KKT Conditions

Nipun Batra and teaching staff

IIT Gandhinagar

August 30, 2025

KKT Conditions

Used for constrained optimization of the form

Minimize $f(x)$, where $x \in \mathbb{R}^k$
such that

$$h_i(x) = 0, \ \forall i = 1, \ldots, m \text{ (m equalities)}$$
$$g_j(x) \leq 0, \ \forall j = 1, \ldots, n \text{ (n inequalities)}$$

Step 1

- Create a new function for minimization,

$$\mathcal{L}(x, \lambda_1, \ldots, \lambda_m, \mu_1, \ldots, \mu_n) = f(x) + \sum_{i=1}^{m} \lambda_i h_i(x) + \sum_{j=1}^{n} \mu_j g_j(x)$$

where,
$\lambda_1 - \lambda_m$ are multipliers for the m equalities
$\mu_1 - \mu_n$ are multiplices for the n inequalities

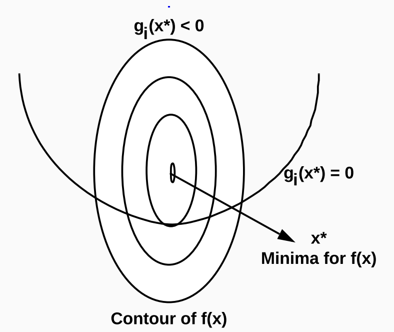
Step 2

- Minimize $\mathcal{L}(x, \lambda, \mu)$ w.rt. $x \implies \nabla_x \mathcal{L}(x, \lambda, \mu) = 0$
  Gives k equations

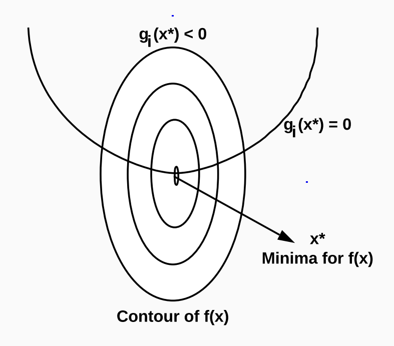
Step 3

- Minimize $\mathcal{L}(x, \lambda, \mu)$ w.rt. $\lambda \implies \nabla_\lambda \mathcal{L}(x, \lambda, \mu) = 0$
  Gives m equations

Step 4



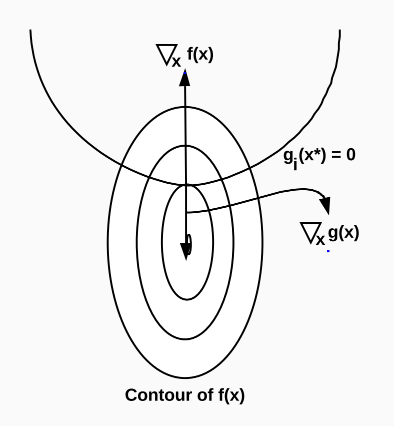
$$g_i(x^*) \leq 0$$
$$\mu_i = 0$$



$$g_i(x^*) = 0$$

In both cases, $\mu_i g_i(x^*) = 0$

Constraint on μ_i's



$$min_x \mathcal{L}(x, \lambda, \mu) \implies \nabla_x f(x) + \nabla_x \mu_i g_i(x) = 0$$

$$\mu_i = \frac{\nabla_x f(x)}{\nabla_x \mu_i g_i(x)} = +ve$$

KKT Conditions

Stationarity (For minimization)

$$\nabla_x f(x) + \sum_{i=1}^{m} \nabla_x \lambda_i h_i(x) + \sum_{i=1}^{n} \nabla_x \mu_i g_i(x) = 0$$

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Equality Constraints

$$\nabla_\lambda f(x) + \sum_{i=1}^{m} \nabla_\lambda \lambda_i h_i(x) + \sum_{i=1}^{n} \nabla_\lambda \mu_i g_i(x) = 0$$

$$\sum_{i=1}^{m} \nabla_\lambda \lambda_i h_i(x) = 0$$

KKT Conditions

Stationarity (For minimization)

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$$\sum_{i=1}^{m} \nabla_\lambda \lambda_i h_i(x) = 0$$

Inequality Constraints (Complementary Slackness)

$$\mu_i g_i(x) = 0 \forall i = 1, \ldots, n$$

$$\mu_i \geq 0$$

Example

Minimize $x^2 + y^2$ such that,

$$\begin{gathered} x^2 + y^2 \leq 5 \\ x + 2y = 4 \\ x, y \geq 0 \end{gathered}$$

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$$g_1(x,y) = x^2 + y^2 - 5$$

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\begin{aligned}
f(x,y) &= x^2 + y^2 \\
h(x,y) &= x + 2y - 4 \\
g_1(x,y) &= x^2 + y^2 - 5 \\
g_2(x,y) &= -x
\end{aligned}
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&h(x,y) = x + 2y - 4\\
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&g_2(x,y) = -x\\
&g_3(x,y) = -y
\end{aligned}
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Example

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$$h(x, y) = x + 2y - 4$$
$$g_1(x, y) = x^2 + y^2 - 5$$
$$g_2(x, y) = -x$$
$$g_3(x, y) = -y$$

$$\mathcal{L}(x, y, \lambda, \mu_1, \mu_2, \mu_3) =$$
$$x^2 + y^2 + \lambda(x + 2y - 4) + \mu_1(x^2 + y^2 - 5) + \mu_2(-x) + \mu_3(-y)$$

Example

Stationarity

$\nabla_x \mathcal{L}(x, y, \lambda, \mu_1, \mu_2, \mu_3) = 0$

$\implies 2x + \lambda + 2\mu_1 x - \mu_2 = 0 \ldots\ldots\ldots\ldots\ldots\ldots (1)$

$\nabla_y \mathcal{L}(x, y, \lambda, \mu_1, \mu_2, \mu_3) = 0$

$\implies 2y + 2\lambda + 2\mu_1 y - \mu_3 = 0 \ldots\ldots\ldots\ldots\ldots\ldots (2)$

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Equality Constraint

$x + 2y = 4 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$

Example

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Equality Constraint

$x + 2y = 4 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$

Slackness

$\mu_1(x^2 + y^2 - 5) = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$

$\mu_2 x = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$

$\mu_3 y = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$

Example

From (6), $\mu_3 = 0$ or $y = 0$
But if, $y = 0$, then $x = 4$ according to (3) . This violates (1).
Hence, $y \neq 0$ and $\mu_3 = 0$

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If $x = 0$, $y = 2$, which implies $x^2 + y^2 = 4 (\leq 5)$
Since (x,y) = (0,2) gives smaller $x^2 + y^2$ terms than 5,
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On further solving we get,
$x = 0.8$
$y = 1.6$