Proof Script for WS2018/19 Convex Optimization*

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1 Convex Analysis

Theorem 1.1 (separation of convex sets)**.** *Let C_1, C_2 be nonempty convex subsets in $\mathbb{E}$.*

1. *Assume C_1 is closed and $C_2 = \{w\} \subset \mathbb{E} \backslash C_1$. Then $\exists v \in \mathbb{E},\ v \neq 0,\ \alpha \in \mathbb{R}$ s.t.*

$$\langle v, w \rangle > \alpha \geq \langle v, u \rangle, \quad \forall u \in C_1.$$

2. *Assume C_1 is open and $C_2 = \{w\} \subset \mathbb{E} \backslash C_1$. Then $\exists v \in \mathbb{E},\ v \neq 0,\ \alpha \in \mathbb{R}$ s.t.*

$$\langle v, w \rangle \geq \alpha \geq \langle v, u \rangle, \quad \forall u \in C_1.$$

3. *Assume $C_1 \cap C_2 = \emptyset$ and C_1 is open. Then $\exists v \in \mathbb{E},\ v \neq 0,\ \alpha \in \mathbb{R}$ s.t.*

$$\left\langle v, u^1 \right\rangle \geq \alpha \geq \left\langle v, u^2 \right\rangle, \quad \forall u^1 \in C_1,\ u^2 \in C_2.$$

4. *Assume $\emptyset \neq \operatorname{int} C_1 \subset \mathbb{E} \backslash C_2$. Then $\exists v \in \mathbb{E},\ v \neq 0,\ \alpha \in \mathbb{R}$ s.t.*

$$\left\langle v, u^1 \right\rangle \geq \alpha \geq \left\langle v, u^2 \right\rangle, \quad \forall u^1 \in C_1,\ u^2 \in C_2.$$

Proof. (1) Consider the projection of w onto C_1, i.e., set $u^* := \arg\min_{u \in C_1} \frac{1}{2}\|u - w\|^2$ or, equivalently via the variational inequality: $\langle u - u^*, u^* - w \rangle \geq 0\ \forall u \in C_1$. Now let $v := w - u^* \neq 0$. Then $\forall u \in C_1$, we have $\langle v, w \rangle = \langle w - u^*, w \rangle = \|w - u^*\|^2 + \langle w - u^*, u^* \rangle \geq \|w - u^*\|^2 + \langle w - u^*, u \rangle = \|v\|^2 + \langle v, u \rangle$. Set $\alpha := \sup\{\langle v, u \rangle : u \in C_1\}$. Note $\alpha < \infty$ since $\langle v, u \rangle \leq \langle v, u^* \rangle\ \forall u \in C$. Thus $\langle v, w \rangle > \alpha \geq \langle v, u \rangle\ \forall u \in C_1$.

(2) Since $\mathbb{E} \backslash C_1$ is closed, $\exists w^k \in \mathbb{E} \backslash \operatorname{cl} C_1$ s.t. $w^k \to w$. For each w^k, by (i), $\exists v^k \in \mathbb{E}$ with $\|v^k\| \equiv 1$ s.t. $\left\langle v^k, w^k \right\rangle \leq \left\langle v^k, u \right\rangle\ \forall u \in \operatorname{cl} C_1$. Hence $v^k \to v \in \mathbb{E}$ along a subsequence s.t. $\|v\| = 1$ and $\alpha := \langle v, w \rangle \leq \langle v, u \rangle\ \forall u \in C_1 \subset \operatorname{cl} C_1$.

