

# Optimization for Machine Learning

## CS-439

Lecture 1: Introduction & Convexity

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EPFL – [github.com/epfml/OptML\\_course](https://github.com/epfml/OptML_course)

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# Outline

- ▶ Convexity, Gradient Methods, Constrained Optimization, Proximal algorithms, Subgradient Methods, **Stochastic Gradient Descent**, Coordinate Descent, Frank-Wolfe, Accelerated Methods, Primal-dual context and certificates, Lagrange and Fenchel Duality, Second-Order methods including Quasi-Newton, Derivative-free optimization.
- ▶ Advanced Contents:
  - ▶ Parallel and Distributed Optimization Algorithms
  - ▶ Computational Trade-Offs (Time vs Data vs Accuracy), Lower Bounds
  - ▶ Non-Convex Optimization: Convergence to Critical Points, Alternating minimization, Neural network training

# Course Organization

- ▶ Lectures
- ▶ Exercises
- ▶ Mini-Project

**Grading:** Written final exam, closed book (75%). Mini-Project (25%).

See details on course webpage on github

# Optimization

- ▶ General optimization problem (**unconstrained minimization**)

$$\begin{array}{ll}\text{minimize} & f(\mathbf{x}) \\ \text{with} & \mathbf{x} \in \mathbb{R}^d\end{array}$$

- ▶ candidate solutions, variables, parameters  $\mathbf{x} \in \mathbb{R}^d$
- ▶ objective function  $f : \mathbb{R}^d \rightarrow \mathbb{R}$
- ▶ typically: technical assumption:  $f$  is continuous and differentiable

# Why? And How?

Optimization is everywhere

*machine learning, big data, statistics, data analysis of all kinds, finance, logistics, planning, control theory, mathematics, search engines, simulations, and many other applications ...*

- ▶ **Mathematical Modeling:**

- ▶ *defining & modeling the optimization problem*

- ▶ **Computational Optimization:**

- ▶ *running an (appropriate) optimization algorithm*

# Optimization for Machine Learning

- ▶ **Mathematical Modeling:**
  - ▶ defining & measuring the machine learning model
- ▶ **Computational Optimization:**
  - ▶ learning the model parameters
- ▶ Theory vs. practice:
  - ▶ libraries are available, algorithms treated as “black box” by most practitioners
  - ▶ **Not here:** we look inside the algorithms and try to understand why and how fast they work!

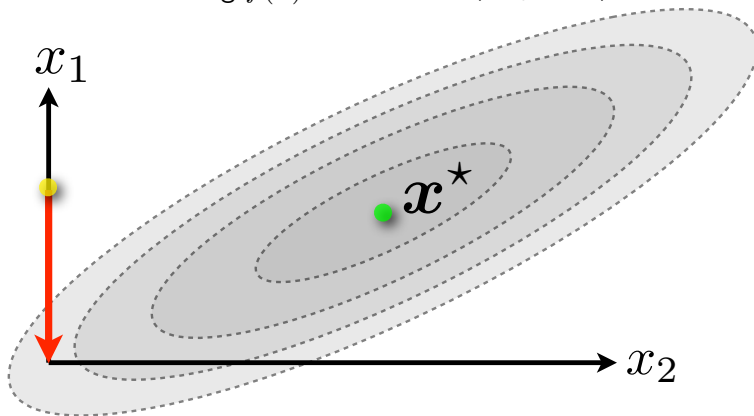
# Optimization Algorithms

- ▶ Optimization at large scale: **simplicity** rules!
- ▶ Main approaches:
  - ▶ **Gradient Descent**
  - ▶ **Stochastic Gradient Descent** (SGD)
  - ▶ **Coordinate Descent**
- ▶ History:
  - ▶ 1847: Cauchy proposes gradient descent
  - ▶ 1950s: Linear Programs, soon followed by non-linear, SGD
  - ▶ 1980s: General optimization, convergence theory
  - ▶ 2005-2015: Large scale optimization (mostly convex), convergence of SGD
  - ▶ 2015-today: Improved understanding of SGD for deep learning

# Example: Coordinate Descent

Goal: Find  $\mathbf{x}^* \in \mathbb{R}^d$  minimizing  $f(\mathbf{x})$ .

