0.1 Symbols

$S^n \equiv$ set of all symmetric matrices

$M_+^n \equiv$ set of all positive definite matrices (PD)

$S_+^n \equiv$ set of all symmetric positive semidefinite matrices (SPSD)

$S_+ +^n \equiv$ set of all symmetric positive definite matrices (SPD)

$cl(X) \equiv$ closure of X

$relint(X) \equiv$ relative interior of X

$int(X) \equiv$ interior of X

0.2 Preliminary

Consider $f : \mathbb{R}^n \to \mathbb{R}$
Gradient of f: $\nabla f(x) = \begin{bmatrix} \partial f / \partial x_i \\ .. \end{bmatrix}$
$f(x) = a^T x \implies \nabla f(x) = a$
$f(x) = x^T Px, P = P^T \implies \nabla f(x) = 2Px$
$f(x) = x^T Px \implies \nabla f(x) = 2(\frac{P^T+P}{2})x = (P^T + P)x$

Taylor expansion approximation:
$f(x) \approx f(x_0) + \nabla^T f(x_0)(x - x_0) + o((x - x_0)^2)$
$f(x + \delta x) \approx f(x_0) + \nabla^T f(x)\delta x + o((\delta x)^2)$

Chain rule:
$f : \mathbb{R} \to \mathbb{R}, g : \mathbb{R} \to \mathbb{R}, h(x) = f(g(x))$
$\nabla h(x) = g'(f(x))\nabla f(x)$

$g : \mathbb{R}^m \to \mathbb{R}, g(x) = f(Ax + b)$
$\nabla g(x) = A^T \nabla f(Ax + b)$

2nd derivative:
$\nabla^2 f(x) = \begin{bmatrix} \partial^2 f / \partial x_1 \partial x_1 & ... \\ .. & \partial^2 f / \partial x_n \partial x_n \end{bmatrix}$
$\nabla f(x) = Px + g$
$\nabla^2 f(x) = P$

Hessian gives the 2nd order approximation:
$f(x) \approx f(x_0) + \nabla^T f(x_0)(x - x_0) + \frac{1}{2}(x - x_0)^T \nabla^2 f(x_0)(x - x_0)$

Matrices:
$A \in \mathbb{R}^{m \times n}$: set of all real matrices
inner product: $\sum_i \sum_j x_{ij} y_{ij} = trace(XY^T) = trace(Y^T X) = \sum_i (XY)_{ii}$
note trace has cyclic property
frobenius norm: $\|X\|_F = (\sum_i \sum_j X_{ij}^2)^{\frac{1}{2}}$
range: $R(A) = \{Ax : x \in \mathbb{R}^n\} = \sum_i a_i x_i$, where a_i is ith column (column space of A)
null space: $N(A) = \{x : Ax = 0\}$

SVD:
$A_{m \times n} = U_{m \times m} \Sigma_{m \times n} V_{n \times n}^T$
U and V are left and right eigenvector matrixes
U and V are orthogonal matrixes($BB^T = B^T B = I$)
Σ is rectangular diagonal matrix of eigenvalues
$A_{m \times n} x_n$
linear transformation: $U \Sigma V^T x$
rotation - scaling - rotation

PSD matrix:
$A\ PSD \iff (\forall x) x^T Ax \geq 0 \iff (\forall i) \lambda_i(A) \geq 0$
$A\ PSD \implies A^{1/2}$ exists

Real symmetric matrices have real eigenvalues:

$$Av = \lambda v$$
$$v^* Av = v^* \lambda v = \lambda \|v\|_2^2$$
$$(v^* Av)^* = v^* A^* v = \lambda^* \|v\|_2^2 \implies \lambda = \lambda^*$$

Affine sets
A set $C \subseteq \mathbb{R}^n$ is affine if $(\forall x_1, x_2 \in C)(\forall \theta \in \mathbb{R}) \implies \theta x_1 + (1 - \theta)x_2 \in C$

Convex sets
A set $C \subseteq \mathbb{R}^n$ is convex if $(\forall x_1, x_2 \in C)(\forall \theta \in \mathbb{R}) 0 \leq \theta \leq 1 \implies \theta x_1 + (1 - \theta)x_2 \in C$

Operations preserving convex sets:

- partial sum
- sum
- coordinate projection
- scaling
- translation
- intersection between any convex sets

