

Lecture
Notes

2025

Optimisation, Control, and Data

Dario Prandi

dario.prandi@centralesupelec.fr

September 23, 2025

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Part I

Optimisation

Chapter 1

Convex Analysis

This chapter closely follows chapter 5 of the lecture notes [2]. For most of the proof in this chapter we refer to [1] or [3].

1.1 Convex sets

Definition 1.1.1

A set $K \subset \mathbb{R}^d$ is *convex* if

$$tx + (1-t)y \in K \quad \forall x, y \in K, t \in [0, 1] \quad (1.1)$$

We have the following fact.

Proposition 1.1.1

The set $K \subset \mathbb{R}^d$ is convex if and only if for any $n \in \mathbb{N}$, and $t_1, \dots, t_n \geq 0$ such that $\sum_{i=1}^n t_i = 1$, it holds

$$x_1, \dots, x_n \in K \implies \sum_{i=1}^n t_i x_i \in K. \quad (1.2)$$

Proof: Property (1.2) with $n = 2$ is exactly the definition of K is convex. The statement then follows by induction on n . ■

Definition 1.1.2

The convex hull $\text{conv}(\Omega)$ of $\Omega \subset \mathbb{R}^d$ is the smallest convex set K containing Ω .

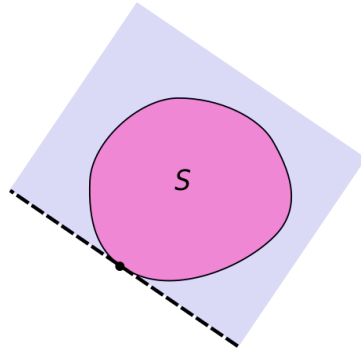
By Proposition 1.1.1, it is immediate to observe that

$$\text{conv}(\Omega) = \left\{ \sum_{i=1}^n t_i x_i \mid t_i \geq 0, \sum_{i=1}^n t_i = 1, x_i \in \Omega \right\}. \quad (1.3)$$

Example 1.1.1 (Convex sets)

- Unit ball w.r.t. any norm.
- Vector subspaces.
- Hyperplanes, i.e., for any $v \in \mathbb{R}^d$ and $\lambda \in \mathbb{R}$,

$$H_{v,\lambda} := \{x \in \mathbb{R}^d \mid \langle v, x \rangle \geq \lambda\}. \quad (1.4)$$

Figure 1.1: Supporting hyperplane for a set S .

An important result (that we will not prove) on convex sets is the following.

Theorem 1.1.1 Separation theorem

Let $K_1, K_2 \subset \mathbb{R}^d$ be two convex sets such with disjoint interior. Then there exists $v \in \mathbb{R}^d$ and $\lambda \in \mathbb{R}$ such that

$$K_1 \subset H_{v,\lambda}, \quad K_2 \subset \mathbb{R}^d \setminus H_{v,\lambda}. \quad (1.5)$$

Here, $H_{v,\lambda}$ is defined in (1.4).

As a direct consequence, we have the following (see Figure 1.1).

Corollary 1.1.2 Supporting hyperplane theorem

Let $K \subset \mathbb{R}^d$ be a convex set and $x \in \partial K$. Then, there exists a supporting hyperplane of K containing x_0 . That is, there exists $v \in \mathbb{R}^d$ and $\lambda \in \mathbb{R}$ such that $K \subset H_{v,\lambda}$ and $x_0 \in \partial H_{v,\lambda}$.

When K is a convex polygon, it is natural to expect it to be determined by its vertices. In order to formalize this intuition we need the following.

Definition 1.1.3

Let $K \subset \mathbb{R}^d$ be a convex set. A point $x \in K$ is an extremum of K if for any $y, z \in K$ and $t \in (0, 1)$ we have that

$$x = ty + (1 - t)z \implies x = y = z. \quad (1.6)$$

The set of extrema of K is denoted by $\text{extr}(K)$.

In particular, for a convex polygon $\text{extr}(K)$ is the set of its vertices.

Proposition 1.1.2

Let $K \subset \mathbb{R}^d$ be a convex set that is compact. Then,

$$\text{conv}(K) = \text{conv}(\text{extr}(K)). \quad (1.7)$$



Figure 1.2: Two examples of polar cone.

1.2 Cones

Definition 1.2.1

A set $K \subset \mathbb{R}^d$ is a cone if

$$tx \in K \quad \forall x \in K, t \geq 0. \quad (1.8)$$

Observe that every cone contains the origin.

Example 1.2.1 (Cones)

- The second order cone

$$C = \{x = (x', x_n) \in \mathbb{R}^d \times \mathbb{R} \mid \|x'\|_2 \leq x_n\}.$$

- Positive orthant $\mathbb{R}_+^d = \{x \in \mathbb{R}^d \mid x_i \geq 0, \quad \forall i \in \llbracket 1, d \rrbracket\}$.
- The set of positive semidefinite matrices $\text{Sym}_+(\mathbb{R}^d)$.

Definition 1.2.2

The conic hull $\text{cone}(\Omega)$ of a set $\Omega \subset \mathbb{R}^d$ is the smallest cone containing Ω . Namely,

$$\text{cone}(\Omega) = \left\{ \sum_{i=1}^n t_i x_i \mid t_i \geq 0 \text{ and } x_i \in \Omega \text{ for any } i \in \llbracket 1, n \rrbracket \right\}. \quad (1.9)$$

Definition 1.2.3

The dual cone K^* of a cone $K \subset \mathbb{R}^d$ is the set

$$K^* := \{y \in \mathbb{R}^d \mid \langle x, y \rangle \geq 0 \quad \forall x \in K\}. \quad (1.10)$$

We have the following properties for the polar cone.

Proposition 1.2.1

The polar cone K^* is a closed, convex cone. If, moreover, the cone K is closed, then $K^{**} = K$.

1.3 Convex functions

We will work with extended functions $F : \mathbb{R}^d \rightarrow \mathbb{R} \cup \{+\infty\}$. The domain of an extended function is

$$\text{dom}(F) = \{x \in \mathbb{R}^d \mid F(x) < +\infty\}. \quad (1.11)$$

An extended function such that $\text{dom}(F) \neq \emptyset$ is called *proper*.

Given a standard function $F : \Omega \rightarrow \mathbb{R}$, we can identify it with the extended function $\bar{F} : \mathbb{R}^d \rightarrow \mathbb{R} \cup \{+\infty\}$ defined by

$$\bar{F}(x) = \begin{cases} F(x) & \text{if } x \in \Omega, \\ +\infty & \text{if } x \in \mathbb{R}^d \setminus \Omega. \end{cases} \quad (1.12)$$

Definition 1.3.1 Convex functions

Let $F : \mathbb{R}^d \rightarrow \mathbb{R} \cup \{+\infty\}$ be an extended function. Then,

- F is convex if

$$F(tx + (1-t)y) \leq tF(x) + (1-t)F(y) \quad \forall x, y \in \mathbb{R}^d, t \in [0, 1]. \quad (1.13)$$

- F is strictly convex if

$$F(tx + (1-t)y) < tF(x) + (1-t)F(y) \quad \forall x, y \in \mathbb{R}^d, x \neq y, t \in [0, 1]. \quad (1.14)$$

- F is strongly convex if there exists $\gamma > 0$ such that

$$F(tx + (1-t)y) \leq tF(x) + (1-t)F(y) - \frac{\gamma}{2}t(1-t)\|x - y\|_2^2 \quad \forall x, y \in \mathbb{R}^d, t \in [0, 1]. \quad (1.15)$$

We say that F is *concave* if $-F$ is convex.

