

Optimality conditions. Optimization with equality / inequality conditions. KKT.

Seminar

Optimization for ML. Faculty of Computer Science. HSE University

Optimality Conditions. Important notions recap

$$f(x) \rightarrow \min_{x \in S}$$

A set S is usually called a budget set.

- A point x^* is a global minimizer if $f(x^*) \leq f(x)$ for all x .
- A point x^* is a local minimizer if there exists a neighborhood N of x^* such that $f(x^*) \leq f(x)$ for all $x \in N$.
- A point x^* is a strict local minimizer (also called a strong local minimizer) if there exists a neighborhood N of x^* such that $f(x^*) < f(x)$ for all $x \in N$ with $x \neq x^*$.
- We call x^* a stationary point (or critical) if $\nabla f(x^*) = 0$. Any local minimizer must be a stationary point.



Figure 1: Illustration of different stationary (critical) points

Unconstrained optimization recap

💡 First-Order Necessary Conditions

If x^* is a local minimizer and f is continuously differentiable in an open neighborhood, then

$$\nabla f(x^*) = 0 \quad (1)$$

💡 Second-Order Sufficient Conditions

Suppose that $\nabla^2 f$ is continuous in an open neighborhood of x^* and that

$$\nabla f(x^*) = 0 \quad \nabla^2 f(x^*) \succ 0. \quad (2)$$

Then x^* is a strict local minimizer of f .

Optimization with equality conditions

Consider simple yet practical case of equality constraints:

$$\begin{aligned} f(x) &\rightarrow \min_{x \in \mathbb{R}^n} \\ \text{s.t. } h_i(x) &= 0, i = 1, \dots, p \end{aligned}$$

Lagrange multipliers recap

The basic idea of Lagrange method implies the switch from conditional to unconditional optimization through increasing the dimensionality of the problem:

$$L(x, \nu) = f(x) + \sum_{i=1}^p \nu_i h_i(x) = f(x) + \nu^T h(x) \rightarrow \min_{x \in \mathbb{R}^n, \nu \in \mathbb{R}^p}$$

Lagrange multipliers recap

The basic idea of Lagrange method implies the switch from conditional to unconditional optimization through increasing the dimensionality of the problem:

$$L(x, \nu) = f(x) + \sum_{i=1}^p \nu_i h_i(x) = f(x) + \nu^T h(x) \rightarrow \min_{x \in \mathbb{R}^n, \nu \in \mathbb{R}^p}$$

Necessary conditions:

$$\nabla_x L(x^*, \nu^*) = 0$$

$$\nabla_\nu L(x^*, \nu^*) = 0$$

Sufficient conditions:

$$\langle y, \nabla_{xx}^2 L(x^*, \nu^*) y \rangle > 0,$$

$$\forall y \neq 0 \in \mathbb{R}^n : \nabla h_i(x^*)^T y = 0$$

Optimization with inequality conditions

Consider simple yet practical case of inequality constraints:

$$\begin{aligned} f(x) &\rightarrow \min_{x \in \mathbb{R}^n} \\ \text{s.t. } g(x) &\leq 0 \end{aligned}$$

Optimization with inequality conditions

Consider simple yet practical case of inequality constraints:

$$\begin{aligned} f(x) &\rightarrow \min_{x \in \mathbb{R}^n} \\ \text{s.t. } g(x) &\leq 0 \end{aligned}$$

$g(x) \leq 0$ is **inactive**. $g(x^*) < 0$:

$$\begin{aligned} g(x^*) &< 0 \\ \nabla f(x^*) &= 0 \\ \nabla^2 f(x^*) &> 0 \end{aligned}$$

$g(x) \leq 0$ is **active**. $g(x^*) = 0$:

$$\begin{aligned} g(x^*) &= 0 \\ -\nabla f(x^*) &= \lambda \nabla g(x^*), \lambda > 0 \\ \langle y, \nabla_{xx}^2 L(x^*, \lambda^*) y \rangle &> 0, \\ \forall y \neq 0 \in \mathbb{R}^n : \nabla g(x^*)^\top y &= 0 \end{aligned}$$

General formulation

General problem of mathematical programming:

$$\begin{aligned} f_0(x) &\rightarrow \min_{x \in \mathbb{R}^n} \\ \text{s.t. } f_i(x) &\leq 0, \quad i = 1, \dots, m \\ h_i(x) &= 0, \quad i = 1, \dots, p \end{aligned}$$

General formulation

General problem of mathematical programming:

$$\begin{aligned} f_0(x) &\rightarrow \min_{x \in \mathbb{R}^n} \\ \text{s.t. } f_i(x) &\leq 0, \quad i = 1, \dots, m \\ h_i(x) &= 0, \quad i = 1, \dots, p \end{aligned}$$

The solution involves constructing a Lagrange function:

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

KKT Necessary conditions

Let x^* , (λ^*, ν^*) be a solution to a mathematical programming problem with zero duality gap (the optimal value for the primal problem p^* is equal to the optimal value for the dual problem d^*). Let also the functions f_0, f_i, h_i be differentiable.