Separating Hyperplanes: if $S, T \subset \mathbb{R}^n$ are convex and disjoint, then $\exists a \neq 0, b$ such that:

$$a^T x \geq b, \forall x \in S$$
$$a^T x \leq b, \forall x \in T$$

Supporting Hyperplane:
if S is convex, $\forall x_0 \in \partial S$ (boundary of S), then $\exists a \neq 0$ such that $a^T x \leq a^T x_0, \forall x \in S$

Convex combination:
$\sum_i \theta_i x_i, \forall \theta_i \in \mathbb{R}, \sum_i \theta_i = 1, \theta_i \geq 0$

Convex hull:
The set of all convex combinations of points in C, the hull is convex

Hyperplane

$$C = \{x : a^T x = b\}, a \in \mathbb{R}^n, a \neq 0, b \in \mathbb{R}$$

Halfspaces

$$\begin{aligned} C = \{x : a^T x \leq b\}, a \in \mathbb{R}^n, a \neq 0, b \in \mathbb{R} \\ \text{let } a^T x_c = b \\ C = \{x : a^T (x - x_c) \leq 0\}, a \in \mathbb{R}^n, a \neq 0 \end{aligned}$$

Elipse

$$\begin{aligned} E(x_c, P) = \{x : (x - x_c)^T P^{-1} (x - x_c) \leq 1\}, P > 0 \\ P = r^2 I \implies \text{ Euclidean Ball} \\ P = Q \begin{bmatrix} \lambda_1 & .. \\ .. & \lambda_n \end{bmatrix} Q^T \\ (x - x_c)^T (Q \begin{bmatrix} \lambda_1 & .. \\ .. & \lambda_n \end{bmatrix} Q^T)^{-1} (x - x_c) \leq 1 \\ \tilde{x}^T \begin{bmatrix} \frac{1}{\lambda_1} & .. \\ .. & \frac{1}{\lambda_n} \end{bmatrix} \tilde{x} \leq 1 \\ \tilde{x}^T \begin{bmatrix} \frac{1}{\lambda_1} & .. \\ .. & \frac{1}{\lambda_n} \end{bmatrix} \tilde{x} = \frac{\tilde{x_1}^2}{\lambda_1} + .. + \frac{\tilde{x_n}^2}{\lambda_n} \leq 1 \end{aligned}$$

volum of elipsoid proportional to $\sqrt{det(P)} = \sqrt{\Pi_i \lambda_i}$

0.3 Problem Types

LP

standard, inequality, general forms

$$\begin{aligned}\min_x c^T x \ s.t. :\\ Ax = b\\ x \succeq 0\end{aligned}$$

$$\begin{aligned}\min_x c^T x \ s.t. :\\ Ax \preceq b\end{aligned}$$

$$\begin{aligned}\min_x c^T x + d \ s.t. :\\ Gx \preceq h\\ Ax = b\end{aligned}$$

QP

$$\begin{aligned}\min_x \frac{1}{2} x^T P x + q^T x + r \ s.t. :\\ Gx \leq h\\ Ax = b\end{aligned}$$

QCQP

$$\begin{aligned}\min_x \frac{1}{2} x^T P_0 x + q_0^T x + r_0, s.t. :\\ \frac{1}{2} x^T P_i x + q_i^T x + r_i \leq 0, \forall i\\ Ax = b\end{aligned}$$

SOCP

$$\begin{aligned}\min_x f^T x \ s.t. :\\ \|A_i x + b_i\|_2 \leq c_i^T x + d_i, \forall i\\ Fx = g\end{aligned}$$

$$\begin{aligned}(\forall i) b_i = 0 \implies LP\\ (\forall i) c_i = 0 \implies QCQP\end{aligned}$$

GP

$$\begin{aligned}\min_x f_0(x) \ s.t. :\\ f_i(x) \leq 1, \forall i\\ h_i(x) = 1, \forall i\\ f_i \ is \ a \ posynomial := \sum_i h_i\\ h_i \ is \ a \ monomial := c x_1^{a_1} x_2^{a_2} .., c > 0, a_i \in \mathbb{R}\end{aligned}$$

Use transform of objective and constraint functions:
$y_i = log x_i, x_i = e^{y_i}$
$\tilde{h}_i$ becomes exponential of affine function
$\tilde{f}_i = log(f_i)$ becomes log sum exp (convex)
If all constraints and objective are monomials, reduces to LP after transform.