(Example:  $d = 2$ )

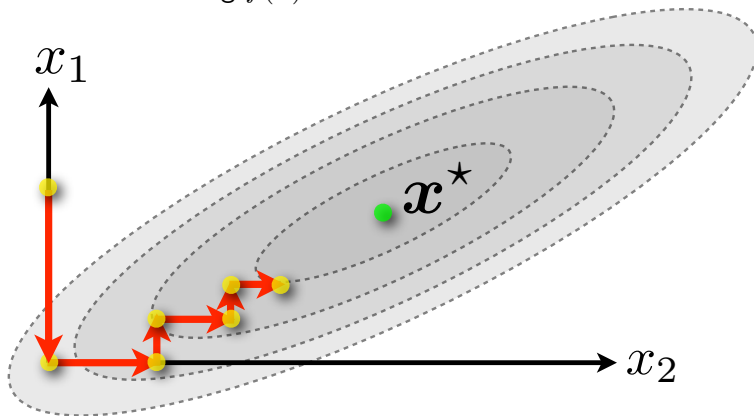


Idea: Update one coordinate at a time, while keeping others fixed.



## Example: Coordinate Descent

Goal: Find  $\mathbf{x}^* \in \mathbb{R}^d$  minimizing  $f(\mathbf{x})$ .



Idea: Update one coordinate at a time, while keeping others fixed.

# Chapter 1

## Theory of Convex Functions

# Warmup: The Cauchy-Schwarz inequality

Let  $\mathbf{u}, \mathbf{v} \in \mathbb{R}^d$ . **Cauchy-Schwarz inequality** (Proof in Section 1.1.2):

$$|\mathbf{u}^\top \mathbf{v}| \leq \|\mathbf{u}\| \|\mathbf{v}\|.$$

Notation:

$$\mathbf{u} = \begin{pmatrix} u_1 \\ u_2 \\ \vdots \\ u_d \end{pmatrix}$$

$$\mathbf{u}^\top = (u_1 \quad u_2 \quad \cdots \quad u_d)$$

- ▶  $\mathbf{u} = (u_1, \dots, u_d), \mathbf{v} = (v_1, \dots, v_d)$ ,  $d$ -dimensional column vectors with real entries
- ▶  $\mathbf{u}^\top$ , transpose of  $\mathbf{u}$ , a  $d$ -dimensional row vector
- ▶  $\mathbf{u}^\top \mathbf{v} = \sum_{i=1}^d u_i v_i$ , scalar (or inner) product of  $\mathbf{u}$  and  $\mathbf{v}$
- ▶  $|\mathbf{u}^\top \mathbf{v}|$ , absolute value of  $\mathbf{u}^\top \mathbf{v}$
- ▶  $\|\mathbf{u}\| = \sqrt{\mathbf{u}^\top \mathbf{u}} = \sqrt{\sum_{i=1}^d u_i^2}$ , Euclidean norm of  $\mathbf{u}$

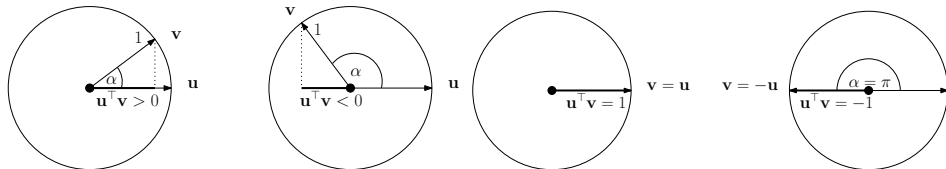
# The Cauchy-Schwarz inequality: Interpretation

Let  $\mathbf{u}, \mathbf{v} \in \mathbb{R}^d$ . Cauchy-Schwarz inequality:  $|\mathbf{u}^\top \mathbf{v}| \leq \|\mathbf{u}\| \|\mathbf{v}\|$ .

For nonzero vectors, this is equivalent to

$$-1 \leq \frac{\mathbf{u}^\top \mathbf{v}}{\|\mathbf{u}\| \|\mathbf{v}\|} \leq 1.$$

Fraction can be used to define the angle  $\alpha$  between  $\mathbf{u}$  and  $\mathbf{v}$ :  $\cos(\alpha) = \frac{\mathbf{u}^\top \mathbf{v}}{\|\mathbf{u}\| \|\mathbf{v}\|}$



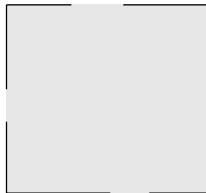
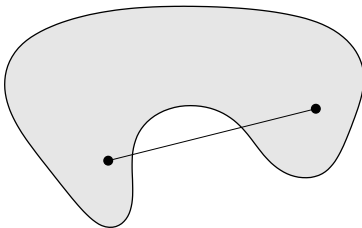
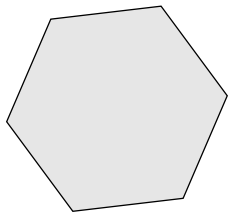
Examples for unit vectors  
( $\|\mathbf{u}\| = \|\mathbf{v}\| = 1$ )

Equality in Cauchy-Schwarz if and only  
if  $\mathbf{u} = \mathbf{v}$  or  $\mathbf{u} = -\mathbf{v}$ .