Observe that it holds

$$\text{convex} \iff \text{strongly convex} \iff \text{strictly convex} \quad (1.16)$$

We say that a standard function $F : K \rightarrow \mathbb{R}$ is convex, strictly convex, strongly convex, or concave, if the same is true for its extension \bar{F} . Observe that this requires K to be convex.

Example 1.3.1

- The prototypical convex function, used in the definition of strongly convex, is the quadratic function

$$F(x) = \frac{\|x\|_2^2}{2} = \frac{1}{2} \sum_{i=1}^d |x_i|^2. \quad (1.17)$$

- More generally, every norm is convex.
- The norm ℓ_p is strictly convex if and only if $p \in (1, +\infty)$.
- $F(x) = x^\top A x$ is convex if A is positive semidefinite (i.e., $A \in \text{Sym}_{\geq 0}(\mathbb{R}^d)$), and strongly convex if A is positive definite.

Proposition 1.3.1

A function $F : K \rightarrow \mathbb{R}$ is convex if and only if its epigraph $\text{epi}(F) \subset \mathbb{R}^{d+1}$ is convex. Here, we let

$$\text{epi}(F) = \{(x, r) \mid r \geq F(x)\}. \quad (1.18)$$

Proof: Assume F is convex and let $(x, r), (y, s) \in \text{epi}(F)$. In particular, $r \geq F(x)$ and $s \geq F(y)$. Let $t \in [0, 1]$ and observe that

$$tr + (1-t)s \geq tF(x) + (1-t)F(y) \geq F(tx + (1-t)y). \quad (1.19)$$

Hence, $t(x, r) + (1-t)(y, s) \in \text{epi}(F)$. A similar reasoning proves the opposite implication. ■

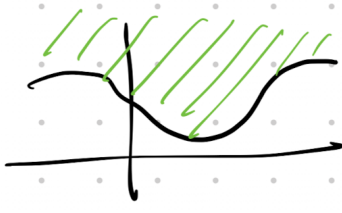


Figure 1.3: Epigraph of a function.

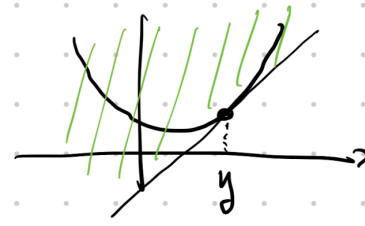


Figure 1.4: Graphical representation of Proposition 1.3.2.

Proposition 1.3.2 Differential characterisations of convexity

Let $F : \mathbb{R}^d \rightarrow \mathbb{R}$ be an everywhere differentiable function. Then,

- F is convex if and only if

$$F(y) \geq F(x) + \langle \nabla F(x), y - x \rangle, \quad \forall x, y \in \mathbb{R}^d. \quad (1.20)$$

- F is strongly convex with parameter $\gamma > 0$ if and only if

$$F(y) \geq F(x) + \langle \nabla F(x), y - x \rangle + \frac{\gamma}{2} \|x - y\|_2^2, \quad \forall x, y \in \mathbb{R}^d. \quad (1.21)$$

- If F is everywhere twice differentiable, then it is convex if and only if

$$\text{Hess } F(x) \geq 0 \quad \forall x \in \mathbb{R}^d, \quad (1.22)$$

and strongly convex if and only if there exists $\gamma > 0$ such that

$$\text{Hess } F(x) \geq \frac{\gamma}{2} I \quad \forall x \in \mathbb{R}^d. \quad (1.23)$$

Here, we denoted by $\text{Hess } F(x)$ the Hessian of F at x .

Proposition 1.3.3

Let $F : K \rightarrow \mathbb{R}$ be convex. Then, F is continuous on the interior of K .

Proof: Let $x_0 \in \text{int}(K)$ and consider $r > 0$ such that $B(x_0, r) \subset K$. Without loss of generality, we assume $x_0 = 0$ (otherwise, replace the function F by its translation $G(x) = F(x) - F(x_0)$).

Convexity will allow to bound the difference $F(y) - F(0)$ with the values of F on the sphere $\partial B(0, r)$. However, without continuity, the function F need not be bounded on the compact set $\partial B(0, r)$, and hence we need some additional care.

Pick $d + 1$ linearly independent points $v_0, \dots, v_{d+1} \in \partial B(0, r)$, and consider the corresponding symplex

$$\Delta = \text{conv}(\{v_0, \dots, v_{d+1}\}) = \left\{ \sum_{i=1}^{d+1} t_i v_i \mid t_i \geq 0, \sum_i t_i = 1 \right\} \subset B(0, r). \quad (1.24)$$

Then, letting $M = \max_{i \in \llbracket 1, d+1 \rrbracket} F(v_i)$, the fact that F is convex yields that for any $x = \sum_{i=1}^{d+1} t_i v_i \in \Delta$ it holds

$$F(x) \leq \sum_{i=1}^{d+1} t_i F(v_i) \leq M. \quad (1.25)$$

In particular, we can fix a radius $r' < r$ such that $B(0, r') \subset \Delta$ where F is bounded.

We now proceed to bound the difference $F(x) - F(0)$. Let $x \in U \subset B(0, r')$ and set $t = \|x\|/r'$. In particular, $t \in [0, 1]$ and the ray $\{sx \mid s \geq 0\}$ meets the sphere $\partial B(x_0, r')$ at the point

$$y = \frac{r'}{\|x\|}(x). \quad (1.26)$$

In particular, $x = (1-t)0 + ty$. By convexity and (1.25), we have

$$F(x) \leq (1-t)F(0) + tF(y) \leq (1-t)F(0) + tM \implies F(x) - F(0) \leq t(M - F(0)). \quad (1.27)$$

To derive a bound from below, we proceed similarly, considering

$$z = \frac{r'}{\|x\| - r'}x. \quad (1.28)$$

Indeed, we then have $0 = (1-t)x + tx$, where $t = \|x\|/r'$ as above. Then, convexity and the fact that $z \in B(0, r')$ yield

$$F(0) \leq (1-t)F(x) + tM \implies F(x) - F(0) \geq -\frac{t}{1-t}(M - F(0)). \quad (1.29)$$

Combining (1.27) and (1.29), we obtain

$$-\frac{t}{1-t}(M - F(0)) \leq F(x) - F(0) \leq t(M - F(0)), \quad t = \frac{\|x\|}{r'} \quad (1.30)$$

Since x was arbitrary in $B(0, r')$ we can take the limit as $x \rightarrow 0$, which implies $t \rightarrow 0$ and thus that

$$\lim_{x \rightarrow 0} |F(x) - F(0)| = 0, \quad (1.31)$$

concluding the proof. ■

The following result is at the core of the relation between optimisation and convexity.

Theorem 1.3.1

Let $F : \mathbb{R}^d \rightarrow \mathbb{R} \cup \{+\infty\}$ be a convex extended function. Then,

- Any local minimum of F is global.
- The set of minima of F is convex.
- If F is strictly convex and admits a minimum, this minimum is unique.
- If F is real-valued and strongly convex, then it has a unique minimum.

Proof: Assume that x^* is a local minimum, i.e., there exists $r > 0$ such that $F(x^*) \leq F(x)$ for any $x \in B(0, r)$. Let $y \in \mathbb{R}^d$ and consider a point on the ray starting at x^* and passing through y :

$$z = x^* + s(y - x^*) = (1-s)x^* + sy \quad s \geq 0. \quad (1.32)$$

Taking $s < \min\{1, r'/\|x^* - y\|\}$ we have that $z \in B(0, r)$. Hence, by local minimality of x^* and convexity of F we have

$$F(x^*) \leq F(z) \leq (1-s)F(x^*) + sF(y) \implies F(x^*) \leq F(y). \quad (1.33)$$

This concludes the proof of the first point.