SDP

general, standard, inequality forms

$$\begin{aligned}\min_x \ c^T x \ s.t. :\\ LMI: \ \sum_i^n x_i F_i + G \preceq_K 0\\ Ax = b\\ x \in \mathbb{R}^n\\ F_i, G \in S^m, K \in S_+^m\end{aligned}$$

$$\begin{aligned}\min_X \ tr(CX) s.t. :\\ tr(A_i X) = b_i, \forall i\\ X \succeq 0\end{aligned}$$

$$\begin{aligned}\min_x \ c^T x \ s.t. :\\ \sum_i^n x_i A_i \preceq_K B\\ Ax = b\\ B, A_i \in S^m, K \in S_+^m\end{aligned}$$

concatenating constraints:

$$\begin{aligned}F^(i)(x) = \sum_j x_j F_i^{(i)} + G^{(i)} \preceq 0\\ Gx \preceq h\\ \implies\\ diag(Gx - h, F^{(1)}(x), .., F^{(m)}(x)) \preceq 0\end{aligned}$$

if all matrices are diagonal, reduces to LP

0.4 Convex/Concave Functions

- Affine
- Pointwise supremum of convex function
  - distance to farthest point in a set
  - support function of set
- Norm
- Non-negative weighted sum of convex functions

0.4.1 log det X, concave

$$let\ X = Z + tV \succ 0$$
$$f = logdet(Z + tV)$$
$$f = logdet(Z^{-0.5}(I + tZ^{-0.5}VZ^{0.5})Z^{0.5})$$
$$f = log(det(Z^{-0.5})det(I + tZ^{-0.5}VZ^{0.5})det(Z^{0.5}))$$
$$f = log(det(Z^{0})det(I + tZ^{-0.5}VZ^{0.5}))$$
$$f = logdet(I + tZ^{-0.5}VZ^{0.5})$$
$$f = log\Pi_i(1 + \lambda_i t)$$
$$f = \sum_i log(1 + \lambda_i t)$$
$$\frac{\partial f}{\partial t} = \sum_i \frac{\lambda_i}{1 + \lambda_i t}$$
$$\frac{\partial^2 f}{\partial t^2} = \sum_i \frac{-\lambda_i^2}{(1 + \lambda_i t)^2} = -\sum_i \frac{\lambda_i^2}{(1 + \lambda_i t)^2} \leq 0$$
$$\nabla^2 f \leq 0 \iff f\ concave$$

0.4.2 log $\sum_i exp(x_i)$, convex

$$\nabla^2 f = \frac{1}{(1^T z)^2}(1^T z diag(z) - zz^T)$$
$$v^T zz^T v = det(v^T zz^T v) = det(vv^T zz^T)$$
$$v^T zz^T v = \sum_j \sum_i z_j z_i v_j v_i$$
$$v^T zz^T v = (\sum_j z_j z_j)(\sum_i z_i v_i)$$
$$v^T zz^T v = (\sum_i z_i v_i)^2$$
$$use\ Holder's\ Inequality:$$
$$\|a\|_2^2 \|b\|_2^2 \geq |a^T b|^2$$
$$let\ a = z_i^{0.5}, b = v_i z_i^{0.5}$$
$$1^T z(\sum_i v_i^2 z_i) - (\sum_i z_i v_i)^2 \geq 0$$
$$v^T \nabla^2 f v = \frac{1}{(1^T z)^2}\left(1^T z(\sum_i v_i^2 z_i) - (\sum_i z_i v_i)^2\right) \geq 0$$
$$\nabla^2 f \geq 0 \iff f\ convex$$