KKT Necessary conditions

Let x^* , (λ^*, ν^*) be a solution to a mathematical programming problem with zero duality gap (the optimal value for the primal problem p^* is equal to the optimal value for the dual problem d^*). Let also the functions f_0, f_i, h_i be differentiable.

$$(1) \nabla_x L(x^*, \lambda^*, \nu^*) = 0$$

$$(2) \nabla_\nu L(x^*, \lambda^*, \nu^*) = 0$$

$$(3) \lambda_i^* \geq 0, i = 1, \dots, m$$

$$(4) \lambda_i^* f_i(x^*) = 0, i = 1, \dots, m$$

$$(5) f_i(x^*) \leq 0, i = 1, \dots, m$$

KKT Some regularity conditions

These conditions are needed in order to make KKT solutions the necessary conditions. Some of them even turn necessary conditions into sufficient. For example, Slater's condition:

KKT Some regularity conditions

These conditions are needed in order to make KKT solutions the necessary conditions. Some of them even turn necessary conditions into sufficient. For example, Slater's condition:

If for a convex problem (i.e., assuming minimization, f_0, f_i are convex and h_i are affine), there exists a point x such that $h(x) = 0$ and $f_i(x) < 0$ (existence of a strictly feasible point), then we have a zero duality gap and KKT conditions become necessary and sufficient.

KKT Sufficient conditions

For smooth, non-linear optimization problems, a second order sufficient condition is given as follows. The solution x^*, λ^*, ν^* , which satisfies the KKT conditions (above) is a constrained local minimum if for the Lagrangian,

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

the following conditions hold:

$$\langle y, \nabla_{xx}^2 L(x^*, \lambda^*, \nu^*) y \rangle > 0$$

$$\forall y \neq 0 \in \mathbb{R}^n : \nabla h_i(x^*)^\top y = 0, \nabla f_0(x^*)^\top y \leq 0, \nabla f_j(x^*)^\top y = 0$$

$$i = 1, \dots, p \quad \forall j : f_j(x^*) = 0$$

Problem 1

Question

Function $f : E \rightarrow \mathbb{R}$ is defined as

$$f(x) = \ln(-Q(x))$$

where $E = \{x \in \mathbb{R}^n : Q(x) < 0\}$ and

$$Q(x) = \frac{1}{2}x^\top Ax + b^\top x + c$$

with $A \in \mathbb{S}_{++}^n$, $b \in \mathbb{R}^n$, $c \in \mathbb{R}$.

Find the maximizer x^* of the function f .

Problem 2

Question

Give an explicit solution of the following task.

$$\begin{aligned} f(x, y) = x + y &\rightarrow \min \\ \text{s.t. } x^2 + y^2 &= 1 \end{aligned}$$

where $x, y \in \mathbb{R}$.

Problem 3

Question

Give an explicit solution of the following task.

$$\begin{aligned} \langle c, x \rangle + \sum_{i=1}^n x_i \log x_i &\rightarrow \min_{x \in \mathbb{R}^n} \\ \text{s.t. } \sum_{i=1}^n x_i &= 1, \end{aligned}$$

where $x \in \mathbb{R}_{++}^n, c \neq 0$.

Problem 4

Question

Give an explicit solution of the following task.

$$\begin{aligned} f(x, y) &= (x - 2)^2 + 2(y - 1)^2 \rightarrow \min \\ \text{s.t. } x + 4y &\leq 3 \\ x &\geq y \end{aligned}$$

where $x, y \in \mathbb{R}$.

Problem 5

Question

Given $y \in \{-1, 1\}$, and $X \in \mathbb{R}^{n \times p}$, the Support Vector Machine problem is:

$$\begin{aligned} \frac{1}{2} \|w\|_2^2 + C \sum_{i=1}^n \xi_i &\rightarrow \min_{w, w_0, \xi_i} \\ \text{s.t. } \xi_i &\geq 0, i = 1, \dots, n \\ y_i(x_i^T w + w_0) &\geq 1 - \xi_i, i = 1, \dots, n \end{aligned}$$

find the KKT stationarity condition.