# Convex Sets

A set  $C$  is **convex** if the line segment between any two points of  $C$  lies in  $C$ , i.e., if for any  $\mathbf{x}, \mathbf{y} \in C$  and any  $\lambda$  with  $0 \leq \lambda \leq 1$ , we have

$$\lambda \mathbf{x} + (1 - \lambda) \mathbf{y} \in C.$$



\*Figure 2.2 from S. Boyd, L. Vandenberghe

**Left** Convex.

**Middle** Not convex, since line segment not in set.

**Right** Not convex, since some, but not all boundary points are contained in the set.

# Properties of Convex Sets

- Intersections of convex sets are convex

**Observation 1.2.** Let  $C_i, i \in I$  be convex sets, where  $I$  is a (possibly infinite) index set. Then  $C = \bigcap_{i \in I} C_i$  is a convex set.

- (later) Projections onto convex sets are *unique*, and *often* efficient to compute

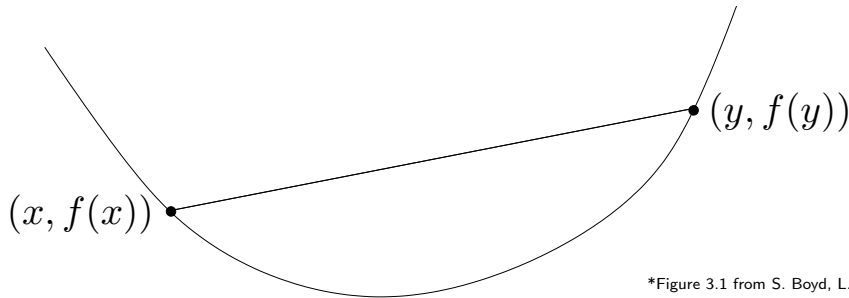
$$P_C(\mathbf{x}') := \operatorname{argmin}_{\mathbf{y} \in C} \|\mathbf{y} - \mathbf{x}'\|$$

# Convex Functions

## Definition

A function  $f : \mathbb{R}^d \rightarrow \mathbb{R}$  is **convex** if (i)  $\text{dom}(f)$  is a convex set and (ii) for all  $\mathbf{x}, \mathbf{y} \in \text{dom}(f)$ , and  $\lambda$  with  $0 \leq \lambda \leq 1$ , we have

$$f(\lambda \mathbf{x} + (1 - \lambda) \mathbf{y}) \leq \lambda f(\mathbf{x}) + (1 - \lambda) f(\mathbf{y}).$$



\*Figure 3.1 from S. Boyd, L. Vandenberghe

**Geometrically:** The line segment between  $(\mathbf{x}, f(\mathbf{x}))$  and  $(\mathbf{y}, f(\mathbf{y}))$  lies above the graph of  $f$ .

# Motivation: Convex Optimization

**Convex Optimization Problems** are of the form

$$\min f(\mathbf{x}) \quad \text{s.t.} \quad \mathbf{x} \in X$$

where both

- ▶  $f$  is a convex function
- ▶  $X \subseteq \text{dom}(f)$  is a convex set (note:  $\mathbb{R}^d$  is convex)

## Crucial Property of Convex Optimization Problems

- ▶ Every local minimum is a **global minimum**, see later...



# Motivation: Solving Convex Optimization - Provably

For convex optimization problems, all algorithms

- Coordinate Descent, Gradient Descent, Stochastic Gradient Descent, Projected and Proximal Gradient Descent

do **converge** to the global optimum! (assuming  $f$  differentiable)

**Example Theorem:** The **convergence rate** is proportional to  $\frac{1}{t}$ , i.e.

$$f(\mathbf{x}_t) - f(\mathbf{x}^*) \leq \frac{c}{t}$$

(where  $\mathbf{x}^*$  is some optimal solution to the problem.)

Meaning: **Approximation error** converges to 0 over time.