Assume now that x_1, x_2 are minima for F . This clearly implies that $F(x_1) = F(x_2) =: m$, and thus, by convexity of F , for any $t \in [0, 1]$ we have

$$m \leq F(tx_1 + (1-t)x_2) \leq tF(x_1) + (1-t)F(x_2) = m \implies F(tx_1 + (1-t)x_2) = m. \quad (1.34)$$

This implies that $tx_1 + (1-t)x_2$ is a minimum for any $t \in [0, 1]$, thus proving the second point.

The same argument as above in the case of a strictly convex function yields to

$$m \leq F(tx_1 + (1-t)x_2) < m \quad \text{if } x_1 \neq x_2. \quad (1.35)$$

This implies immediately that the minimum is unique.

Assume, finally, that F is strongly convex. Since it is strictly convex, we just need to prove the existence of a minimum. By Proposition 1.3.3 we have that F is continuous, and thus it suffices to prove its coercivity: $F(x) \rightarrow +\infty$ if $\|x\| \rightarrow +\infty$.

We provide a proof of this fact in the case where F is differentiable (the general case can be obtained similarly using Proposition 1.4.2, proven later on). In this case, by Proposition 1.3.2 we have that

$$F(y) \geq F(0) + \langle \nabla F(0), y \rangle + \frac{\gamma}{2} \|y\|_2^2 \quad \forall y \in \mathbb{R}^d. \quad (1.36)$$

Since $\langle \nabla F(0), y \rangle \leq \|y\|_2$, the quadratic term on the right-hand side of the above equation, implies that the limit as $\|y\|_2 \rightarrow +\infty$ is $+\infty$. ■

Remark: Strict convexity is not enough to ensure the existence of a minimum. Consider, for example, $F(x) = e^x$.

1.4 Convex conjugate and sub-differential

Definition 1.4.1

The convex conjugate (of Fenchel dual) of an extended function $F : \mathbb{R}^d \rightarrow \mathbb{R} \cup \{+\infty\}$ is the function $F^* : \mathbb{R}^d \rightarrow \mathbb{R} \cup \{+\infty\}$ defined by

$$F^*(y) = \sup_{x \in \mathbb{R}^d} [\langle x, y \rangle - F(x)]. \quad (1.37)$$

Recall the following.

Definition 1.4.2

A function $F : \mathbb{R}^d \rightarrow \mathbb{R}$ is *lower semicontinuous* (l.s.c.) if

$$\liminf_{x \rightarrow x_0} F(x) \geq F(x_0), \quad \forall x_0 \in \mathbb{R}^d. \quad (1.38)$$

Equivalently, F is l.s.c. if its epigraph is closed.

Example 1.4.1

- Every continuous function is lower semicontinuous.
- For any set $\Omega \subset \mathbb{R}^d$, the $0 - \infty$ characteristic function

$$\chi_K = \begin{cases} 0 & \text{if } x \in \Omega, \\ +\infty & \text{otherwise,} \end{cases} \quad (1.39)$$

is lower semicontinuous, but not continuous.

Proposition 1.4.1

Let $F : \mathbb{R}^d \rightarrow \mathbb{R} \cup \{+\infty\}$. Then,

1. The convex conjugate F^* is a lower semicontinuous convex function.
2. We have the Fenchel (or Young, or Fenchel-Young) inequality

$$\langle x, y \rangle \leq F(x) + F^*(y) \quad (1.40)$$

Proof: For any $y_1, y_2 \in \mathbb{R}^d$ and $t \in [0, 1]$ we have

$$\langle x, ty_1 + (1-t)y_2 \rangle - F(x) = t(\langle x, y_1 \rangle - F(x)) + (1-t)(\langle x, y_2 \rangle - F(x)). \quad (1.41)$$

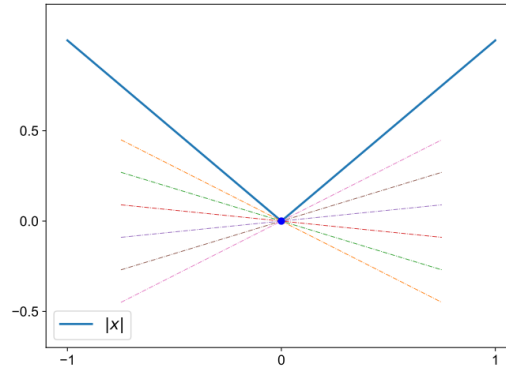


Figure 1.5: Visualization of the subgradients of $F(x) = |x|$ at $x = 0$. Image from [this website](#).

Taking the supremum for $x \in \mathbb{R}^d$ of the above, and recalling that $\sup(g(x) + h(x)) \leq \sup g(x) + \sup h(x)$ proves convexity of F^* .

Lower semicontinuity of F^* follows since it is the supremum for $x \in \mathbb{R}^d$ of $g_x(y) := \langle x, y \rangle - F(x)$, which is affine and in particular lower semicontinuous. Indeed, the supremum of a family of l.s.c. functions is l.s.c..

The second point (Fenchel inequality) is a direct consequence of the definition of F^* . ■

Example 1.4.2

- Let $F(x) = \frac{1}{2}\|x\|_2^2$. Then, $F^*(y) = \frac{1}{2}\|y\|_2^2 = F(y)$. This is the only function with this property.
- Let $F = \chi_K$ be the $0 - \infty$ characteristic function of a convex set $K \subset \mathbb{R}^d$ defined in (1.39). Then,

$$F^*(y) = \sup_{x \in K} \langle x, y \rangle. \quad (1.42)$$

Definition 1.4.3

The *subdifferential* of a convex extended function $F : \mathbb{R}^d \rightarrow \mathbb{R} \cup \{+\infty\}$ at $x \in \mathbb{R}^d$ is the set

$$\partial F(x) = \{v \in \mathbb{R}^d \mid F(y) \geq F(x) + \langle v, y - x \rangle, \quad \forall y \in \mathbb{R}^d\}. \quad (1.43)$$

A vector $v \in \partial F(x)$ is called a *subgradient* for F at x .

Example 1.4.3

Consider $F(x) = |x|$. Then,

$$\partial F(x) = \begin{cases} \{\text{sgn}(x)\} & \text{if } x \neq 0, \\ [-1, 1] & \text{if } x = 0. \end{cases} \quad (1.44)$$

Here, $\text{sgn}(x) = x/|x|$ is the sign function. See Figure 1.5.

Theorem 1.4.1

Let $F : \mathbb{R}^d \rightarrow \mathbb{R} \cup \{+\infty\}$ be a convex function. Then, $x \in \mathbb{R}^d$ is a minimum for F if and only if $0 \in \partial F(x)$

Proof: The fact that x is a minimum means that $F(x) \leq F(y)$ for any $y \in \mathbb{R}^d$, which is the definition of $0 \in \partial F(x)$. ■

We have the following.

Proposition 1.4.2

Let $F : \mathbb{R}^d \rightarrow \mathbb{R} \cup \{+\infty\}$ be a convex function. Then,

- For any $x \in \mathbb{R}^d$ the subdifferential $\partial F(x)$ is non-empty.
- It holds that

$$\partial F(x) = \{v \in \mathbb{R}^d \mid F^*(v) + F(x) = \langle x, v \rangle\}. \quad (1.45)$$

- If F is differentiable at $x \in \mathbb{R}^d$, then $\partial F(x) = \{\nabla F(x)\}$.

Proof: The first part of the theorem is a consequence of the Supporting Hyperplane Theorem (see Corollary 1.1.2) and Proposition 1.3.1. Indeed, the latter implies that the epigraph $\text{epi}(F)$ is convex and hence, by the former, any of its boundary point admits a supporting hyperplane. Using the fact that $\partial \text{epi}(F) = \{(x, F(x)) \mid x \in \mathbb{R}^d\}$ allows to conclude.