(3) Let $C := C_2 - C_1 = \{u^2 - u^1 : u^1 \in C_1,\ u^2 \in C_2\}$. Note that C is a convex, open set, and $0 \notin C$. By (2), $\exists v \in \mathbb{E}$ with $\|v\| = 1$ s.t. $\left\langle -v, u^2 - u^1 \right\rangle \geq \langle -v, 0 \rangle = 0$ or, equivalently, $\left\langle v, u^1 \right\rangle \geq \left\langle v, u^2 \right\rangle\ \forall u^1 \in C_1,\ u^2 \in C_2$. Set $\alpha := \sup\{\left\langle v, u^2 \right\rangle : u^2 \in C_2\}$, then we conclude that $\left\langle v, u^1 \right\rangle \geq \alpha \geq \left\langle v, u^2 \right\rangle\ \forall u^1 \in C_1,\ u^2 \in C_2$.

(4) By applying (3) to $\operatorname{int} C_1$ and C_2, we have $\left\langle v, u^1 \right\rangle \geq \alpha \geq \left\langle v, u^2 \right\rangle\ \forall u^1 \in \operatorname{int} C_1,\ u^2 \in C_2$. The inequality remains true for all $u_1 \in C_1$. $\square$

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Theorem 1.2. *A proper convex function* $J : \mathbb{E} \to \overline{\mathbb{R}}$ *is locally Lipschitz at any* $u \in \operatorname{rint} \operatorname{dom} J$.

Proof. Throughout the proof, we consider $J : \operatorname{aff} \operatorname{dom} J \to \overline{\mathbb{R}}$.

(i) Claim: If $M = \sup\{J(v) : v \in B_\epsilon(u)\} < \infty$ with $\epsilon > 0$, then J is locally Lipschitz at u.

First, by convexity of J we have $\forall v \in B_\epsilon(u) : J(v) \geq 2J(u) - J(2u - v) \geq 2J(u) - M$. Thus, $\sup\{|J(v)| : v \in B_\epsilon(u)\} \leq M + 2|J(u)|$.

Next, we show J is Lipschitz on $B_{\epsilon/2}(u)$. Let $v, w \in B_{\epsilon/2}(u)$ be given. Take $z \in B_\epsilon(u)$ s.t. $w = (1 - t)v + tz$ for some $t \in [0, 1]$ and $\|z - v\| \geq \epsilon/2$. By convexity, $J(w) - J(v) \leq t(J(z) - J(v)) \leq 2t(M - J(u))$. Since $t(z - v) = w - v$, we have $t = \|w - v\|/\|z - v\| \leq 2\|w - v\|/\epsilon$ and $J(w) - J(v) \leq (4(M - J(u))/\epsilon)\|w - v\|$. Analogously, one can show $J(v) - J(w) \leq (4(M - J(u))/\epsilon)\|w - v\|$. Hence, J is Lipschitz on $B_{\epsilon/2}(u)$ with modulus $4(M - J(u))/\epsilon$.

(ii) Let $u \in \operatorname{rint} \operatorname{dom} J$ and $n = \dim(\operatorname{aff} \operatorname{dom} J)$. Then by Carathéodory's theorem, $\exists\{\alpha^i\}_{i=1}^{n+1} \subset (0, 1)$, $\{u^i\}_{i=1}^{n+1} \subset \operatorname{dom} J$ s.t. $u = \sum_{i=1}^{n+1} \alpha^i u^i$, $\sum_{i=1}^{n+1} \alpha^i = 1$, i.e., u belongs to the interior of the convex hull of $\{u^i\}_{i=1}^{n+1}$. Thus one can apply (i) to assert that J is locally Lipschitz at u. □

Theorem 1.3. *For any proper convex function* $J : \mathbb{E} \to \overline{\mathbb{R}}$*, if* $u^* \in \operatorname{dom} J$ *is a local minimizer of* J*, then it is also a global minimizer.*

Proof. By the definition of a local minimizer, $\exists \epsilon > 0$ s.t. $J(u^*) \leq J(u)\ \forall u \in B_\epsilon(u^*)$. For the sake of contradiction, assume $\exists \bar{u} \in \mathbb{E}$ s.t. $J(\bar{u}) < J(u^*)$. By convexity of J, we have $J(\alpha\bar{u} + (1 - \alpha)u^*) \leq J(u^*) - \alpha(J(u^*) - J(\bar{u})) < J(u^*)\ \forall \alpha \in (0, 1]$. This violates the local optimality of u^* as $\alpha \to 0^+$. □