# Motivation: Convergence Theory

$f$	Algorithm	Rate	# Iter	Cost/iter
non-smooth	center of gravity	$\exp\left(-\frac{t}{n}\right)$	$n \log\left(\frac{1}{\varepsilon}\right)$	$\frac{1}{n} \nabla$ , $\frac{1}{n} \text{dim}$ $\int$
non-smooth	ellipsoid method	$\frac{R}{r} \exp\left(-\frac{t}{n^2}\right)$	$n^2 \log\left(\frac{R}{r\varepsilon}\right)$	$\frac{1}{n} \nabla$ , mat-vec $\times$
non-smooth	Vaidya	$\frac{Rn}{r} \exp\left(-\frac{t}{n}\right)$	$n \log\left(\frac{Rn}{r\varepsilon}\right)$	$\frac{1}{n} \nabla$ , mat-mat $\times$
quadratic	CG	exact $\exp\left(-\frac{t}{\kappa}\right)$	$\frac{n}{\kappa} \log\left(\frac{1}{\varepsilon}\right)$	$\frac{1}{n} \nabla$
non-smooth, Lipschitz	PGD	$RL/\sqrt{t}$	$R^2 L^2 / \varepsilon^2$	$\frac{1}{n} \nabla$ , $\frac{1}{n} \text{proj.}$
smooth	PGD	$\beta R^2 / t$	$\beta R^2 / \varepsilon$	$\frac{1}{n} \nabla$ , $\frac{1}{n} \text{proj.}$
smooth	AGD	$\beta R^2 / t^2$	$R\sqrt{\beta/\varepsilon}$	$\frac{1}{n} \nabla$
smooth (any norm)	FW	$\beta R^2 / t$	$\beta R^2 / \varepsilon$	$\frac{1}{n} \nabla$ , $\frac{1}{n} \text{LP}$
strong, conv., Lipschitz	PGD	$L^2 / (\alpha t)$	$L^2 / (\alpha \varepsilon)$	$\frac{1}{n} \nabla$ , $\frac{1}{n} \text{proj.}$
strong, conv., smooth	PGD	$R^2 \exp\left(-\frac{t}{\kappa}\right)$	$\kappa \log\left(\frac{R^2}{\varepsilon}\right)$	$\frac{1}{n} \nabla$ , $\frac{1}{n} \text{proj.}$
strong, conv., smooth	AGD	$R^2 \exp\left(-\frac{t}{\sqrt{\kappa}}\right)$	$\sqrt{\kappa} \log\left(\frac{R^2}{\varepsilon}\right)$	$\frac{1}{n} \nabla$
$f+g$ , $f$ smooth, $g$ simple	FISTA	$\beta R^2 / t^2$	$R\sqrt{\beta/\varepsilon}$	$\frac{1}{n} \nabla$ of $f$ Prox of $g$
$\max_{y \in \mathcal{Y}} \varphi(x, y)$ , $\varphi$ smooth	SP-MP	$\beta R^2 / t$	$\beta R^2 / \varepsilon$	MD on $\mathcal{X}$ MD on $\mathcal{Y}$
linear, $\mathcal{X}$ with $F$ $\nu$ -self-conc.	IPM	$\nu \exp\left(-\frac{t}{\sqrt{\nu}}\right)$	$\sqrt{\nu} \log\left(\frac{\nu}{\varepsilon}\right)$	Newton step on $F$
non-smooth	SGD	$BL/\sqrt{t}$	$B^2 L^2 / \varepsilon^2$	$\frac{1}{n} \text{stoch. } \nabla$ , $\frac{1}{n} \text{proj.}$
non-smooth, strong, conv.	SGD	$B^2 / (\alpha t)$	$B^2 / (\alpha \varepsilon)$	$\frac{1}{n} \text{stoch. } \nabla$ , $\frac{1}{n} \text{proj.}$
$f = \frac{1}{m} \sum f_i$ , $f_i$ smooth strong, conv.	SVRG	—	$(m + \kappa) \log\left(\frac{1}{\varepsilon}\right)$	$\frac{1}{n} \text{stoch. } \nabla$

(Bubeck [Bub15])