To prove the second statement, observe that $v \in \partial F(x)$ is equivalent to

$$\langle y, v \rangle - F(y) \leq \langle x, v \rangle - F(x), \quad \forall y \in \mathbb{R}^d. \quad (1.46)$$

Taking the sup for $y \in \mathbb{R}^d$ yields that $F^*(v) \leq \langle x, v \rangle - F(x)$. The opposite inequality follows from Fenchel inequality (see Proposition 1.4.1).

Concerning the proof of the last statement, the fact that $\nabla F(x) \in \partial F(x)$ follows from the characterisation of convexity for differentiable functions given in Proposition 1.3.2. To prove the opposite implication, let $v \in \partial F(x)$ and observe that by definition of subgradient the directional derivative $\partial_h F(x)$ of f in the direction $h \in \mathbb{R}^d$ at x satisfies

$$\partial_h F(x) = \lim_{t \rightarrow 0} \frac{F(x + th) - F(x)}{t} \geq \langle v, h \rangle. \quad (1.47)$$

Since we know that $\partial_h F(x) = \langle \nabla F(x), h \rangle$, we have that

$$\langle \nabla F(x) - v, h \rangle \geq 0, \quad \forall h \in \mathbb{R}^d. \quad (1.48)$$

But this implies that $\nabla F(x) = v$, concluding the proof. ■

Thanks to the previous result, we are in a position to prove the following property of the convex biconjugate.

Theorem 1.4.2 Fenchel-Moreau Theorem

The biconjugate F^{**} is the largest convex lower semicontinuous function satisfying $F^{**}(x) \leq F(x)$ for any $x \in \mathbb{R}^d$. In particular, $F^{**} = F$ if F is convex and proper.

Proof: We have that $-F^*(y) = \inf_{x \in \mathbb{R}^d} (F(x) - \langle x, y \rangle)$, which implies that for any $y, z \in \mathbb{R}^d$ it holds

$$\langle z, y \rangle - F^*(y) \leq \langle z - x, y \rangle + F(x), \quad \forall x \in \mathbb{R}^d. \quad (1.49)$$

In particular, considering $z = x$ we have

$$F^{**}(x) = \sup_{y \in \mathbb{R}^d} (\langle x, y \rangle - F^*(y)) \leq F(x), \quad (1.50)$$

proving the first part of the statement.

Since F^{**} is convex and l.s.c. by Proposition 1.4.1, in order to complete the proof it suffices to show that if F is convex, then

$$F^{**}(x) \geq F(x), \quad \forall x \in \mathbb{R}^d. \quad (1.51)$$

Let $v \in \partial F(x)$, which exists thanks to Proposition 1.4.2. For such a v , using the characterisation of the subdifferential in Proposition 1.4.2, we have

$$F^*(v) = \langle x, v \rangle - F(x), \quad (1.52)$$

so that $F^{**}(z) \geq \langle v, z - x \rangle + F(x)$ for any $z \in \mathbb{R}^d$. Picking $z = x$ allows to conclude. ■

Proposition 1.4.3

Let $F : \mathbb{R}^d \rightarrow \mathbb{R} \cup \{+\infty\}$ be a convex function and $x, y \in \mathbb{R}^d$. Then, the following are equivalent:

- i. $y \in \partial F(x)$.
- ii. $F(x) + F^*(y) = \langle x, y \rangle$.

If, additionally, F is l.s.c., then the above are also equivalent to

- iii. $x \in \partial F^*(y)$.

Proof: To show that *i* is equivalent to *ii*, we just need to show that $y \in \partial F(x)$ is equivalent to

$$F(x) + F^*(y) \leq \langle x, y \rangle. \quad (1.53)$$

Indeed, the opposite inequality is always true due to Fenchel's inequality (see Proposition 1.4.1).

Observe that the fact that $y \in \partial F(x)$ means that

$$\langle x, y \rangle F(x) \geq \langle z, y \rangle F(z), \quad \forall z \in \mathbb{R}^d. \quad (1.54)$$

That is, the function $z \mapsto \langle z, y \rangle F(z)$ attains its maximum at $z = x$. But, by definition of F^* , this is equivalent to (1.53), thus proving that *i* is equivalent to *ii*.

To complete the proof, observe that by Theorem 1.4.2 the lower semicontinuity of F yield that $F^{**} = F$, so that *ii* is equivalent to $F^{**}(x) + F^*(y) = \langle x, y \rangle$. Using the fact that $i \iff ii$ with F replaced by F^* completes the proof. ■

Chapter 2

Optimization problems

2.1 Convex optimization problems

Definition 2.1.1

An optimization problem is a minimization problem of the form

$$\min_{x \in \mathbb{R}^d} F_0(x) \quad \text{subject to} \quad Ax = y \quad \text{and} \quad F_j(x) \leq 0, \quad j \in \llbracket 1, M \rrbracket. \quad (\text{OP})$$

Here,

1. $F_0 : \mathbb{R}^d \rightarrow \mathbb{R} \cup \{+\infty\}$ is the *objective function*;
2. $F_1, \dots, F_M : \mathbb{R}^d \rightarrow \mathbb{R} \cup \{+\infty\}$ are the *constraining functions*;
3. $A \in \mathbb{R}^{m \times n}$ and $y \in \mathbb{R}^m$ provide the *equality constraints*;

The optimization problem is *convex* (resp. *linear*) if F_0, \dots, F_M are convex (resp. linear) functions.

Definition 2.1.2

Consider an optimization problem (OP). Then,

- The set $\Phi \subset \mathbb{R}^d$ of points $x \in \mathbb{R}^d$ satisfying the constraints is the set of *feasible points*. That is,

$$\Phi = \{x \in \mathbb{R}^d \mid Ax = y, \quad F_j(x) \leq 0 \quad \forall j \in \llbracket 1, M \rrbracket\}. \quad (2.1)$$

In particular, Φ is convex if (OP) is convex.

- Problem (OP) is *feasible* if it admits at least a feasible point (i.e., $\Phi \neq \emptyset$).
- The *optimal value* is $p^\star = \min_{x \in \Phi} F_0(x)$.
- A *minimizer* is a feasible point x^\star such that $F_0(x^\star) \leq F_0(x)$ for all feasible $x \in \Phi$. That is, $F_0(x^\star) = p^\star$.

Observe that the constrained optimization problem (OP) is equivalent to the unconstrained optimization problem

$$\min_{x \in \mathbb{R}^d} F_0(x) + \chi_\Phi, \quad (2.2)$$

where χ_Φ is the $0 - \infty$ characteristic function defined in (1.39).

Let us introduce the notation

$$\mathbb{R}^M = \{v \in \mathbb{R}^M \mid v_j \geq 0 \quad \forall j \in \llbracket 1, M \rrbracket\}. \quad (2.3)$$

Definition 2.1.3 Lagrange and Lagrange dual functions

The *Lagrange function* of the optimization problem (OP) is the function $F : \mathbb{R}^d \times \mathbb{R}^m \times \mathbb{R}_+^M \rightarrow \mathbb{R} \cup \{+\infty\}$ defined by

$$L(x, \xi, \nu) = F_0(x) + \langle \xi, Ax - y \rangle + \sum_{j=1}^m \nu_j F_j(x). \quad (2.4)$$

The *Lagrange dual function* is the function $H : \mathbb{R}^m \times \mathbb{R}_+^M \rightarrow \mathbb{R} \cup \{-\infty\} \cup \{+\infty\}$, defined by

$$H(\xi, \nu) = \inf_{x \in \mathbb{R}^d} L(x, \xi, \nu). \quad (2.5)$$

Proposition 2.1.1

The dual function is always concave. Moreover, if x^* is a minimizer of (OP), we have

$$H(\xi, \nu) \leq F(x^*), \quad \forall \xi \in \mathbb{R}^m, \nu \in \mathbb{R}_+^M. \quad (2.6)$$

Proof: Observe that $-H$ is the supremum w.r.t. $x \in \mathbb{R}^d$ of the functions $g_x(\xi, \nu) = -L(x, \xi, \nu)$. The function g_x is affine, and thus convex. Hence, $-H$ is the pointwise supremum of the family $\{g_x\}_{x \in \mathbb{R}^d}$ of convex function. It is immediate to check that it is convex, and thus that H is concave.