Theorem 1.4. *Any proper function* $J : \mathbb{E} \to \overline{\mathbb{R}}$*, which is bounded from below, coercive, and lsc, has a (global) minimizer.*

Proof. Let $\{u^k\}$ be an infimizing sequence for J, i.e., $\lim_{k\to\infty} J(u^k) = \inf_{u\in\mathbb{E}} J(u) > -\infty$. Since $\{J(u^k)\}$ is uniformly bounded from above, by coercivity of J $\{u^k\}$ is uniformly bounded. By compactness, $u^k \to u^*$ along a subsequence. Since J is lsc, we have $J(u^*) \leq \liminf_{k\to\infty} J(u^k) = \inf_{u\in\mathbb{E}} J(u)$, which implies $J(u^*) = \inf_{u\in\mathbb{E}} J(u)$ or u^* is a minimizer of J. □

Theorem 1.5. *The minimizer of a strictly convex function* $J : \mathbb{E} \to \overline{\mathbb{R}}$ *is unique.*

Proof. Let $u, v \in \mathbb{E}$ be two (global) minimizers s.t. $u \neq v$ and $J(u) = J(v) = J^*$. By strict convexity of J, $J(\alpha u + (1 - \alpha)v) < \alpha J(u) + (1 - \alpha)J(v) = J^*$ for all $\alpha \in (0, 1)$, which contradicts the global optimality of u and v. □

Theorem 1.6. *Let* $J : \mathbb{E} \to \overline{\mathbb{R}}$ *be a convex function. Then for any* $u \in \operatorname{int} \operatorname{dom} J$*,* $\partial J(u)$ *is a nonempty, compact, and convex subset.*

Proof. (i) nonemptiness. Since $(u, J(u)) \notin \operatorname{int} \operatorname{epi} J$, by Theorem 1.1 we have $\exists(p, -\alpha) \in \mathbb{E} \times \mathbb{R}$ s.t. $(p, -\alpha) \neq (0, 0)$, $\alpha \geq 0$ by our choice, and $\langle(p, -\alpha), (u - v, J(u) - J(v))\rangle \geq 0\ \forall v \in \operatorname{dom} J$. In fact, we must have $\alpha > 0$ since otherwise $p = 0$. Thus, we conclude that $p/\alpha \in \partial J(u)$.

(ii) boundedness. By Theorem 1.2, J is locally Lipschitz at u with modulus L_u. Let $p \in \partial J(u)$ be fixed. For any $h \in (\operatorname{dom} J) - u$ whenever $\|h\|$ is sufficiently small, we have $\langle p, h\rangle \leq J(u + h) - J(u) \leq L_u\|h\|$. This holds true only if $\|p\| \leq L_u$, which implies boundedness of $\partial J(u)$.

(iii) closedness. Let $v \in \mathbb{E}$ be arbitrarily fixed and $p^k \to p^*$ where each $p^k \in \partial J(u)$. Then $\forall k : J(v) - J(u) \geq \langle p^k, v - u\rangle$. By continuity, $J(v) - J(u) \geq \langle p^*, v - u\rangle$ when passing $k \to \infty$. Since v can be arbitrary, we assert $p^* \in \partial J(u)$.