0.4.3 geometric mean on R^n_{++}, concave

$$f = (\Pi_i x_i)^{\frac{1}{n}}$$
$$\frac{\partial}{\partial x_i} f = \frac{1}{n}(\Pi_i x_i)^{\frac{1}{n}-1}\Pi_{j\neq i} x_j$$
$$\frac{\partial^2}{\partial x_i^2} f = \frac{1}{n}(\frac{1}{n} - 1)(\Pi_i x_i)^{\frac{1}{n}-2}(\Pi_{j\neq i} x_j)^2$$
$$\frac{\partial^2}{\partial x_i^2} f = \frac{1}{n}(\frac{1}{n} - 1)\frac{(\Pi_i x_i)^{\frac{1}{n}}}{x_i^2}$$
$$\frac{\partial^2}{\partial x_i x_k} f = \frac{1}{n^2}\frac{(\Pi_i x_i)^{\frac{1}{n}}}{x_i x_k}, i \neq k$$
$$\frac{\partial^2}{\partial x_i x_k} f = \frac{1}{n^2}\frac{(\Pi_i x_i)^{\frac{1}{n}}}{x_i x_k} - \delta_{ik}\frac{1}{n}\frac{(\Pi_i x_i)^{\frac{1}{n}}}{x_i^2}$$
$$v^T \nabla^2 f v = \frac{-(\Pi_i x_i)^{\frac{1}{n}}}{n^2}(n\sum_i \frac{v_i^2}{x_i^2} - (\sum_i \frac{v_i}{x_i})^2)$$
$$apply\ Cauchy\ Schwartz\ Inequality:$$
$$let\ a = \mathbf{1}, b_i = \frac{v_i}{x_i}$$
$$\|\mathbf{1}\|_2^2(\sum_i \frac{v_i^2}{x_i}) \geq (\sum_i \frac{v_i}{x_i})^2$$
$$n\sum_i \frac{v_i^2}{x_i^2} - (\sum_i \frac{v_i}{x_i})^2 \geq 0$$
$$v^T \nabla^2 f v \leq 0 \iff f\ concave$$

0.4.4 quadratic over linear, convex

$$f(x,y) = \frac{h(x)}{g(y)}, g(y)\ linear, g(y) \in R_+$$
$$\nabla^2 f = vv^T\ is\ PSD \iff f\ convex$$

0.5 Composition of functions

Mnemonic derivation from scalar composite function

$$f = h(g(x))$$
$$f' = g'(x)h'(g(x))$$
$$f'' = g''(x)h'(g(x)) + (g'(x))^2 h''(g(x))$$

$$\text{h convex \& non-decreasing, g convex} \implies \text{f convex}$$
$$h'' \geq 0, g''(x) \geq 0, h'(g(x)) \geq 0 \implies f'' \geq 0$$

$$\text{h convex \& non-increasing, g concave} \implies \text{f convex}$$
$$h'' \geq 0, g''(x) \leq 0, h'(g(x)) \leq 0 \implies f'' \geq 0$$

$$\text{h concave \& non-decreasing, g concave} \implies \text{f concave}$$
$$h'' \leq 0, g''(x) \leq 0, h'(g(x)) \geq 0 \implies f'' \leq 0$$

$$\text{h concave \& non-increasing, g convex} \implies \text{f concave}$$
$$h'' \leq 0, g''(x) \geq 0, h'(g(x)) \leq 0 \implies f'' \leq 0$$

0.6 Convexity Preservation of Sets

0.6.1 Intersection

$$(\forall \alpha \in A) S_\alpha \text{ is convex cone } \implies \cap_{\alpha \in A} S_\alpha \text{ is convex cone}$$

Any closed convex set can be represented by possibly infinitely many half spaces.

0.6.2 Affine functions

let $f(x) = Ax + b, f : \mathbb{R}^n \to \mathbb{R}^m$
then if S is a convex set we have:

- project forward: $f(S) = \{f(X) : X \in S\}$ is convex
- project back: $f^{-1}(S) = \{X : f(X) \in S\}$ is convex

Example:

$$C = \{y : y = Ax + b, \|x\| \leq 1\}$$

$\|x\| \leq 1$ is convex, $Ax + b$ is affine $\implies$ C is convex
Example:

$$C = \{x : \|Ax + b\| \leq 1\}$$

$\{y : \|y\| \leq 1\}$ is convex $\wedge$ y is an affine function of $x \implies$ C is convex

0.7 Constraint Qualifications

0.7.1 Slater's Constraint Qual.

Optimal solution is in relative interior: $x^* \in relint(S)$

Inequalities $(\forall i) f_i(x)$ convex $\wedge$ $f_i(x) < 0 \implies$ Slater's constraint satisfied.

Inequalities $(\forall i) f_i(x)$ affine $\implies$ $(\forall i) f_i(x) \leq 0 \wedge (\exists i) f_i(x) < 0 \implies$ Slater's constraint satisfied.

Achieving Slater's constraint implies 0 duality gap.