On the other hand, for any feasible point $x \in \Phi$, since $\nu_j \geq 0$ for any $j \in \llbracket 1, M \rrbracket$, we have

$$\langle \xi, Ax - y \rangle + \sum_{j=1}^m \nu_j F_j(x) \leq 0. \quad (2.7)$$

Then, $L(x, \xi, \nu) \leq F_0(x) \leq F_0(x^*)$ and, as a consequence,

$$H(\xi, \nu) \leq \inf_{x \in \Phi} L(x, \xi, \nu) \leq F_0(x^*). \quad (2.8)$$

This completes the proof of the statement. ■

The previous result suggests to introduce the following.

Definition 2.1.4 Primal and dual problem

The *dual problem* to (OP), which is called the *primal problem*, is the optimization problem

$$\max_{\xi \in \mathbb{R}^m, \nu \in \mathbb{R}_+^M} H(\xi, \nu) \quad \text{subject to} \quad \nu_j \geq 0 \quad \forall j \in \llbracket 1, M \rrbracket. \quad (\text{DP})$$

- A pair $(\xi, \nu) \in \mathbb{R}^m \times \mathbb{R}_+^M$ is called *dual feasible*.
- The *dual optimal value* is the solution d^* of (DP).
- A *dual optimal* or *optimal Lagrange multiplier* is a feasible maximizer $(\xi^*, \nu^*) \in \mathbb{R}^m \times \mathbb{R}_+^M$.
- A *primal-dual optimal* is a triple (x^*, ξ^*, ν^*) where x^* is a minimizer for (OP) and (ξ^*, ν^*) is a dual optimal.

Definition 2.1.5 Duality

The primal-dual problems always satisfy *weak duality*, that is $d^* \leq p^*$ where d^* is the dual optimal value and p^* is the primal optimal value.

We say that the problems enjoy *strong duality* if it holds

$$p^* = d^*. \quad (2.9)$$

The above shows the interest of the dual problem: when strong duality holds, in order to solve the minimization problem (OP) it suffices to solve the dual problem (DP).

The following is the most used criterion for strong duality.

Theorem 2.1.1 Slater's constraint quantification

Assume that F_0, \dots, F_M are convex functions with domain $\text{dom}(F_i) = \mathbb{R}^d$ for $i \in \llbracket 1, M \rrbracket$. Then, strong duality holds if there exists $x \in \Phi \subset \mathbb{R}^d$ such that $F_j(x) < 0$ for any $j \in \llbracket 1, M \rrbracket$. In particular, strong duality always holds for feasible optimization problems with no inequality constraints.

If, moreover, F_0, \dots, F_M are lower semicontinuous, then the existence of a primal-dual optimal is guaranteed.

For a proof of the above result, we refer to [1, Section 5.3.2].

Example 2.1.1 (ℓ_1 -minimization problem)

Consider the optimization problem

$$\min_{x \in \mathbb{R}^d} \|x\|_1 \quad \text{subject to} \quad Ax = y, \quad (2.10)$$

for some $A \in \mathbb{R}^{m \times d}$ and $y \in \mathbb{R}^m$.

The Lagrange function is independent of v , since there are no inequality constraints, and is

$$L(x, \xi) = \|x\|_1 + \langle \xi, Ax - y \rangle. \quad (2.11)$$

We have that the dual Lagrange function is

$$H(\xi) = \begin{cases} -\langle \xi, y \rangle & \text{if } \|A^\top \xi\|_\infty \leq 1, \\ -\infty & \text{otherwise.} \end{cases} \quad (2.12)$$

Indeed, it holds

$$H(\xi) = \inf_{x \in \mathbb{R}^d} [\|x\|_1 + \langle A^\top \xi, x \rangle - \langle \xi, y \rangle] \quad (2.13)$$

If $\|A^\top \xi\|_\infty \leq 1$ then $\langle A^\top \xi, x \rangle \geq -\|x\|_1$ and thus the infimum is attained for $x = 0$, yielding $H(\xi) = -\langle \xi, y \rangle$. On the other hand, for $\|A^\top \xi\|_\infty > 1$ let $i \in \llbracket 1, m \rrbracket$ be the index such that $|(A^\top \xi)_i| = \|A^\top \xi\|_\infty$ and consider $x = -\text{sgn}((A^\top \xi)_i)e_i$, so that $\langle A^\top \xi, x \rangle = -\|A^\top \xi\|_\infty$ and $\|x\|_1 = 1$. Thus, for any $\lambda > 0$,

$$H(\xi) \leq \lambda [1 - \|A^\top \xi\|_\infty] - \langle \xi, y \rangle \xrightarrow{\lambda \rightarrow +\infty} -\infty. \quad (2.14)$$

Hence, the dual program is given by

$$\max_{\xi \in \mathbb{R}^m} (-\langle \xi, y \rangle) \quad \text{subject to} \quad \|A^\top \xi\|_\infty \leq 1. \quad (2.15)$$

By Theorem 2.1.1 strong optimization holds for this primal-dual problems, provided the primal problem be feasible.

Geometric interpretation

Let us follow [1, Section 5.3] and present a geometric interpretation of the previous discussion. Assume that there are no equality constraints and a single inequality constraint, and define

$$\mathcal{G} = \{(F_1(x), F_0(x)) \mid x \in \mathbb{R}^d\}. \quad (2.16)$$

By construction, the problem is feasible if and only if \mathcal{G} intersects the left-half plane. Furthermore, we have

$$p^\star = \min\{t \mid (u, t) \in \mathcal{G}, u \leq 0\}. \quad (2.17)$$

Since $L(x, v) = (v, 1)^\top (F_1(x), F_0(x))$, we also have

$$H(v) = \inf\{(v, 1)^\top (u, t) \mid (u, t) \in \mathcal{G}\}. \quad (2.18)$$

Hence, if this infimum is finite, the inequality $(v, 1)^\top (u, t) \geq H(v)$ defines a supporting hyperplane for \mathcal{G} .

If the problem is convex, then \mathcal{G} is convex and under Slater's condition its interior intersects the left-hand plane. This insures that strong duality holds.

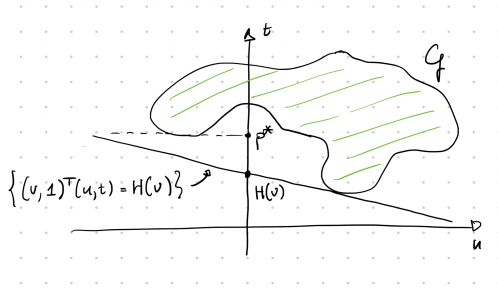


Figure 2.1: Geometric interpretation. The value of the dual function $H(v)$ identifies a supporting hyperplane for the set \mathcal{G} .

