

Strong convexity criteria. Optimality conditions. Lagrange function.

Daniil Merkulov

Optimization for ML. Faculty of Computer Science. HSE University



First-order differential criterion of convexity

The differentiable function $f(x)$ defined on the convex set

$S \subseteq \mathbb{R}^n$ is convex if and only if $\forall x, y \in S$:

$$f(y) \geq f(x) + \nabla f^T(x)(y - x)$$

Let $y = x + \Delta x$, then the criterion will become more tractable:

$$f(x + \Delta x) \geq f(x) + \nabla f^T(x)\Delta x$$



Figure 1: Convex function is greater or equal than Taylor linear approximation at any point

Second-order differential criterion of convexity

Twice differentiable function $f(x)$ defined on the convex set $S \subseteq \mathbb{R}^n$ is convex if and only if $\forall x \in \text{int}(S) \neq \emptyset$:

$$\nabla^2 f(x) \succeq 0$$

In other words, $\forall y \in \mathbb{R}^n$:

$$\langle y, \nabla^2 f(x)y \rangle \geq 0$$

Tools for discovering convexity

- Definition (Jensen's inequality)

Tools for discovering convexity

- Definition (Jensen's inequality)
- Differential criteria of convexity

Tools for discovering convexity

- Definition (Jensen's inequality)
- Differential criteria of convexity
- Operations, that preserve convexity

Tools for discovering convexity

- Definition (Jensen's inequality)
- Differential criteria of convexity
- Operations, that preserve convexity
- Connection with epigraph

The function is convex if and only if its epigraph is a convex set.

Tools for discovering convexity

- Definition (Jensen's inequality)
- Differential criteria of convexity
- Operations, that preserve convexity
- Connection with epigraph

The function is convex if and only if its epigraph is a convex set.

- Connection with sublevel set

If $f(x)$ - is a convex function defined on the convex set $S \subseteq \mathbb{R}^n$, then for any β sublevel set \mathcal{L}_β is convex.

The function $f(x)$ defined on the convex set $S \subseteq \mathbb{R}^n$ is closed if and only if for any β sublevel set \mathcal{L}_β is closed.

Tools for discovering convexity

- Definition (Jensen's inequality)
- Differential criteria of convexity
- Operations, that preserve convexity
- Connection with epigraph

The function is convex if and only if its epigraph is a convex set.

- Connection with sublevel set

If $f(x)$ - is a convex function defined on the convex set $S \subseteq \mathbb{R}^n$, then for any β sublevel set \mathcal{L}_β is convex.

The function $f(x)$ defined on the convex set $S \subseteq \mathbb{R}^n$ is closed if and only if for any β sublevel set \mathcal{L}_β is closed.

- Reduction to a line

$f : S \rightarrow \mathbb{R}$ is convex if and only if S is a convex set and the function $g(t) = f(x + tv)$ defined on $\{t \mid x + tv \in S\}$ is convex for any $x \in S, v \in \mathbb{R}^n$, which allows checking convexity of the scalar function to establish convexity of the vector function.

Example: norm cone

Let a norm $\|\cdot\|$ be defined in the space U . Consider the set:

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

which represents the epigraph of the function $x \mapsto \|x\|$. This set is called the cone norm. According to the statement above, the set K is convex.  Code for the figures

$p = 1$ Norm Cone



$p = 2$ Norm Cone



$p = \infty$ Norm Cone



Strong convexity

$f(x)$, defined on the convex set $S \subseteq \mathbb{R}^n$, is called μ -strongly convex (strongly convex) on S , if:

$$f(\lambda x_1 + (1-\lambda)x_2) \leq \lambda f(x_1) + (1-\lambda)f(x_2) - \frac{\mu}{2} \lambda(1-\lambda) \|x_1 - x_2\|^2$$

for any $x_1, x_2 \in S$ and $0 \leq \lambda \leq 1$ for some $\mu > 0$.