(iv) convexity. Let $v \in \mathbb{E}$ be arbitrarily fixed, and $p, q \in \partial J(u)$. Then we have

$$J(v) \geq J(u) + \langle p, v-u \rangle \,,$$
$$J(v) \geq J(u) + \langle q, v-u \rangle \,.$$

Hence, $\forall 0 \leq \alpha \leq 1 : J(v) \geq J(u) + \langle \alpha p + (1-\alpha)q, v-u \rangle$, i.e., $\alpha p + (1-\alpha) q \in \partial J(u)$. □

Theorem 1.7. *Let $J : \mathbb{E} \to \overline{\mathbb{R}}$ be a convex function. Then ∂J is a monotone operator, i.e. $\forall u^1, u^2 \in \operatorname{dom} J,\ p^1 \in \partial J(u^1),\ p^2 \in \partial J(u^2)$:*

$$\left\langle p^1 - p^2, u^1 - u^2 \right\rangle \geq 0.$$

Proof. By applying the definition of subdifferential at arbitrarily given $u^1, u^2 \in \operatorname{dom} J$, we have

$$J(u^2) \geq J(u^1) + \left\langle p^1, u^2 - u^1 \right\rangle ,$$
$$J(u^1) \geq J(u^2) + \left\langle p^2, u^1 - u^2 \right\rangle .$$

Adding the two inequalities yields $\left\langle p^1 - p^2, u^1 - u^2 \right\rangle \geq 0$. □

Theorem 1.8. *Let $J : \mathbb{E} \to \overline{\mathbb{R}}$ be a proper, convex, lsc function. Then ∂J is a closed set-valued map, i.e., $p^* \in \partial J(u^*)$ whenever*

$$\exists (u^k, p^k) \to (u^*, p^*) \in (\operatorname{dom} J) \times \mathbb{E} \ \text{ s.t. } p^k \in \partial J(u^k)\ \forall k.$$

Proof. Let $v \in \mathbb{E}$ be arbitrarily fixed. For each k, $p^k \in \partial J(u^k) \ \Rightarrow\ J(v) \geq J(u^k) + \left\langle p^k, v - u^k \right\rangle$. Passing $k \to \infty$, we have $\left\langle p^k, v - u^k \right\rangle \to \langle p^*, v - u^* \rangle$ and $J(u^*) \leq \liminf_{k\to\infty} J(u^k)$. Hence, $J(u^*) + \langle p^*, v - u^* \rangle \leq \liminf_{k\to\infty} \{J(u^k) + \left\langle p^k, v - u^k \right\rangle\} \leq J(v)$. Since v can be arbitrary, $p^* \in \partial J(u^*)$. □

Theorem 1.9. *Given any proper convex function $J : \mathbb{E} \to \overline{\mathbb{R}}$, the sufficient and necessary condition for u^* being a (global) minimizer for J is: $0 \in \partial J(u^*)$.*

Proof. (i) sufficiency. $0 \in \partial J(u^*) \ \Rightarrow\ J(u) \geq J(u^*) + \langle 0, u - u^* \rangle = J(u^*)\ \forall u \in \mathbb{E}$.

(ii) necessity. $J(u^*) \leq J(u)\ \forall u \in \mathbb{E} \ \Rightarrow\ J(u^*) + \langle 0, u - u^* \rangle \leq J(u)\ \forall u \ \Rightarrow\ 0 \in \partial J(u^*)$. □

Theorem 1.10 (Fenchel-Young inequality)**.** *For any convex function $J : \mathbb{E} \to \overline{\mathbb{R}}$ and $(u, p) \in \mathbb{E} \times \mathbb{E}$, we have*

$$J(u) + J^*(p) \geq \langle u, p \rangle \,.$$

The equality holds iff $p \in \partial J(u)$ with $(u, p) \in \operatorname{dom} J \times \operatorname{dom} J^*$.