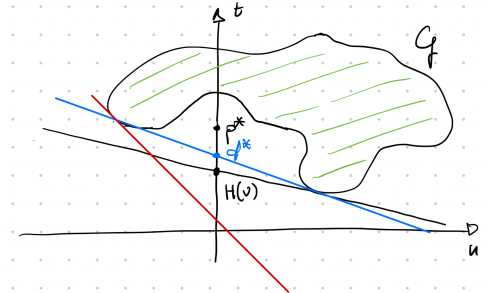


Figure 2.2: Geometric interpretation. Solving the dual problem yields the blue hyperplane. In this case $p^* > d^*$ and strong duality does not hold.

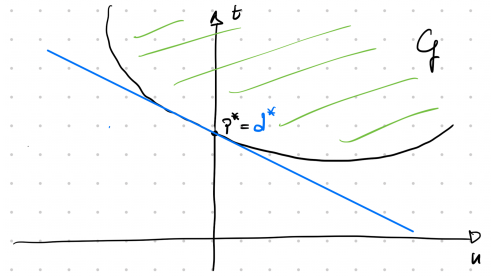


Figure 2.3: Geometric interpretation of Slater's condition. When the set \mathcal{G} is convex and has interior that intersects the left-hand plane, the best supporting hyperplane yields the optimal value p^* .

2.2 Conic optimization problems

Definition 2.2.1

A conic optimization problem is a minimization problem of the form

$$\min_{x \in \mathbb{R}^d} F_0(x) \quad \text{subject to} \quad x \in K \quad \text{and} \quad F_j(x) \leq 0, \quad j \in \llbracket 1, M \rrbracket. \quad (\text{COP})$$

Here, $F_0, \dots, F_M : \mathbb{R}^d \rightarrow \mathbb{R} \cup \{+\infty\}$ are convex functions and $K \subset \mathbb{R}^d$ is a convex cone.

Also conic optimization problems have their duality theory.

Definition 2.2.2 Duality for conic optimization problems

The *Lagrange function* of the optimization problem (COP) is the function $F : \mathbb{R}^d \times \mathbb{R}^m \times \mathbb{R}_+^M \rightarrow \mathbb{R} \cup \{+\infty\}$ defined by

$$L(x, \xi, v) = F_0(x) - \langle \xi, x \rangle + \sum_{j=1}^m v_j F_j(x). \quad (2.19)$$

The *Lagrange dual function* is the function $H : \mathbb{R}^m \times \mathbb{R}_+^M \rightarrow \mathbb{R} \cup \{-\infty\} \cup \{+\infty\}$, defined by

$$H(\xi, v) = \inf_{x \in \mathbb{R}^d} L(x, \xi, v). \quad (2.20)$$

The dual problem associated with (COP) is then

$$\max_{\xi \in \mathbb{R}^m, v \in \mathbb{R}_+^M} H(\xi, v) \quad \text{subject to} \quad \xi \in K^*, v \in \mathbb{R}_+^M. \quad (2.21)$$

Here, K^* is the dual cone of K (see Definition 1.2.3)

The duality theory is set up in order to have weak duality.

Proposition 2.2.1

The dual function is always concave. Moreover, if x^* is a minimizer of (COP), we have

$$H(\xi, v) \leq F(x^*), \quad \forall \xi \in \mathbb{R}^m, v \in \mathbb{R}_+^M. \quad (2.22)$$

The proof of this result can be done as for Proposition 2.1.1, taking into account the definition of dual cone.

Similar conditions as in Slater's constraint qualification (Theorem 2.1.1) ensure strong duality for conic problems; for instance, if there exists a point in the interior of K such that all inequality constraints hold strictly, see e.g., [1, Section 5.9].

Example 2.2.1

For a convex cone $K \subset \mathbb{R}^d$ and a vector $v \in \mathbb{R}^d$, consider the conic optimization problem

$$\min_{x \in \mathbb{R}^d} \langle x, v \rangle \quad \text{subject to} \quad x \in K, \|x\|_2^2 \leq 1. \quad (2.23)$$

The Lagrange function is given by

$$L(x, \xi, v) = \langle x, v \rangle - \langle \xi, x \rangle + v(\|x\|_2^2 - 1), \quad \xi \in K^*, v \geq 0. \quad (2.24)$$

Minimizing the above w.r.t. x one immediately obtains

$$H(\xi, v) = -v - \frac{1}{4v} \|\xi - v\|_2^2, \quad \xi \in K^*, v \geq 0. \quad (2.25)$$

For fixed ξ it is easy to maximize $H(\xi, v)$ w.r.t. $v \geq 0$, yielding $v = \|\xi - v\|_2^2/2$. Thus, the dual problem simplifies to

$$\max_{\xi \in \mathbb{R}^m} \left(-\frac{\|\xi - v\|_2^2}{2} \right) \quad \text{subject to} \quad \xi \in K^*. \quad (2.26)$$

That is, the optimal value of the dual problem is the optimal value of the above, and any dual optimal (ξ^*, v^*) is such that $v^* = \|\xi^* - v\|_2^2/2$ and ξ^* is optimal for the above.

Observe, that minimizers for (2.26) are the orthogonal projections of v on the dual cone K^* .

2.3 Saddle-point interpretation and penalty method

Theorem 2.3.1 Saddle-point property

Consider an optimisation problem (convex or conical). Then, the primal-dual optimal values p^* and d^* satisfy

$$= F_0(x) p^* = \inf_{x \in \mathbb{R}^d} \sup_{\xi \in \mathbb{R}^m, v \in \mathbb{R}_+^M} L(x, \xi, v) \quad \text{and} \quad d^* = \sup_{\xi \in \mathbb{R}^m, v \in \mathbb{R}_+^M} \inf_{x \in \mathbb{R}^d} L(x, \xi, v). \quad (2.27)$$

In particular,

- Strong duality is equivalent to the fact that

$$\inf_{x \in \mathbb{R}^d} \sup_{\xi \in \mathbb{R}^m, v \in \mathbb{R}_+^M} L(x, \xi, v) = \sup_{\xi \in \mathbb{R}^m, v \in \mathbb{R}_+^M} \inf_{x \in \mathbb{R}^d} L(x, \xi, v). \quad (2.28)$$

- Primal-dual optimizer (x^*, ξ^*, v^*) are exactly the saddle points of L . That is,

$$L(x^*, \xi, v) \leq L(x^*, \xi^*, v^*) \leq L(x, \xi^*, v^*), \quad \forall x \in \mathbb{R}^d, (\xi, v) \in \mathbb{R}^m \times \mathbb{R}_+^M. \quad (2.29)$$

Proof: We consider a convex optimisation problem (the same considerations hold *mutas mutandis* for conical problems). The fact that d^* satisfies (2.27) is a direct consequence of the definition. On the other hand, we have

$$\sup_{\xi \in \mathbb{R}^m, v \in \mathbb{R}_+^M} L(x, \xi, v) = F_0(x) + \sup_{\xi \in \mathbb{R}^m} \langle \xi, Ax - y \rangle + \sup_{v_j \geq 0} \sum_{j=1}^M v_j F_j(x) = \begin{cases} F_0(x) & \text{if } Ax = y \text{ and } F_j(x) \leq 0 \forall j \in \llbracket 1, M \rrbracket, \\ +\infty & \text{otherwise.} \end{cases} \quad (2.30)$$

In other words, the above supremum is $+\infty$ if x is not feasible (i.e., $x \notin \Phi$). This shows that minimizing the above w.r.t. $x \in \mathbb{R}^d$ yields p^* . ■

As a consequence of the saddle-point property, we recover a classical method (penalty method or Tychonoff regularization), that allows to transform constrained problems in different but equivalent unconstrained problems that are typically easier to solve.