Figure 3: Strongly convex function is greater or equal than Taylor quadratic approximation at any point

First-order differential criterion of strong convexity

Differentiable $f(x)$ defined on the convex set $S \subseteq \mathbb{R}^n$ is μ -strongly convex if and only if $\forall x, y \in S$:

$$f(y) \geq f(x) + \nabla f^T(x)(y - x) + \frac{\mu}{2} \|y - x\|^2$$

First-order differential criterion of strong convexity

Differentiable $f(x)$ defined on the convex set $S \subseteq \mathbb{R}^n$ is μ -strongly convex if and only if $\forall x, y \in S$:

$$f(y) \geq f(x) + \nabla f^T(x)(y - x) + \frac{\mu}{2} \|y - x\|^2$$

Let $y = x + \Delta x$, then the criterion will become more tractable:

$$f(x + \Delta x) \geq f(x) + \nabla f^T(x)\Delta x + \frac{\mu}{2} \|\Delta x\|^2$$

First-order differential criterion of strong convexity

Differentiable $f(x)$ defined on the convex set $S \subseteq \mathbb{R}^n$ is μ -strongly convex if and only if $\forall x, y \in S$:

$$f(y) \geq f(x) + \nabla f^T(x)(y - x) + \frac{\mu}{2}\|y - x\|^2$$

Let $y = x + \Delta x$, then the criterion will become more tractable:

$$f(x + \Delta x) \geq f(x) + \nabla f^T(x)\Delta x + \frac{\mu}{2}\|\Delta x\|^2$$

Theorem

Let $f(x)$ be a differentiable function on a convex set $X \subseteq \mathbb{R}^n$. Then $f(x)$ is strongly convex on X with a constant $\mu > 0$ if and only if

$$f(x) - f(x_0) \geq \langle \nabla f(x_0), x - x_0 \rangle + \frac{\mu}{2}\|x - x_0\|^2$$

for all $x, x_0 \in X$.

Proof of first-order differential criterion of strong convexity

Necessity: Let $0 < \lambda \leq 1$. According to the definition of a strongly convex function,

$$f(\lambda x + (1 - \lambda)x_0) \leq \lambda f(x) + (1 - \lambda)f(x_0) - \frac{\mu}{2}\lambda(1 - \lambda)\|x - x_0\|^2$$

or equivalently,

$$\begin{aligned} f(x) - f(x_0) - \frac{\mu}{2}(1 - \lambda)\|x - x_0\|^2 &\geq \frac{1}{\lambda}[f(\lambda x + (1 - \lambda)x_0) - f(x_0)] = \\ &= \frac{1}{\lambda}[f(x_0 + \lambda(x - x_0)) - f(x_0)] = \frac{1}{\lambda}[\lambda\langle \nabla f(x_0), x - x_0 \rangle + o(\lambda)] = \\ &= \langle \nabla f(x_0), x - x_0 \rangle + \frac{o(\lambda)}{\lambda}. \end{aligned}$$

Thus, taking the limit as $\lambda \downarrow 0$, we arrive at the initial statement.

Proof of first-order differential criterion of strong convexity

Sufficiency: Assume the inequality in the theorem is satisfied for all $x, x_0 \in X$. Take $x_0 = \lambda x_1 + (1 - \lambda)x_2$, where $x_1, x_2 \in X$, $0 \leq \lambda \leq 1$. According to the inequality, the following inequalities hold:

$$f(x_1) - f(x_0) \geq \langle \nabla f(x_0), x_1 - x_0 \rangle + \frac{\mu}{2} \|x_1 - x_0\|^2,$$

$$f(x_2) - f(x_0) \geq \langle \nabla f(x_0), x_2 - x_0 \rangle + \frac{\mu}{2} \|x_2 - x_0\|^2.$$

Multiplying the first inequality by λ and the second by $1 - \lambda$ and adding them, considering that

$$x_1 - x_0 = (1 - \lambda)(x_1 - x_2), \quad x_2 - x_0 = \lambda(x_2 - x_1),$$

and $\lambda(1 - \lambda)^2 + \lambda^2(1 - \lambda) = \lambda(1 - \lambda)$, we get

$$\begin{aligned} \lambda f(x_1) + (1 - \lambda)f(x_2) - f(x_0) - \frac{\mu}{2} \lambda(1 - \lambda) \|x_1 - x_2\|^2 \geq \\ \langle \nabla f(x_0), \lambda x_1 + (1 - \lambda)x_2 - x_0 \rangle = 0. \end{aligned}$$

Thus, inequality from the definition of a strongly convex function is satisfied. It is important to mention, that $\mu = 0$ stands for the convex case and corresponding differential criterion.

