Convex Optimization

Lagrange Duality

1. Lagrange Dual Function

Standard form problem (not necessarily convex):

$$\begin{array}{ll} \text{minimize} & f_0(x) \\ \text{subject to} & f_i(x) \leq 0, \quad i = 1, \dots, m \\ & h_i(x) = 0, \quad i = 1, \dots, p \end{array}$$

variable $x \in \mathbb{R}^n$, domain $\mathcal{D}$, optimal value p^*.

Lagrangian:

$L : \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}^p \to \mathbb{R}$, with $\mathrm{dom}\, L = \mathcal{D} \times \mathbb{R}^m \times \mathbb{R}^p$,

$$L(x, \lambda, \nu) = f_0(x) + \sum_{i=1}^{m} \lambda_i f_i(x) + \sum_{i=1}^{p} \nu_i h_i(x)$$

Lagrange dual function: $g : \mathbb{R}^m \times \mathbb{R}^p \to \mathbb{R}$,

$$\begin{aligned} g(\lambda, \nu) &= \inf_{x \in \mathcal{D}} L(x, \lambda, \nu) \\ &= \inf_{x \in \mathcal{D}} \left(f_0(x) + \sum_{i=1}^{m} \lambda_i f_i(x) + \sum_{i=1}^{p} \nu_i h_i(x) \right) \end{aligned}$$

g is concave, can be $-\infty$ for some λ, ν.

Lower bound property:

If $\lambda \succeq 0$, then $g(\lambda, \nu) \leq p^*$.

2. The Dual Problem

Lagrange dual problem:

$$\begin{array}{ll} \text{maxmize} & g(\lambda, \nu) \\ \text{subject to} & \lambda \succeq 0 \end{array}$$

A convex optimization problem, optimal value denoted d^*.

Weak duality:

$$d^* \leq p^*$$

Strong duality:

$$d^* = p^*$$

Slater's constraint qualification:

Strong duality holds for a convex problem

$$\begin{array}{ll} \text{minimize} & f_0(x) \\ \text{subject to} & f_i(x) \leq 0, \quad i = 1, \ldots, m \\ & Ax = b \end{array}$$

if it is strictly feasible,

$$\exists x \in \operatorname{int} \mathcal{D}: \quad f_i(x) \leq 0, \quad i = 1, \ldots, m, \quad Ax = b$$

3. Karush-Kuhn-Tucker (KKT) Conditions

Complementary slackness:

Assume strong duality holds, x^* is primal optimal, (λ^*, ν^*) is dual optimal

$$
\begin{aligned}
f_0(x^*) = g(\lambda^*, \nu^*) &= \inf_x \left(f_0(x) + \sum_{i=1}^m \lambda_i^* f_i(x) + \sum_{i=1}^p \nu_i^* h_i(x) \right) \\
&\leq f_0(x^*) + \sum_{i=1}^m \lambda_i^* f_i(x^*) + \sum_{i=1}^p \nu_i^* h_i(x^*) \\
&\leq f_0(x^*)
\end{aligned}
$$

hence, the two inequalities hold with equality:

- x^* minimizes $L(x, \lambda^*, \nu^*)$
- $\lambda_i^* f_i(x^*) = 0$ for $i = 1, \dots, m$ (known as complementary slackness):

$$
\lambda_i^* > 0 \Rightarrow f_i(x^*) = 0, \quad f_i(x^*) < 0 \Rightarrow \lambda_i^* = 0
$$

KKT conditions:

1. primal constraints: $f_i(x) \leq 0, i = 1, \dots, m, h_i(x) = 0, i = 1, \dots, p$
2. dual constraints: $\lambda \succeq 0$
3. complementary slackness: $\lambda_i f_i(x) = 0, i = 1, \dots, m$
4. gradient of Lagrangian with respect to x vanishes:

$$
\nabla f_0(x) + \sum_{i=1}^m \lambda_i \nabla f_i(x) + \sum_{i=1}^p \nu_i \nabla h_i(x) = 0
$$

if strong duality holds and x, λ, ν are optimal, then they must satisfy the KKT conditions.

KKT conditions for convex problem:

If $\tilde{x}, \tilde{\lambda}, \tilde{\nu}$ satisfy KKT for a convex problem, then they are optimal:

- from complementary slackness: $f_0(\tilde{x}) = L(\tilde{x}, \tilde{\lambda}, \tilde{\nu})$
- from 4th condition (and convexity): $g(\tilde{\lambda}, \tilde{\nu}) = L(\tilde{x}, \tilde{\lambda}, \tilde{\nu})$

hence, $f_0(\tilde{x}) = g(\tilde{\lambda}, \tilde{\nu})$.