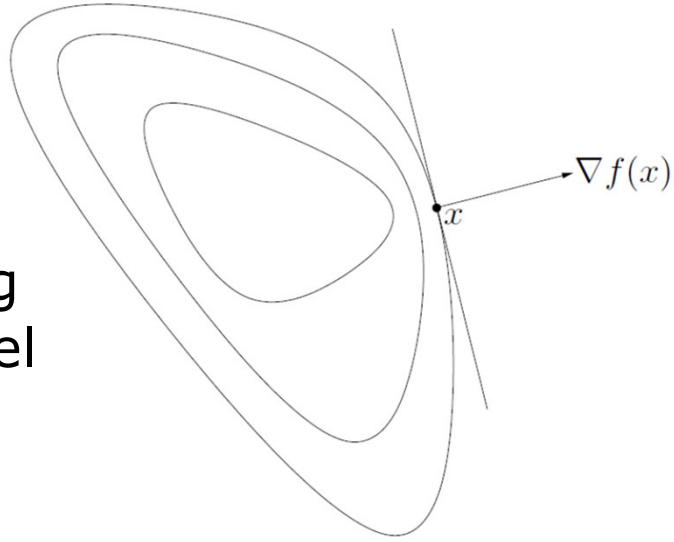


Differentiable quasiconvex functions

First-order conditions

- f is differentiable
- f is quasiconvex $\Leftrightarrow$ $\mathbf{dom}\ f$ is convex, $\forall x, y \in \mathbf{dom}\ f, f(y) \leq f(x) \Rightarrow \nabla f(x)^{\mathsf{T}}(y - x) \leq 0$

$\nabla f(x)$ defines a supporting hyperplane to the sublevel set $\{y | f(y) \leq f(x)\}$ at x



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First-order conditions

- f is differentiable
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- It is possible that $\nabla f(x) = 0$, but x is not a global minimizer of f.

Second-order conditions

- f is twice differentiable
- f is quasiconvex $\Rightarrow$ $\forall x \in \mathbf{dom}\ f, \forall y \in \mathbf{R}^n, y^{\mathsf{T}}\nabla f(x) = 0 \Rightarrow y^{\mathsf{T}}\nabla^2 f(x) y \geq 0$

Differentiable quasiconvex functions

First-order conditions

- f is differentiable
- f is quasiconvex $\Leftrightarrow$ $\mathbf{dom}\ f$ is convex,$\forall x, y \in \mathbf{dom}\ f, f(y) \leq f(x) \Rightarrow \nabla f(x)^{\mathsf{T}}(y - x) \leq 0$
- It is possible that $\nabla f(x) = 0$, but x is not a global minimizer of f.

Second-order conditions

- f is twice differentiable
- $\forall x \in \mathbf{dom}\ f, \forall y \in \mathbf{R}^n, y^{\mathsf{T}}\nabla f(x) = 0 \Rightarrow y^{\mathsf{T}}\nabla^2 f(x)y > 0 \Rightarrow f$ is quasiconvex

Operations that preserve quasiconvexity

Nonnegative weighted maximum

- f_i is quasicovex, $w_i \geq 0 \Rightarrow f = \max\{w_1 f_1, \ldots, w_n f_n\}$ is quasiconvex

- $g(x, y)$ is quasiconvex in x for each $y, w(y) \geq 0 \Rightarrow f(x) = \sup_{y \in C}(w(y) g(x, y))$ is quasiconvex

Operations that preserve quasiconvexity

Composition

- $g: \mathbf{R}^n \to \mathbf{R}$ is quasiconvex, $h: \mathbf{R} \to \mathbf{R}$ is nondecreasing $\Rightarrow f = h \circ g$ is quasiconvex
- $f: \mathbf{R}^n \to \mathbf{R}$ is quasiconvex $\Rightarrow g(x) = f(Ax + b)$ is quasiconvex
- $f: \mathbf{R}^n \to \mathbf{R}$ is quasiconvex $\Rightarrow g(x) = f(\frac{Ax+b}{c^\top x+d})$ is quasiconvex,$\operatorname{dom} g = \{x | c^\top x + d > 0, (Ax + b)/(c^\top x + d) \in \operatorname{dom} f\}$

Minimization

- $f(x, y)$ is quasicovex in x and y, C is a convex set $\Rightarrow g(x) = \inf_{y \in C} f(x, y)$ is quasiconvex

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Log-concave and log-convex functions

Definition

- $f: \mathbf{R}^n \to \mathbf{R}, f(x) > 0, \forall x \in \operatorname{dom} f, \log f(x)$ is concave (convex) $\Rightarrow f$ is log-concave (convex)
- A log-convex function is convex
- A nonnegative concave function is log-concave

Condition

- $f: \mathbf{R}^n \to \mathbf{R}, f(x) > 0, \forall x \in \operatorname{dom} f, f$ is log-concave $\Leftrightarrow \forall x, y \in \operatorname{dom} f, 0 \leq \theta \leq 1$

$$f(\theta x + (1-\theta)y) \geq f(x)^{\theta} f(y)^{1-\theta}$$

Examples

- $f(x) = a^{\mathsf{T}}x + b, \operatorname{dom} f = \{x | a^{\mathsf{T}}x + b > 0\}$ is log-concave
- $f(x) = x^a, \operatorname{dom} f = \mathbf{R}_{++}, a \leq 0 \Rightarrow f$ is log-convex, $a \geq 0 \Rightarrow f$ is log-concave
- $f(x) = e^{ax}$ is log-convex and log-concave
- $\phi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-u^2/2}\, du$ is log-concave
- $\Gamma(x) = \int_0^{\infty} u^{x-1} e^{-u}\, du$ is log-convex for $x \geq 1$
- $\det X$ and $\frac{\det X}{\operatorname{tr} X}$ are log-concave on $\mathbf{S}_{++}^n$