Second-order differential criterion of strong convexity

Twice differentiable function $f(x)$ defined on the convex set $S \subseteq \mathbb{R}^n$ is called μ -strongly convex if and only if $\forall x \in \text{int}(S) \neq \emptyset$:

$$\nabla^2 f(x) \succeq \mu I$$

In other words:

$$\langle y, \nabla^2 f(x)y \rangle \geq \mu \|y\|^2$$

Second-order differential criterion of strong convexity

Twice differentiable function $f(x)$ defined on the convex set $S \subseteq \mathbb{R}^n$ is called μ -strongly convex if and only if $\forall x \in \text{int}(S) \neq \emptyset$:

$$\nabla^2 f(x) \succeq \mu I$$

In other words:

$$\langle y, \nabla^2 f(x)y \rangle \geq \mu \|y\|^2$$

Theorem

Let $X \subseteq \mathbb{R}^n$ be a convex set, with $\text{int}X \neq \emptyset$. Furthermore, let $f(x)$ be a twice continuously differentiable function on X . Then $f(x)$ is strongly convex on X with a constant $\mu > 0$ if and only if

$$\langle y, \nabla^2 f(x)y \rangle \geq \mu \|y\|^2$$

for all $x \in X$ and $y \in \mathbb{R}^n$.

Proof of second-order differential criterion of strong convexity

The target inequality is trivial when $y = \mathbf{0}_n$, hence we assume $y \neq \mathbf{0}_n$.

Necessity: Assume initially that x is an interior point of X . Then $x + \alpha y \in X$ for all $y \in \mathbb{R}^n$ and sufficiently small α . Since $f(x)$ is twice differentiable,

$$f(x + \alpha y) = f(x) + \alpha \langle \nabla f(x), y \rangle + \frac{\alpha^2}{2} \langle y, \nabla^2 f(x) y \rangle + o(\alpha^2).$$

Based on the first order criterion of strong convexity, we have

$$\frac{\alpha^2}{2} \langle y, \nabla^2 f(x) y \rangle + o(\alpha^2) = f(x + \alpha y) - f(x) - \alpha \langle \nabla f(x), y \rangle \geq \frac{\mu}{2} \alpha^2 \|y\|^2.$$

This inequality reduces to the target inequality after dividing both sides by α^2 and taking the limit as $\alpha \downarrow 0$.

If $x \in X$ but $x \notin \text{int}X$, consider a sequence $\{x_k\}$ such that $x_k \in \text{int}X$ and $x_k \rightarrow x$ as $k \rightarrow \infty$. Then, we arrive at the target inequality after taking the limit.

Proof of second-order differential criterion of strong convexity

Sufficiency: Using Taylor's formula with the Lagrange remainder and the target inequality, we obtain for $x + y \in X$:

$$f(x + y) - f(x) - \langle \nabla f(x), y \rangle = \frac{1}{2} \langle y, \nabla^2 f(x + \alpha y) y \rangle \geq \frac{\mu}{2} \|y\|^2,$$

where $0 \leq \alpha \leq 1$. Therefore,

$$f(x + y) - f(x) \geq \langle \nabla f(x), y \rangle + \frac{\mu}{2} \|y\|^2.$$

Consequently, by the first order criterion of strong convexity, the function $f(x)$ is strongly convex with a constant μ . It is important to mention, that $\mu = 0$ stands for the convex case and corresponding differential criterion.

Convex and concave function

Example

Show, that $f(x) = c^\top x + b$ is convex and concave.

Simplest strongly convex function

Example

Show, that $f(x) = x^\top Ax$, where $A \succeq 0$ - is convex on \mathbb{R}^n . Is it strongly convex?

Convexity and continuity

Let $f(x)$ - be a convex function on a convex set $S \subseteq \mathbb{R}^n$.
Then $f(x)$ is continuous $\forall x \in \text{ri}(S)$.^a

Proper convex function

Function $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is said to be **proper convex function** if it never takes on the value $-\infty$ and not identically equal to ∞ .

Indicator function

$$\delta_S(x) = \begin{cases} \infty, & x \in S, \\ 0, & x \notin S, \end{cases}$$

is a proper convex function.

^aPlease, read here about difference between interior and relative interior.

Convexity and continuity

Let $f(x)$ - be a convex function on a convex set $S \subseteq \mathbb{R}^n$.
Then $f(x)$ is continuous $\forall x \in \text{ri}(S)$.^a

Proper convex function

Function $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is said to be **proper convex function** if it never takes on the value $-\infty$ and not identically equal to ∞ .

Indicator function

$$\delta_S(x) = \begin{cases} \infty, & x \in S, \\ 0, & x \notin S, \end{cases}$$

is a proper convex function.