Given two parameters $\eta > 0$ and $\lambda \geq 0$, we consider the following two problems:

$$\min_{x \in \mathbb{R}^d} F_0(x) \quad \text{subject to} \quad F_1(x) \leq \eta, \quad (\text{PO}_2(\eta))$$

and

$$\min_{x \in \mathbb{R}^d} F_0(x) + \lambda F_1(x). \quad (\text{PO}_2(\lambda))$$

We have the following.

Theorem 2.3.2 Penalty method

Assume that F_0, F_1 are lower semicontinuous, satisfy the assumptions of Theorem 2.1.1, and that $F_1(x) \geq 0$ for all $x \in \mathbb{R}^d$. Then, for $x^* \in \mathbb{R}^d$ the following statements are equivalent:

- There exists $\eta \geq 0$ such that x^* is a minimizer of $(\text{PO}_2(\eta))$.
- There exists $\lambda \geq 0$ such that x^* is a minimizer of $(\text{PO}_2(\lambda))$.

Proof: Assume that x^* is a minimizer for $(\text{PO}_2(\eta))$, and recall that for this problem

$$L(x, v) = F_0(x) + v(F_1(x) - \eta), \quad x \in \mathbb{R}^d, v \geq 0. \quad (2.31)$$

By Theorem 2.1.1, we have that strong duality holds for $(\text{PO}_2(\eta))$ and that there exists a primal-dual optimal (x^*, v^*) . By the saddle-point property (Theorem 2.3.1) it holds that $L(x^*, v^*) \leq L(x, v^*)$ for any $x \in \mathbb{R}^d$. Since the constant term $-v^*\eta$ does not affect the minimization, this proves that x^* is a minimizer of $(\text{PO}_2(\lambda))$ with $\lambda = v^*$.

For the converse statement, assume now that x^* is a minimizer of $(\text{PO}_2(\lambda))$. Choose $\eta = F_1(x^*) \geq 0$, so that the dual function of problem $(\text{PO}_2(\eta))$ satisfies

$$H(\lambda) = \inf_{x \in \mathbb{R}^d} L(x, \lambda) = \inf_{x \in \mathbb{R}^d} [F_0(x) + \lambda F_1(x)] - \lambda F_1(x^*) = F_0(x^*). \quad (2.32)$$

Here, we used that x^* is a minimizer for $(\text{PO}_2(\lambda))$. Since weak duality implies that $H(\lambda) \leq F_0(x)$ for any feasible $x \in \mathbb{R}^d$, and x^* is feasible due to the choice of η , it follows that x^* is a minimizer of $(\text{PO}_2(\eta))$. ■

Remark: The non-negativity assumption on F_1 can be removed by replacing $F_1(x)$ in $(\text{PO}_2(\lambda))$ by $\min\{0, F_1(x)\}$.

Chapter 3

Numerical methods for (non)convex optimization

3.1 Gradient descent

We are concerned with the following unconstrained minimization problem

$$\min_{x \in \mathbb{R}^d} f(x), \quad (3.1)$$

where $f : \mathbb{R}^d \rightarrow \mathbb{R}$ is a sufficiently smooth (say C^1) function.

Since the gradient $\nabla f(x)$ encodes the direction of maximal growth of f at x , it is natural to expect that moving in the direction $-\nabla f(x)$ will lead to a minimum x^\star (3.1).

Definition 3.1.1 Gradient flow

Assume that $f \in C^1(\mathbb{R}^d)$. The associated gradient flow from $x_0 \in \mathbb{R}^d$ is ordinary differential equation:

$$\dot{x} = -\nabla f(x), \quad x(0) = x_0. \quad (3.2)$$

By Cauchy-Lipschitz theorem, (3.2) admits local solutions. In order for them to be global, we assume the following.

Assumption 3.1.1. The function $f \in C^1(\mathbb{R}^d)$ and, moreover, $\nabla f : \mathbb{R}^d \rightarrow \mathbb{R}^d$ is Lipschitz continuous with constant $L > 0$. That is,

$$\|\nabla f(x) - \nabla f(y)\|_2 \leq L\|x - y\|_2, \quad \forall x, y \in \mathbb{R}^d. \quad (3.3)$$

Observe that if $f \in C^2(\mathbb{R}^d)$, the above assumption is verified by assuming that $\text{Hess } f(x) \leq L\text{Id}$ in the sense of symmetric matrices (i.e., all eigenvalues of $\text{Hess } f(x)$ are bounded above by L).

Recall also that a function $f \in C^2(\mathbb{R}^d)$ that is strongly convex (i.e., there exists $\gamma > 0$ such that $\text{Hess } f(x) \geq \gamma/2$ for any $x \in \mathbb{R}^d$) always admits a unique minimizer (see Proposition 1.3.2 and Theorem 1.3.1).

Theorem 3.1.1

Assume that $f \in C^2(\mathbb{R}^d)$ is strongly convex function satisfying Assumption 3.1.1. Then, for any initial condition $x_0 \in \mathbb{R}^d$, the gradient flow (3.2) converges to the unique minimizer $x^\star = \arg \min_{x \in \mathbb{R}^d} f(x)$.

Proof: Since x^\star is unique, it is characterized by property $\nabla f(x^\star) = 0$. In particular, the statement is trivial if $x_0 = x^\star$. Otherwise, let $V(x) = \frac{1}{2}\|\nabla f(x)\|_2^2$ and observe that $\nabla V(x) = \text{Hess } f(x)\nabla f(x)$. Computing V along a solution $t \mapsto x(t)$ of (3.2) we have

$$\begin{aligned} \frac{d}{dt}V(x(t)) &= \nabla V(x(t))^\top \dot{x}(t) \\ &= \nabla f(x(t))^\top \text{Hess } f(x(t))\dot{x}(t) \\ &= -\nabla f(x(t))^\top \text{Hess } f(x(t))\nabla f(x(t)) \\ &\leq -\frac{\gamma}{2}\|\nabla f(x(t))\|_2^2 = -\gamma V(x(t)). \end{aligned} \quad (3.4)$$

Here, we used the fact that $\text{Hess } f(x) \geq \gamma/2$. By integration of the above, we then obtain that for any $t \geq 0$ it holds

$$V(x(t)) \leq V(x_0)e^{-\gamma t} \iff \|\nabla f(x(t))\|_2 \leq \|\nabla f(x_0)\|_2 e^{-\gamma t/2}. \quad (3.5)$$

Recall that $\nabla f(x^*) = 0$, this implies that

$$\lim_{t \rightarrow +\infty} \|\nabla f(x(t)) - \nabla f(x^*)\|_2 \leq \|\nabla f(x_0)\|_2 \lim_{t \rightarrow +\infty} e^{-\gamma t/2} = 0. \quad (3.6)$$

Let us now use the above to show that $x(t) \rightarrow x^*$ as $t \rightarrow +\infty$. Indeed, we have

$$\begin{aligned} \frac{d}{dt} \frac{1}{2} \|x(t) - x^*\|_2^2 &= \langle x(t) - x^*, \dot{x}(t) \rangle \\ &= -\langle x(t) - x^*, \nabla f(x(t)) \rangle \\ &= -\langle x(t) - x^*, \nabla f(x(t)) - \nabla f(x^*) \rangle. \end{aligned} \quad (3.7)$$

By Lemma 3.1.2, to be proven later, this implies

$$\frac{d}{dt} \frac{1}{2} \|x(t) - x^*\|_2^2 \leq -\frac{1}{L} \|\nabla f(x(t)) - \nabla f(x_0)\|_2^2 \leq 0. \quad (3.8)$$