Properties

- Twice differentiable log-convex/concave functions
  - f is twice differentiable, $\mathrm{dom}\, f$ is convex
  - $\nabla^2 \log f(x) = \frac{1}{f(x)} \nabla^2 f(x) - \frac{1}{f(x)^2} \nabla f(x) \nabla f(x)^{\mathsf{T}}$
  - f is log-convex $\Leftrightarrow f(x) \nabla^2 f(x) \succcurlyeq \nabla f(x) \nabla f(x)^{\mathsf{T}}$
  - f is log-concave $\Leftrightarrow f(x) \nabla^2 f(x) \preccurlyeq \nabla f(x) \nabla f(x)^{\mathsf{T}}$

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Convexity with respect to a generalized inequality

- K-convex
  - $K \subseteq \mathbf{R}^m$ is a proper cone with associated generalized inequality $\preccurlyeq_K$
  - $f: \mathbf{R}^n \to \mathbf{R}^m$ is K-convex if $\forall x, y \in \operatorname{dom} f, 0 \le \theta \le 1$

    $$f(\theta x + (1-\theta)y) \preccurlyeq_K \theta f(x) + (1-\theta) f(y)$$
  - $f: \mathbf{R}^n \to \mathbf{R}^m$ is stricly $K-$convex if $\forall x \neq y \in \operatorname{dom} f, 0 < \theta < 1$

    $$f(\theta x + (1-\theta)y) \prec_K \theta f(x) + (1-\theta) f(y)$$

Examples

Componentwise Inequality

- $K = \mathbf{R}_+^m$

- $f: \mathbf{R}^n \to \mathbf{R}^m$ is convex with respect to componentwise inequality $\Leftrightarrow \forall x, y \in \operatorname{dom} f, 0 \leq \theta \leq 1,$

  $f(\theta x + (1-\theta)y) \preccurlyeq \theta f(x) + (1-\theta) f(y)$

- Each f_i is a convex function

Examples

Matrix Convexity

- $f: \mathbf{R}^n \to \mathbf{S}^m$ is convex with respect to matrix inequality $\Leftrightarrow \forall x, y \in \operatorname{dom} f, 0 \leq \theta \leq 1$

  $f(\theta x + (1-\theta)y) \preccurlyeq \theta f(x) + (1-\theta) f(y)$

- $f(X) = XX^{\mathsf{T}}, X \in \mathbf{R}^{m \times n}$ is matrix convex
- X^p is matrix convex on $\mathbf{S}^n_{++}$ for $1 \leq p \leq 2$ or $-1 \leq p \leq 0$, and matrix concave for $0 \leq p \leq 1$

Convexity with respect to generalized inequalities

Dual characterization of K-convexity

- A function f is (strictly) K-convex $\Leftrightarrow$ For every $w \succcurlyeq_{K^*} 0$, the real-valued function $w^{\mathsf{T}} f$ is (strictly) convex in the ordinary sense.

Differentiable K-convex functions

- A differentiable function f is K-convex $\Leftrightarrow \operatorname{dom} f$ is convex, $\forall x, y \in \operatorname{dom} f$,

$$f(y) \succcurlyeq_K f(x) + Df(x)(y - x)$$

- A differentiable function f is strictly K-convex $\Leftrightarrow \operatorname{dom} f$ is convex, $\forall x, y \in \operatorname{dom} f, x \neq y$,

$$f(y) \succ_K f(x) + Df(x)(y - x)$$

Convexity with respect to generalized inequalities

Composition theorem

- $g: \mathbf{R}^n \to \mathbf{R}^p$ is K-convex, $h: \mathbf{R}^p \to \mathbf{R}$ is convex, and $\tilde{h}$ (the extended-value extension of h) is K-nondecreasing $\Rightarrow h \circ g$ is convex.

Example

- $g: \mathbf{R}^{m\times n} \to \mathbf{S}^n, g(X) = X^\mathsf{T}AX + B^\mathsf{T}X + X^\mathsf{T}B + C$ is convex, where $A \succcurlyeq 0, B \in \mathbf{R}^{m\times n}$ and $C \in \mathbf{S}^n$
- $h: \mathbf{S}^n \to \mathbf{R}, h(Y) = -\log\det(-Y)$ is convex and increasing on $\operatorname{dom} h = -\mathbf{S}^n_{++}$
- $f(X) = -\log\det(-(X^\mathsf{T}AX + B^\mathsf{T}X + X^\mathsf{T}B + C))$ is convex on $\operatorname{dom} f = \{X \in \mathbf{R}^{m\times n} | X^\mathsf{T}AX + B^\mathsf{T}X + X^\mathsf{T}B + C \prec 0\}$

Monotonicity with respect to a generalized inequality

- $K \subseteq \mathbf{R}^n$ is a proper cone with associated generalized inequality $\preccurlyeq_K$
  - $f: \mathbf{R}^n \to \mathbf{R}$ is K-nondecreasing if

$$x \preccurlyeq_K y \Rightarrow f(x) \leq f(y)$$

  - $f: \mathbf{R}^n \to \mathbf{R}$ is K-increasing if

$$x \preccurlyeq_K y, x \neq y \Rightarrow f(x) < f(y)$$

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