^aPlease, read here about difference between interior and relative interior.

Closed function

Function $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is said to be **closed** if for each $\alpha \in \mathbb{R}$, the sublevel set is a closed set.
Equivalently, if the epigraph is closed, then the function f is closed.



Figure 4: The concept of a closed function is introduced to avoid such breaches at the border.

Facts about convexity

- $f(x)$ is called (strictly, strongly) concave, if the function $-f(x)$ - is (strictly, strongly) convex.

Facts about convexity

- $f(x)$ is called (strictly, strongly) concave, if the function $-f(x)$ - is (strictly, strongly) convex.
- Jensen's inequality for the convex functions:

$$f\left(\sum_{i=1}^n \alpha_i x_i\right) \leq \sum_{i=1}^n \alpha_i f(x_i)$$

for $\alpha_i \geq 0$; $\sum_{i=1}^n \alpha_i = 1$ (probability simplex)

For the infinite dimension case:

$$f\left(\int_S x p(x) dx\right) \leq \int_S f(x) p(x) dx$$

If the integrals exist and $p(x) \geq 0$, $\int_S p(x) dx = 1$.

Facts about convexity

- $f(x)$ is called (strictly, strongly) concave, if the function $-f(x)$ is (strictly, strongly) convex.
- Jensen's inequality for the convex functions:

$$f\left(\sum_{i=1}^n \alpha_i x_i\right) \leq \sum_{i=1}^n \alpha_i f(x_i)$$

for $\alpha_i \geq 0$; $\sum_{i=1}^n \alpha_i = 1$ (probability simplex)

For the infinite dimension case:

$$f\left(\int_S x p(x) dx\right) \leq \int_S f(x) p(x) dx$$

If the integrals exist and $p(x) \geq 0$, $\int_S p(x) dx = 1$.

- If the function $f(x)$ and the set S are convex, then any local minimum $x^* = \arg \min_{x \in S} f(x)$ will be the global one. Strong convexity guarantees the uniqueness of the solution.

Operations that preserve convexity

- Non-negative sum of the convex functions:

$$\alpha f(x) + \beta g(x), (\alpha \geq 0, \beta \geq 0).$$



Figure 5: Pointwise maximum (supremum) of convex functions is convex

Operations that preserve convexity

- Non-negative sum of the convex functions:
 $\alpha f(x) + \beta g(x), (\alpha \geq 0, \beta \geq 0).$
- Composition with affine function $f(Ax + b)$ is convex, if $f(x)$ is convex.



Figure 5: Pointwise maximum (supremum) of convex functions is convex

Operations that preserve convexity

- Non-negative sum of the convex functions:
 $\alpha f(x) + \beta g(x)$, $(\alpha \geq 0, \beta \geq 0)$.
- Composition with affine function $f(Ax + b)$ is convex, if $f(x)$ is convex.
- Pointwise maximum (supremum) of any number of functions: If $f_1(x), \dots, f_m(x)$ are convex, then $f(x) = \max\{f_1(x), \dots, f_m(x)\}$ is convex.



Figure 5: Pointwise maximum (supremum) of convex functions is convex

Operations that preserve convexity

- Non-negative sum of the convex functions:
 $\alpha f(x) + \beta g(x)$, ($\alpha \geq 0, \beta \geq 0$).
- Composition with affine function $f(Ax + b)$ is convex, if $f(x)$ is convex.
- Pointwise maximum (supremum) of any number of functions: If $f_1(x), \dots, f_m(x)$ are convex, then $f(x) = \max\{f_1(x), \dots, f_m(x)\}$ is convex.
- If $f(x, y)$ is convex on x for any $y \in Y$:
 $g(x) = \sup_{y \in Y} f(x, y)$ is convex.



Figure 5: Pointwise maximum (supremum) of convex functions is convex

Operations that preserve convexity

- Non-negative sum of the convex functions:
 $\alpha f(x) + \beta g(x)$, ($\alpha \geq 0, \beta \geq 0$).
- Composition with affine function $f(Ax + b)$ is convex, if $f(x)$ is convex.
- Pointwise maximum (supremum) of any number of functions: If $f_1(x), \dots, f_m(x)$ are convex, then $f(x) = \max\{f_1(x), \dots, f_m(x)\}$ is convex.
- If $f(x, y)$ is convex on x for any $y \in Y$:
 $g(x) = \sup_{y \in Y} f(x, y)$ is convex.
- If $f(x)$ is convex on S , then $g(x, t) = tf(x/t)$ - is convex with $x/t \in S, t > 0$.