# Convex Functions & Sets

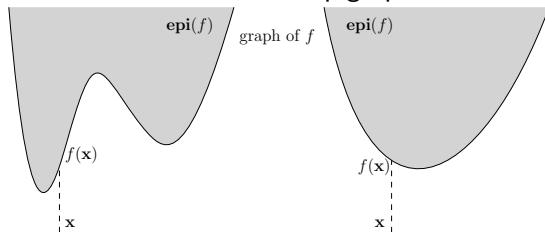
The **graph** of a function  $f : \mathbb{R}^d \rightarrow \mathbb{R}$  is defined as

$$\{(\mathbf{x}, f(\mathbf{x})) \mid \mathbf{x} \in \mathbf{dom}(f)\},$$

The **epigraph** of a function  $f : \mathbb{R}^d \rightarrow \mathbb{R}$  is defined as

$$\mathbf{epi}(f) := \{(\mathbf{x}, \alpha) \in \mathbb{R}^{d+1} \mid \mathbf{x} \in \mathbf{dom}(f), \alpha \geq f(\mathbf{x})\},$$

**Observation 1.4.** A function is convex *iff* its epigraph is a convex set.



# Convex Functions & Sets

**Proof:**

recall  $\mathbf{epi}(f) := \{(\mathbf{x}, \alpha) \in \mathbb{R}^{d+1} \mid \mathbf{x} \in \mathbf{dom}(f), \alpha \geq f(\mathbf{x})\}$

# Convex Functions

## Examples of convex functions

- ▶ Linear functions:  $f(\mathbf{x}) = \mathbf{a}^\top \mathbf{x}$
- ▶ Affine functions:  $f(\mathbf{x}) = \mathbf{a}^\top \mathbf{x} + b$
- ▶ Exponential:  $f(x) = e^{\alpha x}$
- ▶ Norms. Every norm on  $\mathbb{R}^d$  is convex.

## Convexity of a norm $\|\mathbf{x}\|$

By the triangle inequality  $\|\mathbf{x} + \mathbf{y}\| \leq \|\mathbf{x}\| + \|\mathbf{y}\|$  and homogeneity of a norm  $\|a\mathbf{x}\| = |a| \|\mathbf{x}\|$ ,  $a$  scalar:

$$\|\lambda \mathbf{x} + (1 - \lambda) \mathbf{y}\| \leq \|\lambda \mathbf{x}\| + \|(1 - \lambda) \mathbf{y}\| = \lambda \|\mathbf{x}\| + (1 - \lambda) \|\mathbf{y}\|.$$

We used the triangle inequality for the inequality and homogeneity for the equality.

# Jensen's Inequality

## Lemma (Jensen's inequality)

Let  $f$  be convex,  $\mathbf{x}_1, \dots, \mathbf{x}_m \in \mathbf{dom}(f)$ ,  $\lambda_1, \dots, \lambda_m \in \mathbb{R}_+$  such that  $\sum_{i=1}^m \lambda_i = 1$ .  
Then

$$f\left(\sum_{i=1}^m \lambda_i \mathbf{x}_i\right) \leq \sum_{i=1}^m \lambda_i f(\mathbf{x}_i).$$

For  $m = 2$ , this is [convexity](#). The proof of the general case is Exercise 2.

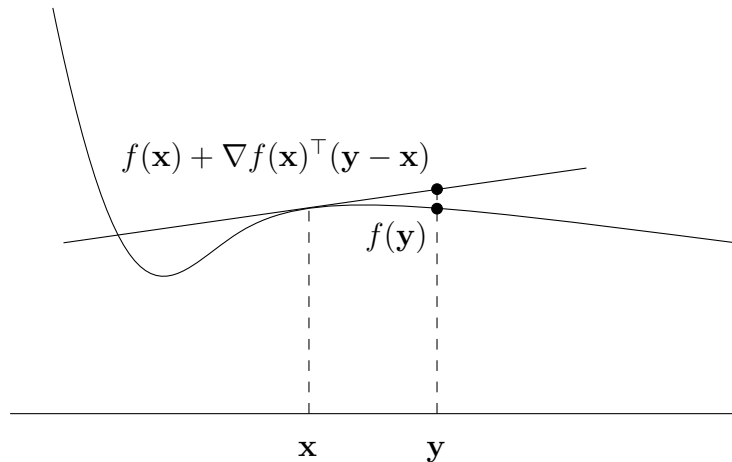
# Convex Functions are Continuous

**Lemma 1.6.:** Let  $f$  be convex and suppose that  $\text{dom}(f)$  is open. Then  $f$  is continuous.

Not entirely obvious (Exercise 3).