0.7.2 KKT

Assumes optimality achieved with 0 duality gap: $\nabla L(x^*, \lambda^*, v^*) = 0$

$$L(x^*, \lambda^*, v^*) = f_0(x^*) + \sum_i \lambda_i^* f_i(x^*) + \sum_i v_i h_i(x^*)$$
$$\nabla L(x^*, \lambda^*, v^*) = \nabla f_0(x^*) + \sum_i \lambda_i^* \nabla f_i(x^*) + \sum_i v_i \nabla h_i(x^*)$$

We have the constraints:

$$f_i(x^*) \leq 0$$
$$\lambda_i^* \geq 0$$
$$h_i(x^*) = 0$$
$$\lambda_i^* f_i(x^*) = 0$$
$$\nabla L(x^*, \lambda^*, v^*) = \nabla f_0(x^*) + \sum_i \lambda_i^* \nabla f_i(x^*) + \sum_i v_i \nabla h_i(x^*)$$

Primal inequality constraints convex and equality constraints affine and KKT satisfied $\implies$ 0 duality gap with specified points for primal and dual. (sufficient).

If Slater's constraint satisfied then the above is sufficient and necessary:
Primal inequality constraints convex and equality constraints affine and KKT satisfied $\iff$ 0 duality gap with specified points for primal and dual.

0.8 Definitions

0.8.1 Convex Function

$$f(\theta x + (1-\theta)y) \leq \theta f(x) + (1-\theta)f(y), \forall\theta = [0,1]$$

For convenience we sometimes define an extended value function:

$$\tilde{f}(x) = \begin{cases} f(x), & x \in dom(f) \\ \infty, & other\ wise \end{cases}$$

if $f(x)$ convex, then $\tilde{f}$ is also convex

Sublevel set of a function

$$C(\alpha) = \{x \in dom(f) : f(x) \leq \alpha\}$$

For convex function, all sublevel sets are convex ($\forall\alpha$). Converse is not true.

Quasi-convex function: if its sublevel sets are all convex.

Epigraph of functions:
$epi(f) = \{(x,t) : x \in dom(f), f(x) \leq t\} \in \mathbb{R}^{n+1}$, $f \in \mathbb{R}^n \to \mathbb{R}$.

f is convex function $\iff$ $epi(f)$ is convex set

0.8.2 First order condition

Suppose f is differentiable and domain of f is convex. Then:
f convex $\iff$
$(\forall x, x_0 \in dom(f)) f(x) \geq f(x_0) + \nabla f(x_0)^T(x - x_0)$

rough proof:
suppose $f(x)$ is convex but $(\exists x, x_0) f(x) < f(x) + \nabla f(x_0)^T(x - x_0)$
then this means the function should bend across the tangent line which violates the convexity

proof for converse direction:
suppose that $(\exists x, x_0) f(x) \geq f(x) + \nabla f(x_0)^T(x - x_0)$
to show that $f(x)$ is convex lets take $x, y \in dom(f), z = \theta x + (1-\theta)y$
$\theta f(x) + (1-\theta)f(y) \geq f(z) + \nabla f(z)^T(\theta x - \theta z + (1-\theta)y - (1-\theta)z)$
$\theta f(x) + (1-\theta)f(y) \geq f(\theta x + (1-\theta)y)$
$f(x)$ is convex

0.8.3 Second order condition

Suppose f is twice differentiable and $dom(f)$ is convex,
then $f(x)$ is convex $\iff$ $\nabla^2 f(x) \geq 0$ (PSD, eg: wrt. S^n_+)

proof for scalar case:
suppose that $f(x)$ is convex, then the first-order condition holds
for $x, y \in dom(f) : f(x) \geq f(y) + f'(y)(x - y)$
for $y, x \in dom(f) : f(y) \geq f(x) + f'(x)(y - x)$
$f'(x)(y - x) \leq f(y) - f(x) \leq f'(y)(y - x)$
$f'(x)(y - x) \leq f'(y)(y - x) \implies 0 \leq (y - x)(f'(x) - f'(y))$
take $y \to x : 0 \leq f''(x)$
$f''(x) \geq \frac{f'(x+\delta x) - f'(x)}{\delta x}$