Proof. (i) $J(u) + J^*(p) \geq \langle u, p \rangle$ follows directly from the definition of convex conjugate. (ii) The equality holds only if $(u, p) \in \operatorname{dom} J \times \operatorname{dom} J^*$. Moreover, $p \in \partial J(u)$ is the sufficient and necessary condition for $\min_{u \in \mathbb{E}} \{J(u) - \langle u, p \rangle\}$. □

Theorem 1.11 (order reversing)**.** *For any $J_1, J_2 : \mathbb{E} \to \overline{\mathbb{R}}$, we have $J_1^*(\cdot) \leq J_2^*(\cdot)$ whenever $J_1(\cdot) \geq J_2(\cdot)$.*

Proof. Given any (u, p), we have $\langle u, p \rangle - J_1(u) \leq \langle u, p \rangle - J_2(u)$. Taking supremum over u on both sides yields $J_1^*(p) \leq J_2^*(p)$. □

Theorem 1.12. *Let $J : \mathbb{E} \to \overline{\mathbb{R}}$, and $J^{**} = (J^*)^*$ be the biconjugate of J. In general:*

1. $J^{**}(\cdot) \leq J(\cdot)$.

2. J^* *is convex and lsc.*

If J *is proper, convex, and lsc, then:*

3. $J^{**}(\cdot) = J(\cdot)$.

4. $p \in \partial J(u)$ *iff* $u \in \partial J^*(p)$.

Proof. (1) Since $J^{**}(u) = \sup_p\{\langle p, u\rangle - J^*(p)\}$ and, by Theorem 1.10, $\langle p, u\rangle - J^*(p) \leq J(u)\ \forall p$, we have $J^{**}(u) \leq J(u)$ for arbitrarily given u.

(2) (i) convexity. Let $p, q \in \mathbb{E}$, $0 \leq \alpha \leq 1$. Then $J^*(\alpha p+(1-\alpha)q) = \sup_u\{\langle u, \alpha p + (1-\alpha)q\rangle - J(u)\} \leq \sup_u\{\langle \alpha u, p\rangle - \alpha J(u)\} + \sup_u\{\langle (1-\alpha)u, q\rangle - (1-\alpha)J(u)\} = \alpha J^*(p) + (1-\alpha)J^*(q)$.

(ii) lsc. Note $\operatorname{epi} J^* = \{(p, \alpha) \in \mathbb{E} \times \mathbb{R} : \langle u, p\rangle - J(u) \leq \alpha\ \forall u\} = \cap_u \operatorname{epi} \Phi_u$ where $\Phi_u(\cdot) = \langle u, \cdot\rangle - J(u)$. Since each $\operatorname{epi} \Phi_u$ and any arbitrary intersection of closed sets is closed, $\operatorname{epi} J^*$ is closed and hence J^* is lsc.

(3) For the sake of contradiction, assume $\exists \bar{u} \in \operatorname{dom} J^{**}$ s.t. $J(\bar{u}) > J^{**}(\bar{u})$. Let $0 < d < J(\bar{u}) - J^{**}(\bar{u})$ be fixed. Since $(\bar{u}, J(\bar{u}) - d) \notin \operatorname{epi} J$ and $\operatorname{epi} J$ is convex and closed, by Theorem 1.1, $\exists (\bar{p}, -1) \in \mathbb{E} \times \mathbb{R}$ s.t. $\langle (\bar{p}, -1), (\bar{u}, J(\bar{u}) - d)\rangle \geq \langle (\bar{p}, -1), (u, \alpha)\rangle\ \forall (u, \alpha) \in \operatorname{epi} J$. In particular, $\langle \bar{p}, \bar{u}\rangle - J(\bar{u}) + d \geq \langle \bar{p}, u\rangle - J(u)\ \forall u \in \operatorname{dom} J$. Hence, $\langle \bar{p}, \bar{u}\rangle - J(\bar{u}) + d \geq J^*(\bar{p}) \geq \langle \bar{p}, \bar{u}\rangle - J^{**}(\bar{u})$ by Theorem 1.10. Thus we have $J^{**}(\bar{u}) + d \geq J(\bar{u})$ as a contradiction to our assumption.

