Handout 9 - ECON703 (Fall 2023)

1 Derivatives of Functions with Multiple Arguments

Definition 1.1 (Gradient). *Let $f : \mathbb{R}^n \to \mathbb{R}$ be a function. The gradient of f at $a \in \mathbb{R}^n$, denoted $\nabla f(a)$, is defined as:*

$$\nabla f(a) = \begin{bmatrix} \frac{\partial f}{\partial x_1}(a) \\ \vdots \\ \frac{\partial f}{\partial x_n}(a) \end{bmatrix}$$

The gradient generalizes the derivative for functions with multiple arguments.

Later, we will define the **Jacobian-Matrix** for vector-valued functions. The gradient is its equivalent for scalar-valued functions.

Example 1.1. *Consider $f : \mathbb{R}^3 \to \mathbb{R}$ given by $f(x, y, z) = xy + z$. Then the gradient of f at a point (a, b, c) is*

$$\nabla f(a, b, c) = \begin{bmatrix} b \\ a \\ 1 \end{bmatrix}$$

Definition 1.2 (Hessian). *Let $f : \mathbb{R}^n \to \mathbb{R}$ be a function for which each second-order partial derivative exists. The Hessian of f at $a \in \mathbb{R}^n$, denoted $H_f(a)$ or $D^2_f(a)$, is defined as*

$$H_f(a) = \begin{bmatrix} \frac{\partial^2 f}{\partial x_1^2}(a) & \frac{\partial^2 f}{\partial x_1 \partial x_2}(a) & \dots & \frac{\partial^2 f}{\partial x_1 \partial x_n}(a) \\ \frac{\partial^2 f}{\partial x_2 \partial x_1}(a) & \frac{\partial^2 f}{\partial x_2^2}(a) & \dots & \frac{\partial^2 f}{\partial x_2 \partial x_n}(a) \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 f}{\partial x_n \partial x_1}(a) & \frac{\partial^2 f}{\partial x_n \partial x_2}(a) & \dots & \frac{\partial^2 f}{\partial x_n^2}(a) \end{bmatrix}$$

It is a natural equivalent of the second derivative for the case of a scalar-valued function.

Example 1.2. *Consider $f : \mathbb{R}^3 \to \mathbb{R}$ given by $f(x, y, z) = xy + z$. Then the Hessian of f at a point (a, b, c) is*

$$H_f(a, b, c) = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

2 Extrema

Definition 2.1 (Global Extrema of Functions). *Let $A \subset \mathbb{R}^n$ and $f : A \to \mathbb{R}$. We say that $f(\overline{a})$ is a global maximum of f on A if $\overline{a} \in A$ and $\forall x \in A : \ f(\overline{a}) \geq f(x)$.*

Analogously, we say that $f(\underline{a})$ is a global minimum of f on A if $\underline{a} \in A$ and $\forall x \in A : \ f(\underline{a}) \leq f(x)$.

Definition 2.2 (Global Maximizer/Minimizer of a Function). *Let $A \subset \mathbb{R}^n$ and $f : A \to \mathbb{R}$. We say that $\overline{a} \in A$ maximizes f on A, denoted $\overline{a} \in \arg\max_{x \in A} f(x)$, if $\forall x \in A : \ f(\overline{a}) \geq f(x)$.*

Analogously, we say that $\underline{a} \in A$ minimizes f on A, denoted $\underline{a} \in \arg\min_{x \in A} f(x)$, if $\forall x \in A : \ f(\underline{a}) \leq f(x)$.

Note that both $\arg\max$ and $\arg\min$ are technically set-valued. However, in an abuse of notation, we often write statements such as $\overline{a} = \arg\max_{x \in A} f(x)$ if the $\arg\max$ is a singleton.

Definition 2.3 (Local Extrema of Functions)**.** *Let $A \subset \mathbb{R}^n$ and $f : A \to \mathbb{R}$. We say that $f(\overline{a})$ is a local maximum of f on A if $\overline{a} \in A$ and $\exists r > 0$ s.t. $\forall x \in B_r(\overline{a}) \cap A : \ f(\overline{a}) \geq f(x)$.*

Analogously, we say that $f(\underline{a})$ is a local minimum of f on A if $\underline{a} \in A$ and $\exists r > 0$ s.t. $\forall x \in B_r(\underline{a}) \cap A : f(\underline{a}) \leq f(x)$.

Definition 2.4 (Local Maximizer/Minimizer of a Function)**.** *Let $A \subset \mathbb{R}^n$ and $f : A \to \mathbb{R}$. We say that $\overline{a} \in A$ locally maximizes f on A, if $\exists r > 0$ s.t. $\forall x \in B_r(\overline{a}) \cap A : \ f(\overline{a}) \geq f(x)$.*

Analogously, we say that $\underline{a} \in A$ locally minimizes f on A, if $\exists r > 0$ s.t. $\forall x \in B_r(\underline{a}) \cap A : f(\underline{a}) \leq f(x)$.