conversely, suppose that $f'(z) \geq 0, \forall z \in dom(f)$, take $x, y \in dom(f)$ WLOG $x < y$
$\int_x^y f''(z)(y - z)dz \geq 0$
$f''(z) \geq 0, (y - z) \geq 0 = I_1 + I_2$
$I_1 = \int_x^y f''(z)ydz - yf'(z)|_x^y = y(f'(y) - f'(x))$
$I_2 = -\int_x^y f''(z)dz$
$dv = f''(z)dz \implies v = f''(z)$
$u = z \implies du = dz$
$I_2 = -zf'(z)|_x^y + \int_x^y f(z)dz = -yf'(y) + xf'(x) + f(y) - f(x)$
$I_1 + I_2 = yf'(y) - yf'(x) - yf'(y) + xf'(x) + f(y) - f(x) \geq 0$
$\implies f(y) \geq f(x) + f'(x)(y - x)$ first order condition: $x < y$
first order condition holds $\implies f(x)$ convex

0.8.4 Inequalities

$x \preceq_K y \iff y - x \in K$

x is a minimum in S wrt. cone K:

$x \in S : (\forall y \in S) f(y) \succeq_K f(x) \iff f(y) - f(x) \in S$
$S \subseteq x + K$

x is a minimal in S wrt. cone K:

$$x \in S : (\forall y \in S) f(y) \preceq_K f(x) \implies x = y$$
$$x \in S : (\forall y \in S) f(x) - f(y) \in K \implies x = y$$
$$(x - K) \cap S = \{x\}$$

0.8.5 Cone

$$(\forall x \in C, \forall \theta \geq 0)\theta x \in C$$

0.8.6 Convex Cone

Eg: S^n, S^n_+ are convex cones
convexity check for S^N_+:

$$\begin{aligned} x_1 \in S^n_+ &\implies v^T x_1 v \geq 0 \\ x_2 \in S^n_+ &\implies v^T x_2 v \geq 0 \\ v^T(\theta x_1 + (1-\theta)x_2)v &\geq 0 \\ v^T \theta x_1 v + (1-\theta)v^T x_2 v &\implies x \in S^n_+ \end{aligned}$$

convexity check for cone:

$$\begin{aligned} x_1 \in S^n_+ &\implies \theta x_1 \in S^n_+, \theta \geq 0 \\ (\forall v) v^T x v \geq 0 &\implies v^T(\theta x)v \geq 0 \implies \text{ cone} \end{aligned}$$

0.8.7 Proper Cone

Definition:

- convex
- closed(contains all limit points)
- solid(non-empty interior)
- pointed(contains no line): $x \in K \implies -x \notin K$

Then the proper cone K defines a generalized inequality ($\leq_K$) in $\mathbb{R}^n$

$$\begin{aligned} x \leq_K y &\implies y - x \in K \\ x <_K y &\implies y - x \in int(K) \end{aligned}$$

Example: $K = R^n_+$ (non-negative orthant):

$$n = 2$$
$$x \leq_{R^2_+} y \implies y - x \in R^2_+$$

Cone provides partial ordering using difference of 2 objects.
$X \leq_{S^n_+} Y \iff Y - X \in S^n_+ \iff Y - X$ is PSD

0.8.8 Norm Cone

$$K = \{(x,t) \in \mathbb{R}^{n+1} : \|x\| \leq t\}, x \in \mathbb{R}^n$$

0.8.9 Dual norm

$\|z\|_* := \sup_x \{z^T x : \|x\|_p \leq 1\}$

Dual of L1-norm:
$\|z\|_* := \sup_x \{z^T x : \|x\|_1 \leq 1\}$
max $\sum_i z_i x_i$,
subject to : $\sum_i \|x_i\| \leq 1$
select x_i corresponding to z_i with maximum absolute value
equivalent to $\|z\|_* = \|z\|_\infty$

Dual of L-∞-norm:
$\|z\|_* := \sup_x \{z^T x : \|x\|_\infty \leq 1\}$
max $\sum_i z_i x_i$,
subject to : $\|x_i\| \leq 1, \forall i$
choose $x_i = 1$ if $z_i \geq 0$ and $x_i = 0$ if $z_i < 0$
equivalent to $\|z\|_* = \|z\|_1$

Dual norm of Lp-norm: Lq-norm where $1/p + 1/q = 1$

Properties:

- K^* closed and convex
- $K_1 \subseteq K_2 \implies k^*_2 \subseteq K^*_1$
- K has non-empty interior $\implies K^*$ pointed
- $cl(K)$ pointed $\implies K^*$ has non-tempty interior
- $K^{**} = cl(convhull(K))$
- K convex and closed $\implies K = K^{**}$

0.8.10 Operator norm

$\|X\|_{a,b} = sup\{\|Xu\|_a : \|u\|_b \leq 1\}, X \in \mathbb{R}^{m \times n}$

0.8.11 Dual cone

$$
\begin{aligned}
&K \ is \ a \ cone \\
K^* &= \{y : x^T y \geq 0, \forall x \in K\}
\end{aligned}
$$

0.8.12 Dual norm cone

$$
\begin{aligned}
K^* &= \{(u,v) : \|u\|_* \leq v\} \\
where \ K &= \{(x,t) : \|x\| \leq t\}
\end{aligned}
$$

0.8.13 support function of a set

$$
\begin{aligned}
S_C(x) &= \sup\{x^T y : y \in C\} \\
dom(S_C) &= \{x : \sup_{y \in C} c^T y < \infty\}
\end{aligned}
$$

It is pointwise supremum of convex function, so it is convex.

0.9 Appendix

0.9.1 Gradient of Log Det

$f(x) = log(detX)$

$$
\begin{aligned}
f(X+\delta X) &= logdet(X+\delta X)\\
&= logdet((X^{\frac{1}{2}}(I+X^{-\frac{1}{2}})\delta X X^{-\frac{1}{2}})X^{\frac{1}{2}})\\
&= logdet(X) + logdet(I + X^{-\frac{1}{2}}\delta X X^{-\frac{1}{2}})\\
&\text{let } M = X^{-\frac{1}{2}}\delta X X^{-\frac{1}{2}}\\
&= logdet(X) + logdet(I+M)
\end{aligned}
$$

claim eigenvalues of $I+M$: $1+\lambda_i$

$$
\begin{aligned}
Mv_i &= \lambda_i v_i\\
(I+M)v_i &= (1+\lambda_i)v_i\\
det(M) &= \prod_i (1+\lambda_i)\\
f(X+\delta X) &= logdet(X) + log\prod_i(1+\lambda_i)\\
&= logdet(X) + \sum_i log(1+\lambda_i)\\
&\approx logdet(X) + \sum_i \lambda_i \text{ since } \delta X \text{ is small}\\
&\approx logdet(X) + trace(X^{-\frac{1}{2}}\delta X X^{\frac{1}{2}})\\
&\approx logdet(X) + trace(X^{-1}\delta X)\\
trace(X^{-1}\delta X) &= (X^{-T})^T\delta X\\
f(X+\delta X) &= f(X) + (\nabla f(X))^T\delta X \implies \nabla f(X) = X^{-1}\\
logdet(X) &= log(X) \implies f'(X) = \frac{1}{X}
\end{aligned}
$$

0.9.2 2nd order approximation of Log Det

$f(X+\delta X) = f(X) + < \nabla f(X), \delta X > + 1/2 < \delta X, \nabla^2 f(x)\delta X >$

first look at first order approximation: $g(X) = X^{-1}$

$$
\begin{aligned}
g(X+\delta X) &= (X+\delta X)^{-1} = (X^{\frac{1}{2}}(I + X^{-\frac{1}{2}}\delta X X^{-\frac{1}{2}})X^{\frac{1}{2}})^{-1}\\
&= X^{-\frac{1}{2}}(I + X^{-\frac{1}{2}}\delta X X^{-\frac{1}{2}})^{-1}X^{-\frac{1}{2}}\\
&\text{for small A(small eigenvalues): } (I+A)^{-1} \approx I - A\\
&= X^{-\frac{1}{2}}(I - X^{-\frac{1}{2}}\delta X X^{-\frac{1}{2}})X^{-\frac{1}{2}}\\
&= X^{-1} - X^{-1}\delta X X^{-1}
\end{aligned}
$$

$$logdet(X+\delta X) = logdet(X) + tr(X^{-1}\delta X) - \frac{1}{2}tr(\delta X X^{-1}\delta X X^{-1})$$

0.10 Miscellaneous Properties

$(a+x)^{-1} \approx 1-x$
$\lim_{t\to 0} \frac{f(x+\epsilon t)-f(x)}{t} = \frac{\partial f(x)}{\partial x}\epsilon$