(4) $p \in \partial J(u) \ \Leftrightarrow\ J(u) + J^*(p) = \langle u, p\rangle \ \Leftrightarrow\ J^{**}(u) + J^*(p) = \langle u, p\rangle \ \Leftrightarrow\ u \in \partial J^*(p)$. □

Theorem 1.13. *Assume that* $J : \mathbb{E} \to \overline{\mathbb{R}}$ *is proper, convex, and lsc. Then* J *is* μ*-strongly convex iff* J^* *is* $\frac{1}{\mu}$*-Lipschitz differentiable.*

Proof. (only if) Let $p \in \partial J(u)$ be arbitrarily given. By μ-strong convexity of J, we have

$$J(v) \geq J(u) + \langle p, v - u\rangle + \frac{\mu}{2}\|v - u\|^2 \quad \forall v. \tag{1}$$

Then $\forall q : J^*(q) = \sup_v\{\langle q, v\rangle - J(v)\} \leq \sup_v\{\langle q, v\rangle - J(u) - \langle p, v - u\rangle - \frac{\mu}{2}\|v - u\|^2\} = \langle q, u\rangle - J(u) + \sup_v\{\langle q - p, v - u\rangle - \frac{\mu}{2}\|v - u\|^2\} = \langle q, u\rangle - J(u) + \frac{1}{2\mu}\|q - p\|^2 = \langle p, u\rangle - J(u) + \langle q - p, u\rangle + \frac{1}{2\mu}\|q - p\|^2 = J^*(p) + \langle q - p, u\rangle + \frac{1}{2\mu}\|q - p\|^2$. Here we have used the identity $\langle p, u\rangle - J(u) = J^*(p)$. We have actually derived $\lim_{q \to p} \|J^*(q) - J^*(p) - \langle q - p, u\rangle\| / \|q - p\| = 0$, which asserts that J^* is (Frechét-)differentiable at p with $\nabla J^*(p) = u$.

Finally we show ∇J^* is $\frac{1}{\mu}$-Lipschitz. Let $u = \nabla J^*(p)$, $v = \nabla J^*(q)$, or equivalently $p \in \partial J(u)$, $q \in \partial J(v)$. Then by (1) we have

$$\begin{aligned} J(v) &\geq J(u) + \langle p, v - u\rangle + \frac{\mu}{2}\|v - u\|^2, \\ J(u) &\geq J(v) + \langle q, u - v\rangle + \frac{\mu}{2}\|u - v\|^2. \end{aligned}$$

Adding the above two inequalities, we obtain $\mu\|u - v\|^2 \leq \langle p - q, u - v\rangle \leq \|p - q\|\|u - v\|$ and thus $\|u - v\| \leq \frac{1}{\mu}\|p - q\|$.

(if) Note that $J^*(q) = J^*(p) + \int_0^1 \langle \nabla J^*(p + s(q - p)), q - p\rangle\, ds = J^*(p) + \langle \nabla J^*(p), q - p\rangle + \int_0^1 \langle \nabla J^*(p + s(q - p)) - \nabla J^*(p), q - p\rangle\, ds \ \leq\ J^*(p) + \langle \nabla J^*(p), q - p\rangle + \frac{1}{2\mu}\|q - p\|^2$. Let $p \in \partial J(u) \ \Leftrightarrow\ u = \nabla J^*(p)$. Then $J^*(q) \leq J^*(p) + \langle q - p, u\rangle + \frac{1}{2\mu}\|q - p\|^2$. Taking the convex conjugate on both sides, we deduce $J(v) = J^{**}(v) \geq \sup_q\{\langle q, v\rangle - (J^*(p) + \langle q - p, u\rangle + \frac{1}{2\mu}\|q - p\|^2)\} = -J^*(p) + \langle p, v\rangle + \frac{\mu}{2}\|v - u\|^2 = J(u) + \langle p, v - u\rangle + \frac{\mu}{2}\|v - u\|^2$. □

Theorem 1.14 (weak duality)**.** *Let* $K \in \mathbb{R}^{m \times n}$*, and* $F : \mathbb{R}^m \to \overline{\mathbb{R}}$*,* $G : \mathbb{R}^n \to \overline{\mathbb{R}}$ *are proper, convex, and lsc. Then it holds that* $\inf_u\{F(Ku) + G(u)\} \geq \sup_p\{-G^*(-K^\top p) - F^*(p)\}$.