Definition 2.5 (Critical Points / First Order Conditions)**.** *Let $f : A \to \mathbb{R}$ for $A \subset \mathbb{R}^n$. A point $x^* \in int(A)$ is called a critical point of f if $\nabla f(x^*) = 0$. $\nabla f(x^*) = 0$ is often called the* **First Order Condition**.

3 Karush-Kuhn-Tucker Optimization

To make sense of KKT optimization theoretically, we would have to consider the question of **Dual Problems**. For those of you interested in the theoretical background, search for

- Theorem of Lagrange
- Theorem of Kuhn and Tucker
- Primal Problems and Dual Problems
- Duality Gap and Strong Duality

Sundaram, R. (1996). A First Course in Optimization Theory.
Cambridge: Cambridge University Press. doi:10.1017/CBO9780511804526

However, here we will think about how to apply the technique instead.

Definition 3.1 (The KKT Optimization Problem)**.** *Let $X \subset \mathbb{R}^n$ be a convex subset of Euclidean space. Let $f : X \to \mathbb{R}$ be the objective function. Let $g : \mathbb{R}^n \to \mathbb{R}^m$ be the function corresponding to the inequality constraints. Let $h : \mathbb{R}^n \to \mathbb{R}^l$ be the function corresponding to the equality constraint.*

The KKT optimization problem is as follows:

$$\max_{x \in X} f(x) \quad \textit{subject to:} \quad g(x) \leq 0 \quad \textit{and} \quad h(x) = 0$$

We can form the corresponding Lagrangian function as follows:

$$\mathcal{L}(x, \mu, \lambda) = f(x) - \mu' g(x) - \lambda' h(x)$$

Definition 3.2 (The KKT Conditions)**.** *The Karush-Kuhn-Tucker conditions for a maximum at x^* are*

- **Stationarity***:*
$$0 = \nabla f(x^*) - \sum_{j=1}^{l} \lambda_j \nabla h_j(x^*) - \sum_{i=1}^{m} \mu_i \nabla g_i(x^*)$$
- **Primal Feasibility***:*
$$\forall j = 1, \ldots, l : \ h_j(x^*) = 0 \quad \forall i = 1, \ldots, m : \ g_i(x^*) \leq 0$$
- **Dual Feasibility***:*
$$\forall i = 1, \ldots, m : \ \mu_i \geq 0$$
- **Complementary Slackness***:*
$$\forall i = 1, \ldots, m : \ \mu_i g_i(x^*) = 0$$