Integrating the above, we obtain $\|x(t) - x^*\|_2 \leq \|x_0 - x^*\|_2$, which implies that $x(t) \in \bar{B}(x^*, \|x_0 - x^*\|_2)$ (i.e., the evolution $t \mapsto x(t)$ is uniformly bounded in time). By compactness, there exists a sequence of times $(t_n)_n \subset \mathbb{R}_+$ and a point x_∞ such that $x(t_n) \rightarrow x_\infty$. However, the fact that $f \in C^2(\mathbb{R}^d)$ implies that $\nabla f(x(t_n)) \rightarrow \nabla f(x_\infty)$, and thus (3.6) yields that $\nabla f(x_\infty) = \nabla f(x^*) = 0$. By existence and uniqueness of the minimizer of f , this shows that $x_\infty = x^*$. ■

Lemma 3.1.2 Co-coercivity

Let $f \in C^1(\mathbb{R}^d)$ be convex and such that ∇f is Lipschitz continuous with constant $L > 0$. Then, we have that

1. Quadratic upper bound (compare with Proposition 1.3.2):

$$f(y) \leq f(x) + \langle \nabla f(x), y - x \rangle + \frac{L}{2} \|y - x\|^2, \quad \forall x, y \in \mathbb{R}^d. \quad (3.9)$$

2. If x^* is a minimizer for f ,

$$\frac{1}{2L} \|\nabla f(y)\|_2^2 \leq f(y) - f(x^*) \leq \frac{1}{2} \|y - x^*\|_2^2, \quad \forall y \in \mathbb{R}^d. \quad (3.10)$$

3. Co-coercivity:

$$\|\nabla f(x) - \nabla f(y)\|_2^2 \leq L \langle x - y, \nabla f(x) - \nabla f(y) \rangle, \quad \forall x, y \in \mathbb{R}^d. \quad (3.11)$$

Proof: The quadratic upper bound is a direct consequence of (3.3) and the linear lower bound given by convexity (see Proposition 1.3.2).

To prove the second part of the statement, since $\nabla f(x^*) = 0$ the right-hand inequality follows from the quadratic lower bound (3.9) with $x = x^*$. On the other hand, still by (3.9) with $x = y$ and $y = z$ we obtain

$$\begin{aligned} f(x^*) &= \inf_z f(z) \\ &\leq \inf_z \left[f(y) + \langle \nabla f(y), z - y \rangle + \frac{L}{2} \|y - z\|^2 \right] \\ &\leq \inf_{\|v\|=1} \inf_{t \geq 0} \left[f(y) + t \langle \nabla f(y), v \rangle + \frac{Lt^2}{2} \right] \\ &= \inf_{\|v\|=1} \left[f(y) - \frac{1}{2L} (\langle \nabla f(y), v \rangle)^2 \right] \\ &= f(y) - \frac{1}{2L} \|\nabla f(y)\|_2^2. \end{aligned} \quad (3.12)$$

To conclude the proof, let us fix $x \in \mathbb{R}^d$ and consider the two functions

$$f_x(z) = f(z) - \langle \nabla f(x), z \rangle \quad \text{and} \quad f_y(z) = f(z) - \langle \nabla f(y), z \rangle. \quad (3.13)$$

It is immediate to check that $\nabla f_x(z) = \nabla f(z) - \nabla f(x)$ is Lipschitz continuous of constant L , and that f_x is convex. Since $z = x$ minimizes f_x by convexity, the left-hand inequality in (3.10) applied to f_x at $x^* = x$ shows that

$$f(y) - f(x) - \langle \nabla f(x), y - x \rangle = f_x(y) - f_x(x) \geq \frac{1}{2L} \|\nabla f_x(y)\|_2^2 = \frac{1}{2L} \|\nabla f(y) - \nabla f(x)\|_2^2. \quad (3.14)$$

The same reasoning applied to f_y , which is minimized by $z = y$, yields

$$f(x) - f(y) - \langle \nabla f(y), x - y \rangle \geq \frac{1}{2L} \|\nabla f(y) - \nabla f(x)\|_2^2. \quad (3.15)$$

Combining the two inequalities completes the proof. \blacksquare

A natural time-discretization of the gradient flow (3.2) is via the Explicit Euler scheme, which yields the gradient descent algorithm.

Definition 3.1.2 Gradient descent algorithm

The gradient descent algorithm for $f \in C^1(\mathbb{R}^d)$ starting at $x_0 \in \mathbb{R}^d$ with parameters $(\alpha_n)_n \subset \mathbb{R}_+$, is

$$x_{n+1} = x_n - \alpha_n \nabla f(x_n). \quad (3.16)$$

Here the parameters α_n are typically chosen adaptively with a line search. However, also a constant choice $\alpha = \alpha_n$ sufficiently small will suffice. Let us show now a result of convergence of the algorithm above.

Theorem 3.1.3

Let $f \in C^1(\mathbb{R}^d)$ be convex, coercive (i.e., $f(x) \rightarrow +\infty$ as $x \rightarrow +\infty$), and such that ∇f is Lipschitz continuous with constant $L > 0$, and admitting a unique minimizer x^* . Assume that

$$\sum_{n=0}^{+\infty} \alpha_n = +\infty \quad \text{and} \quad \alpha_n \leq \frac{1}{L}, \quad \forall n \in \mathbb{N}. \quad (3.17)$$

Then, the iterations of the algorithm (3.16) converge to x^* (i.e., $x_n \rightarrow x^*$ as $n \rightarrow +\infty$).

Proof: Fix $n \in \mathbb{N}$. To ease the notation, set $x = x_n$, $\alpha = \alpha_n$, and $x^+ = x_{n+1} = x - \alpha \nabla f(x)$. Then, By the quadratic upper bound of Lemma 3.1.2, we have

$$f(x_{n+1}) \leq f(x_n) + \langle \nabla f(x_n), x_{n+1} - x_n \rangle + \frac{L}{2} \|x_{n+1} - x_n\|_2^2 = f(x_n) - \alpha_n \left(1 - \frac{\alpha_n L}{2}\right) \|\nabla f(x_n)\|_2^2. \quad (3.18)$$

The above implies that

$$\sum_{n=0}^{N-1} \alpha_n \left(1 - \frac{\alpha_n L}{2}\right) \|\nabla f(x_n)\|_2^2 \leq \sum_{n=0}^{N-1} (f(x_n) - f(x_{n+1})) = f(x_0) - f(x_N) \leq f(x_0) - f(x^*). \quad (3.19)$$

Since the r.h.s. is independent of N and $1 - L\alpha_n/2 \geq 1/2$, this shows that

$$\sum_{n=0}^{N-1} \alpha_n \|\nabla f(x_n)\|_2^2 \leq \frac{1}{2} \sum_{n=0}^{N-1} \alpha_n \left(1 - \frac{\alpha_n L}{2}\right) \|\nabla f(x_n)\|_2^2 < +\infty. \quad (3.20)$$

Since $\sum_n \alpha_n = +\infty$ by assumption, one easily shows by contradiction that $\|\nabla f(x_n)\|_2 \rightarrow 0$ as $n \rightarrow +\infty$.

Observe that, by (3.18) and the assumption $\alpha_n \leq 1/L$, we deduce that $f(x_{n+1}) < f(x_n)$ for any $n \in \mathbb{N}$. In particular, by coercivity, there exists $R > 0$ such that $x_n \in \bar{B}(0, R)$ for any $n \in \mathbb{N}$, and thus the same argument used at the end of the proof of Theorem 3.1.1 shows that $\|\nabla f(x_n)\|_2^2$ implies convergence to the unique minimum. \blacksquare

Remark: The coercivity assumption can be relaxed to asking that the level set $\{x \mid f(x) \leq f(x_0)\}$ be bounded. Is it also possible to remove the assumption of uniqueness of the minimum, in which case we have that every cluster point of the iterates is a minimum.

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