Proof. Let $\mathcal{L}(u,p) = \langle p, Ku\rangle - F^*(p) + G(u)$, then $\inf_u\{F(Ku) + G(u)\} = \inf_u \sup_p \mathcal{L}(u,p)$ and $\sup_p\{-G^*(-K^\top p) - F^*(p)\} = \sup_p \inf_u \mathcal{L}(u,p)$. It remains to verify $\inf_u \sup_p \mathcal{L}(u,p) \geq \sup_p \inf_u \mathcal{L}(u,p)$. For an arbitrarily fixed (u,p), we have $\sup_{p'} \mathcal{L}(u,p') \geq \mathcal{L}(u,p) \geq \inf_{u'} \mathcal{L}(u',p)$. Hence, the conclusion follows. □

Theorem 1.15 (Fenchel-Rockafellar duality)**.** *Assume $\exists \bar{u} \in \operatorname{dom} G$ s.t. F is continuous at $K\bar{u}$. Then the strong duality holds: $\mathcal{P}^* = \mathcal{D}^*$. Moreover, (u^*, p^*) is the optimal solution pair iff*

$$\begin{cases} Ku^* \in \partial F^*(p^*), \\ -K^\top p^* \in \partial G(u^*). \end{cases}$$

Proof. Define $\Phi(v) := \inf_u\{F(Ku+v) + G(u)\}$. Since $\forall v^1, v^2 \in \mathbb{R}^m,\ \alpha \in [0,1] : \alpha\Phi(v^1) + (1-\alpha)\Phi(v^2) = \inf_{u^1}\{\alpha F(Ku^1 + v^1) + \alpha G(u^1)\} + \inf_{u^2}\{(1-\alpha)F(Ku^2+v^2) + (1-\alpha)G(u^2)\} = \inf_{u^1,u^2}\{\alpha F(Ku^1+v^1) + (1-\alpha)F(Ku^2+v^2) + \alpha G(u^1) + (1-\alpha)G(u^2)\} \geq \inf\{F(Ku + \alpha v^1 + (1-\alpha)v^2) + G(u) : u = \alpha u^1 + (1-\alpha)u^2\} \geq \Phi(\alpha v^1 + (1-\alpha)v^2)$, we prove that Φ is a convex function.

Without loss of generality, assume $\Phi(0) > -\infty$. By our assumption, $\exists \epsilon > 0$ s.t. $\forall \|v\| < \epsilon$: $\Phi(v) \leq F(K\bar{u}+v) + G(\bar{u}) \leq M$ for some $M < \infty$, i.e., $v \in \operatorname{dom}\Phi$. By Theorem 1.2, Φ is locally Lipschitz at 0, and $\Phi(0) = \Phi^{**}(0) = \sup_p -\Phi^*(p)$, where $\Phi^*(p) = \sup_v\{\langle p, v\rangle - \inf_u\{F(Ku + v) + G(u)\}\} = \sup_{v,u}\{\langle p, v + Ku\rangle + \left\langle -K^\top p, u\right\rangle - F(Ku+v) - G(u)\} = F^*(p) + G^*(-K^\top p)$. Thus, $\mathcal{P}^* = \mathcal{D}^*$ is proven.