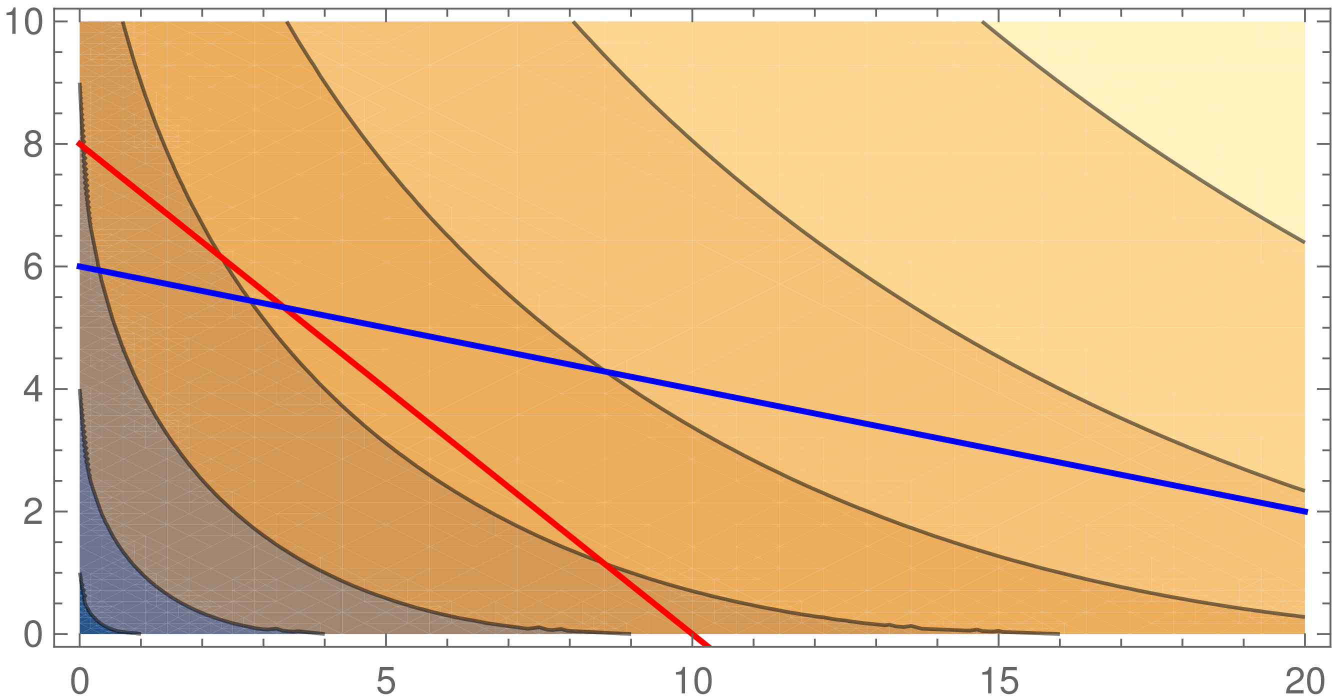

Figure 1: A visualization of a simple KKT problem

Example 3.1. *Consider the following optimization problem:*

$$\max_{(x,y)\in\mathbb{R}^2} xy \quad s.t. \quad x \geq 0 \quad \wedge \quad y \geq 0$$
$$\wedge \quad x + y \leq 5$$

This gives us the Lagrangian

$$\begin{aligned}\mathcal{L} &= xy - \lambda_1(-x) - \lambda_2(-y) - \lambda_3(x+y-5)\\ &= xy + \lambda_1 x + \lambda_2 y - \lambda_3(x+y-5)\end{aligned}$$

Forming the KKT conditions gives us:

- **Stationarity***:*

$$\begin{aligned}0 &= y + \lambda_1 - \lambda_3\\ 0 &= x + \lambda_2 - \lambda_3\end{aligned}$$

- **Primal Feasibility***:*

$$x \geq 0 \quad \wedge \quad y \geq 0 \wedge \quad x + y \leq 5$$

- **Dual Feasibility***:*

$$\lambda_1 \geq 0 \quad \wedge \quad \lambda_2 \geq 0 \quad \wedge \quad \lambda_3 \geq 0$$

- **Complementary Slackness***:*

$$\lambda_1 x = 0 \quad \wedge \quad \lambda_2 y = 0 \quad \wedge \quad \lambda_3(x+y-5) = 0$$

With these conditions, we can solve for a candidate.

$$\begin{aligned}
& x \neq 0 \quad \wedge \quad y \neq 0 && \textit{since} \quad (x,y) = (1,1) \quad \textit{is feasible and gives a higher value.} \\
\implies \quad & \lambda_1 = 0 \quad \wedge \quad \lambda_2 = 0 && \textit{by complementary slackness} \\
\implies \quad & y = \lambda_3 \quad \wedge \quad x = \lambda_3 && \textit{by stationarity} \\
\implies \quad & x = y = \lambda_3 > 0 && \\
\implies \quad & x + y = 5 && \textit{by complementary slackness} \\
\implies \quad & x = y = 2.5 &&
\end{aligned}$$

So $(x, y) = (2.5, 2.5)$ *is our solution candidate.*

Definition 3.3 (Constraint Qualification)**.** *There are several conditions called* **Constraint Qualifications** *that tell us settings in which an optimizer must satisfy the KKT conditions. They vary in complexity and applicability and tell us when* **Strong Duality** *holds.*

Wikipedia: KKT regularity conditions

Three common constraint qualifications are the following:

Definition 3.4 (Linearity Constraint Qualification)**.** *If all constraints are affine functions, no further criteria need to be met.*

Definition 3.5 (Linear Independence Constraint Qualification)**.** *The gradients of the active inequality constraints (i.e. those binding in* x^**) and the gradients of the equality constraints are linearly independent at* x^**.*

Definition 3.6 (Slater's Condition)**.** *For a convex problem, i.e., minimizing a convex function (maximizing a concave function) under convex inequality and linear equality constraints, there exists a point such that* $h(x) = 0$ *and* $g_i(x) < 0$*. In other words, if the feasible region has an interior point.*

Example 3.2. *In the previous example, all constraints were affine, so a solution to the maximization problem must satisfy the KKT conditions by Linearity Constraint Qualification. To verify that our solution candidate is the maximizer, note that every feasible point satisfies* $x + y \leq 5$ *and therefore* $xy \leq \left(\frac{x+y}{2}\right)^2 \leq \left(\frac{5}{2}\right)^2$*.*

A good source for the intuition behind KKT optimization is this Arizona Math Camp video. This is a video by a channel called "**Arizona Math Camp**" that I would highly recommend watching.