# Differentiable Functions

Graph of the affine function  $f(\mathbf{x}) + \nabla f(\mathbf{x})^\top (\mathbf{y} - \mathbf{x})$  is a **tangent hyperplane** to the graph of  $f$  at  $(\mathbf{x}, f(\mathbf{x}))$ .





# First-order Characterization of Convexity

Lemma ([BV04, 3.1.3])

Suppose that  $\text{dom}(f)$  is open and that  $f$  is differentiable; in particular, the **gradient** (vector of partial derivatives)

$$\nabla f(\mathbf{x}) := \left( \frac{\partial f}{\partial x_1}(\mathbf{x}), \dots, \frac{\partial f}{\partial x_d}(\mathbf{x}) \right)$$

exists at every point  $\mathbf{x} \in \text{dom}(f)$ . Then  $f$  is convex if and only if  $\text{dom}(f)$  is convex and

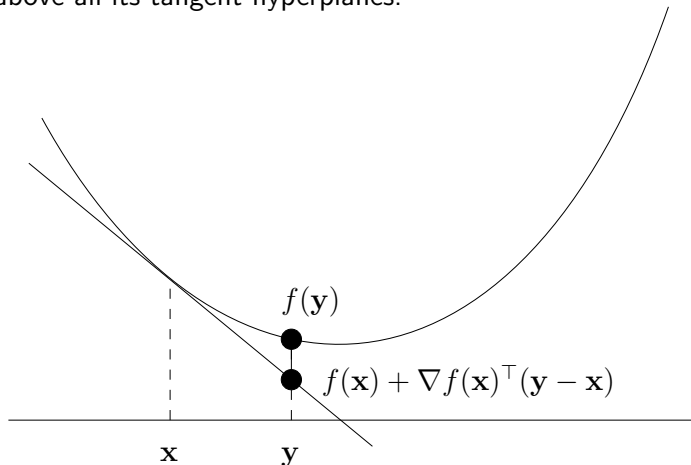
$$f(\mathbf{y}) \geq f(\mathbf{x}) + \nabla f(\mathbf{x})^\top (\mathbf{y} - \mathbf{x}) \quad (1)$$

holds for all  $\mathbf{x}, \mathbf{y} \in \text{dom}(f)$ .

# First-order Characterization of Convexity

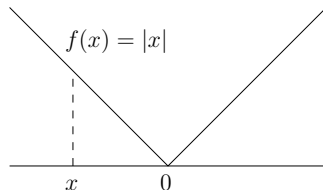
$$f(\mathbf{y}) \geq f(\mathbf{x}) + \nabla f(\mathbf{x})^\top (\mathbf{y} - \mathbf{x}), \quad \mathbf{x}, \mathbf{y} \in \text{dom}(f).$$

Graph of  $f$  is above all its tangent hyperplanes.

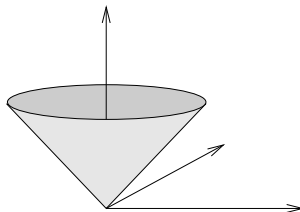


# Nondifferentiable Functions...

are also relevant in practice.



More generally,  $f(\mathbf{x}) = \|\mathbf{x}\|$  (Euclidean norm). For  $d = 2$ , graph is the **ice cream cone**:



## Second-order Characterization of Convexity

Lemma ([BV04, 3.1.4])

Suppose that  $\text{dom}(f)$  is open and that  $f$  is twice differentiable; in particular, the **Hessian** (matrix of second partial derivatives)

$$\nabla^2 f(\mathbf{x}) = \begin{pmatrix} \frac{\partial^2 f}{\partial x_1 \partial x_1}(\mathbf{x}) & \frac{\partial^2 f}{\partial x_1 \partial x_2}(\mathbf{x}) & \cdots & \frac{\partial^2 f}{\partial x_1 \partial x_d}(\mathbf{x}) \\ \frac{\partial^2 f}{\partial x_2 \partial x_1}(\mathbf{x}) & \frac{\partial^2 f}{\partial x_2 \partial x_2}(\mathbf{x}) & \cdots & \frac{\partial^2 f}{\partial x_2 \partial x_d}(\mathbf{x}) \\ \vdots & \vdots & \cdots & \vdots \\ \frac{\partial^2 f}{\partial x_d \partial x_1}(\mathbf{x}) & \frac{\partial^2 f}{\partial x_d \partial x_2}(\mathbf{x}) & \cdots & \frac{\partial^2 f}{\partial x_d \partial x_d}(\mathbf{x}) \end{pmatrix}$$

exists at every point  $\mathbf{x} \in \text{dom}(f)$  and is symmetric. Then  $f$  is convex if and only if  $\text{dom}(f)$  is convex, and for all  $\mathbf{x} \in \text{dom}(f)$ , we have

$$\nabla^2 f(\mathbf{x}) \succeq 0 \quad (\text{i.e. } \nabla^2 f(\mathbf{x}) \text{ is positive semidefinite}).$$