Figure 5: Pointwise maximum (supremum) of convex functions is convex

Operations that preserve convexity

- Non-negative sum of the convex functions:
 $\alpha f(x) + \beta g(x), (\alpha \geq 0, \beta \geq 0).$
- Composition with affine function $f(Ax + b)$ is convex, if $f(x)$ is convex.
- Pointwise maximum (supremum) of any number of functions: If $f_1(x), \dots, f_m(x)$ are convex, then $f(x) = \max\{f_1(x), \dots, f_m(x)\}$ is convex.
- If $f(x, y)$ is convex on x for any $y \in Y$:
 $g(x) = \sup_{y \in Y} f(x, y)$ is convex.
- If $f(x)$ is convex on S , then $g(x, t) = tf(x/t)$ - is convex with $x/t \in S, t > 0$.
- Let $f_1 : S_1 \rightarrow \mathbb{R}$ and $f_2 : S_2 \rightarrow \mathbb{R}$, where $\text{range}(f_1) \subseteq S_2$. If f_1 and f_2 are convex, and f_2 is increasing, then $f_2 \circ f_1$ is convex on S_1 .

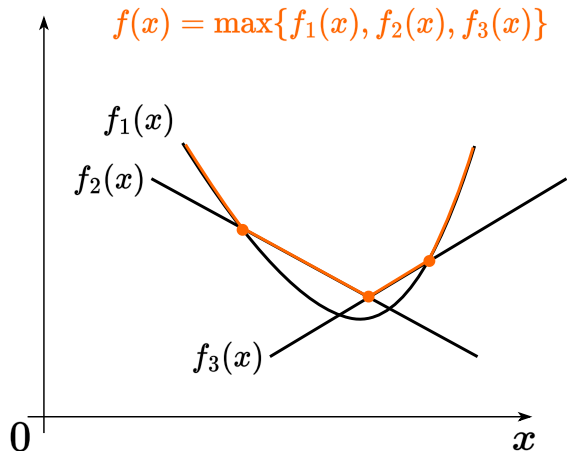


Figure 5: Pointwise maximum (supremum) of convex functions is convex

Maximum eigenvalue of a matrix is a convex function

Example

Show, that $f(A) = \lambda_{max}(A)$ - is convex, if $A \in S^n$.

Other forms of convexity

- Log-convexity: $\log f$ is convex; Log convexity implies convexity.

Other forms of convexity

- Log-convexity: $\log f$ is convex; Log convexity implies convexity.
- Log-concavity: $\log f$ concave; **not** closed under addition!

Other forms of convexity

- Log-convexity: $\log f$ is convex; Log convexity implies convexity.
- Log-concavity: $\log f$ concave; **not** closed under addition!
- Exponential convexity: $[f(x_i + x_j)] \succeq 0$, for x_1, \dots, x_n

Other forms of convexity

- Log-convexity: $\log f$ is convex; Log convexity implies convexity.
- Log-concavity: $\log f$ concave; **not** closed under addition!
- Exponential convexity: $[f(x_i + x_j)] \succeq 0$, for x_1, \dots, x_n
- Operator convexity: $f(\lambda X + (1 - \lambda)Y)$

Other forms of convexity

- Log-convexity: $\log f$ is convex; Log convexity implies convexity.
- Log-concavity: $\log f$ concave; **not** closed under addition!
- Exponential convexity: $[f(x_i + x_j)] \succeq 0$, for x_1, \dots, x_n
- Operator convexity: $f(\lambda X + (1 - \lambda)Y)$
- Quasiconvexity: $f(\lambda x + (1 - \lambda)y) \leq \max\{f(x), f(y)\}$

Other forms of convexity

- Log-convexity: $\log f$ is convex; Log convexity implies convexity.
- Log-concavity: $\log f$ concave; **not** closed under addition!
- Exponential convexity: $[f(x_i + x_j)] \succeq 0$, for x_1, \dots, x_n
- Operator convexity: $f(\lambda X + (1 - \lambda)Y)$
- Quasiconvexity: $f(\lambda x + (1 - \lambda)y) \leq \max\{f(x), f(y)\}$
- Pseudoconvexity: $\langle \nabla f(y), x - y \rangle \geq 0 \longrightarrow f(x) \geq f(y)$