(A symmetric matrix  $M$  is positive semidefinite if  $\mathbf{x}^\top M \mathbf{x} \geq 0$  for all  $\mathbf{x}$ , and positive definite if  $\mathbf{x}^\top M \mathbf{x} > 0$  for all  $\mathbf{x} \neq \mathbf{0}$ .)

## Second-order Characterization of Convexity

Example:  $f(x_1, x_2) = x_1^2 + x_2^2$ .

$$\nabla^2 f(\mathbf{x}) = \begin{pmatrix} 2 & 0 \\ 0 & 2 \end{pmatrix} \succeq 0.$$

# Operations that Preserve Convexity

## Lemma (Exercise 5)

- (i) Let  $f_1, f_2, \dots, f_m$  be convex functions,  $\lambda_1, \lambda_2, \dots, \lambda_m \in \mathbb{R}_+$ . Then  $f := \sum_{i=1}^m \lambda_i f_i$  is convex on  $\text{dom}(f) := \bigcap_{i=1}^m \text{dom}(f_i)$ .
- (ii) Let  $f$  be a convex function with  $\text{dom}(f) \subseteq \mathbb{R}^d$ ,  $g : \mathbb{R}^m \rightarrow \mathbb{R}^d$  an affine function, meaning that  $g(\mathbf{x}) = A\mathbf{x} + \mathbf{b}$ , for some matrix  $A \in \mathbb{R}^{d \times m}$  and some vector  $\mathbf{b} \in \mathbb{R}^d$ . Then the function  $f \circ g$  (that maps  $\mathbf{x}$  to  $f(A\mathbf{x} + \mathbf{b})$ ) is convex on  $\text{dom}(f \circ g) := \{\mathbf{x} \in \mathbb{R}^m : g(\mathbf{x}) \in \text{dom}(f)\}$ .

# Local Minima are Global Minima

## Definition

A **local minimum** of  $f : \text{dom}(f) \rightarrow \mathbb{R}$  is a point  $\mathbf{x}$  such that there exists  $\varepsilon > 0$  with

$$f(\mathbf{x}) \leq f(\mathbf{y}) \quad \forall \mathbf{y} \in \text{dom}(f) \text{ satisfying } \|\mathbf{y} - \mathbf{x}\| < \varepsilon.$$

## Lemma

Let  $\mathbf{x}^*$  be a **local minimum** of a convex function  $f : \text{dom}(f) \rightarrow \mathbb{R}$ . Then  $\mathbf{x}^*$  is a **global minimum**, meaning that  $f(\mathbf{x}^*) \leq f(\mathbf{y}) \quad \forall \mathbf{y} \in \text{dom}(f)$ .

## Proof.

Suppose there exists  $\mathbf{y} \in \text{dom}(f)$  such that  $f(\mathbf{y}) < f(\mathbf{x}^*)$ .

Define  $\mathbf{y}' := \lambda \mathbf{x}^* + (1 - \lambda) \mathbf{y}$  for  $\lambda \in (0, 1)$ .

From convexity, we get that  $f(\mathbf{y}') < f(\mathbf{x}^*)$ . Choosing  $\lambda$  so close to 1 that  $\|\mathbf{y}' - \mathbf{x}^*\| < \varepsilon$  yields a contradiction to  $\mathbf{x}^*$  being a local minimum. □

# Critical Points are Global Minima

## Lemma

Suppose that  $f$  is convex and differentiable over an open domain  $\text{dom}(f)$ . Let  $\mathbf{x} \in \text{dom}(f)$ . If  $\nabla f(\mathbf{x}) = \mathbf{0}$  (**critical point**), then  $\mathbf{x}$  is a **global minimum**.

## Proof.

Suppose that  $\nabla f(\mathbf{x}) = \mathbf{0}$ . According to our Lemma on the first-order characterization of convexity, we have



Geometrically, tangent hyperplane is horizontal at  $\mathbf{x}$ .



# Strictly Convex Functions

Definition ([BV04, 3.1.1])

A function  $f : \text{dom}(f) \rightarrow \mathbb{R}$  is **strictly convex** if (i)  $\text{dom}(f)$  is convex and (ii) for all  $\mathbf{x} \neq \mathbf{y} \in \text{dom}(f)$  and all  $\lambda \in (0, 1)$ , we have

$$f(\lambda \mathbf{x} + (1 - \lambda) \mathbf{y}) < \lambda f(\mathbf{x}) + (1 - \lambda) f(\mathbf{y}). \quad (2)$$



convex, but not strictly convex



strictly convex

Lemma

Let  $f : \text{dom}(f) \rightarrow \mathbb{R}$  be strictly convex. Then  $f$  has at most one global minimum.

# Constrained Minimization

## Definition

Let  $f : \text{dom}(f) \rightarrow \mathbb{R}$  be convex and let  $X \subseteq \text{dom}(f)$  be a convex set. A point  $\mathbf{x} \in X$  is a **minimizer** of  $f$  **over**  $X$  if

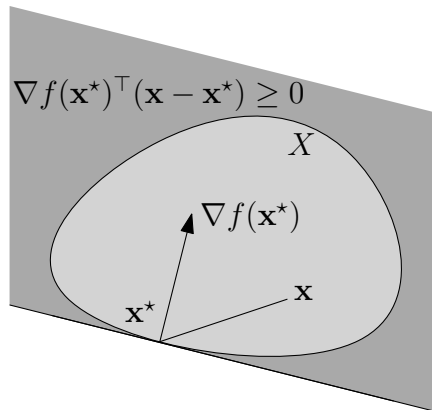
$$f(\mathbf{x}) \leq f(\mathbf{y}) \quad \forall \mathbf{y} \in X.$$

## Lemma

*Suppose that  $f : \text{dom}(f) \rightarrow \mathbb{R}$  is convex and differentiable over an open domain  $\text{dom}(f) \subseteq \mathbb{R}^d$ , and let  $X \subseteq \text{dom}(f)$  be a convex set. Point  $\mathbf{x}^* \in X$  is a minimizer of  $f$  over  $X$  if and only if*

$$\nabla f(\mathbf{x}^*)^\top (\mathbf{x} - \mathbf{x}^*) \geq 0 \quad \forall \mathbf{x} \in X.$$

# Constrained Minimization



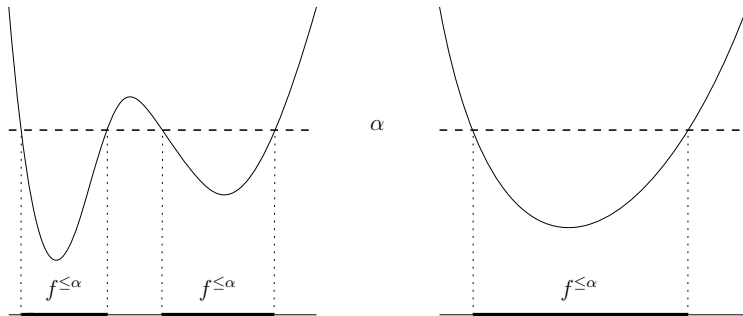
# Existence of a minimizer

How do we know that a global minimum exists?

Not necessarily the case, even if  $f$  bounded from below ( $f(x) = e^x$ )

## Definition

$f : \mathbb{R}^d \rightarrow \mathbb{R}$ ,  $\alpha \in \mathbb{R}$ . The set  $f^{\leq \alpha} := \{\mathbf{x} \in \mathbb{R}^d : f(\mathbf{x}) \leq \alpha\}$  is the  $\alpha$ -sublevel set of  $f$



# The Weierstrass Theorem

## Theorem

*Let  $f : \mathbb{R}^d \rightarrow \mathbb{R}$  be a convex function, and suppose there is a nonempty and bounded sublevel set  $f^{\leq \alpha}$ . Then  $f$  has a global minimum.*

## Proof:

We know that  $f$ —as a continuous function—attains a minimum over the closed and bounded (= compact) set  $f^{\leq \alpha}$  at some  $\mathbf{x}^*$ . This  $\mathbf{x}^*$  is also a global minimum as it has value  $f(\mathbf{x}^*) \leq \alpha$ , while any  $\mathbf{x} \notin f^{\leq \alpha}$  has value  $f(\mathbf{x}) > \alpha \geq f(\mathbf{x}^*)$ .

Generalizes to suitable domains  $\text{dom}(f) \neq \mathbb{R}^d$ .

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