Other forms of convexity

- Log-convexity: $\log f$ is convex; Log convexity implies convexity.
- Log-concavity: $\log f$ concave; **not** closed under addition!
- Exponential convexity: $[f(x_i + x_j)] \succeq 0$, for x_1, \dots, x_n
- Operator convexity: $f(\lambda X + (1 - \lambda)Y)$
- Quasiconvexity: $f(\lambda x + (1 - \lambda)y) \leq \max\{f(x), f(y)\}$
- Pseudoconvexity: $\langle \nabla f(y), x - y \rangle \geq 0 \longrightarrow f(x) \geq f(y)$
- Discrete convexity: $f : \mathbb{Z}^n \rightarrow \mathbb{Z}$; “convexity + matroid theory.”

Polyak- Lojasiewicz condition. Linear convergence of gradient descent without convexity

PL inequality holds if the following condition is satisfied for some $\mu > 0$,

$$\|\nabla f(x)\|^2 \geq \mu(f(x) - f^*) \forall x$$

It is interesting, that Gradient Descent algorithm has

The following functions satisfy the PL-condition, but are not convex. [🔗Link to the code](#)

$$f(x) = x^2 + 3 \sin^2(x)$$



Polyak- Łojasiewicz condition. Linear convergence of gradient descent without convexity

PL inequality holds if the following condition is satisfied for some $\mu > 0$,

$$\|\nabla f(x)\|^2 \geq \mu(f(x) - f^*) \forall x$$

It is interesting, that Gradient Descent algorithm has

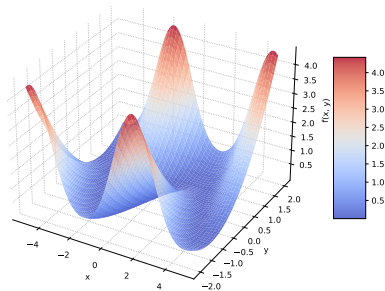
The following functions satisfy the PL-condition, but are not convex. [🔗Link to the code](#)

$$f(x) = x^2 + 3 \sin^2(x)$$



$$f(x, y) = \frac{(y - \sin x)^2}{2}$$

Non-convex PL function



Convex optimization problem



Note, that there is an agreement in notation of mathematical programming. The problems of the following type are called **Convex optimization problem**:

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

where all the functions $f_0(x), f_1(x), \dots, f_m(x)$ are convex and all the equality constraints are affine. It sounds a bit strange, but not all convex problems are convex optimization problems.

$$f_0(x) \rightarrow \min_{x \in S}, \quad (\text{CP})$$

where $f_0(x)$ is a convex function, defined on the convex set S . The necessity of affine equality constraint is essential.

Figure 8: The idea behind the definition of a convex optimization problem

Linear Least Squares aka Linear Regression



Figure 9: Illustration

In a least-squares, or linear regression, problem, we have measurements $X \in \mathbb{R}^{m \times n}$ and $y \in \mathbb{R}^m$ and seek a vector $\theta \in \mathbb{R}^n$ such that $X\theta$ is close to y . Closeness is defined as the sum of the squared differences:

$$\sum_{i=1}^m (x_i^\top \theta - y_i)^2 = \|X\theta - y\|_2^2 \rightarrow \min_{\theta \in \mathbb{R}^n}$$

For example, we might have a dataset of m users, each represented by n features. Each row x_i^\top of X is the features for user i , while the corresponding entry y_i of y is the measurement we want to predict from x_i^\top , such as ad spending. The prediction is given by $x_i^\top \theta$.

Linear Least Squares aka Linear Regression ¹

1. Is this problem convex? Strongly convex?

Linear Least Squares aka Linear Regression ¹

1. Is this problem convex? Strongly convex?
2. What do you think about convergence of Gradient Descent for this problem?

¹Take a look at the  example of real-world data linear least squares problem

l_2 -regularized Linear Least Squares

In the underdetermined case, it is often desirable to restore strong convexity of the objective function by adding an l_2 -penalty, also known as Tikhonov regularization, l_2 -regularization, or weight decay.

$$\|X\theta - y\|_2^2 + \frac{\mu}{2}\|\theta\|_2^2 \rightarrow \min_{\theta \in \mathbb{R}^n}$$

Note: With this modification the objective is μ -strongly convex again.

Take a look at the code

Neural networks?