As for the optimality condition, note that $\forall (u,p) : \mathcal{G}(u,p) = F(Ku) + G(u) + G^*(-K^\top p) + F^*(p) = F(Ku) + F^*(p) - \langle Ku, p\rangle + G(u) + G^*(-K^\top p) - \left\langle -K^\top p, u\right\rangle \geq 0$. The equality holds, i.e., $\mathcal{G}(u^*,p^*) = 0$, iff $Ku^* \in \partial F^*(p^*)$ and $-K^\top p^* \in \partial G(u^*)$ according to Theorem 1.10. □

Theorem 1.16 (Moreau identity)**.** *Let $\tau > 0$ and $J : \mathbb{E} \to \overline{\mathbb{R}}$ be proper, convex, and lsc. Then the following identity holds:*

$$\operatorname{id}(\cdot) = \operatorname{prox}_{\tau J}(\cdot) + \tau \operatorname{prox}_{\frac{1}{\tau}J^*}(\cdot/\tau).$$

Proof. $v = \tau \operatorname{prox}_{\frac{1}{\tau}J^*}(u/\tau) \iff \left(I + \frac{1}{\tau}\partial J^*\right)^{-1}(u/\tau) \ni v/\tau \iff \partial J^*(v/\tau) \ni u - v \iff v/\tau \in \partial J(u-v) \iff u - v = (I + \tau\partial J)^{-1}(u) = \operatorname{prox}_{\tau J}(u)$. □

Theorem 1.17. *Let $F, G : \mathbb{E} \to \overline{\mathbb{R}}$ be proper, convex, and lsc. Then*

$$(F \square G)^* = F^* + G^*.$$

Proof. $\forall p \in \mathbb{E} : (F\square G)^*(p) = \sup_{u,v}\{\langle p, u\rangle - F(v) - G(u-v)\} = \sup_{u,v}\{\langle p, v\rangle - F(v) + \langle p, u-v\rangle - G(u-v)\} = F^*(p) + G^*(p)$. □

2 Optimization Algorithms

Theorem 2.1. *If $\left\langle \nabla J(u^k), d^k \right\rangle < 0$, then $J(u^k + \tau d^k) < J(u^k)$ for all sufficiently small $\tau > 0$.*

Proof. The conclusion follows directly from the Taylor expansion: $J(u^k + \tau d^k) = J(u^k) + \tau \left\langle \nabla J(u^k), d^k \right\rangle + o(\tau) = J(u^k) + \tau \left(\left\langle \nabla J(u^k), d^k \right\rangle + o(1) \right) < J(u^k)$, for all $\tau > 0$ sufficiently small. □

Lemma 2.2 (feasibility of line search)**.** *Assume that $J : \mathbb{E} \to \mathbb{R}$ is continuously differentiable, $\left\langle \nabla J(u^k), d^k \right\rangle < 0\ \forall k$, and $0 < c_1 < c_2 < 1$. Then there exists an open interval in which the step size τ satisfies the Armijo- and the curvature conditions.*

Proof. Consider $\phi(\tau) := J(u^k + \tau d^k)$ and $\psi(\tau) := J(u^k) + \tau c_1 \left\langle \nabla J(u^k), d^k \right\rangle$ for $\tau \geq 0$. Since $\phi'(0) = \left\langle \nabla J(u^k), d^k \right\rangle < \psi'(0)$, $\phi(\tau) < \psi(\tau)$ for all $\tau > 0$ sufficiently close to 0. On the other hand, $\phi(\cdot)$ is bounded from below but $\psi(\cdot)$ is not. Hence, ϕ and ψ intersect at $\tau = \tau' > 0$ (for the first time as τ increases from 0). Thus, $0 < \tau < \tau'$ fulfills the Armijo condition.

By the mean value theorem, $\exists \tau'' \in (0, \tau')$ s.t. $J(u^k + \tau' d^k) - J(u^k) = \tau' \left\langle \nabla J(u^k + \tau'' d^k), d^k \right\rangle$. This implies $\left\langle \nabla J(u^k + \tau'' d^k), d^k \right\rangle = c_1 \left\langle \nabla J(u^k), d^k \right\rangle > c_2 \left\langle \nabla J(u^k), d^k \right\rangle$ since $c_1 < c_2$ and $\left\langle \nabla J(u^k), d^k \right\rangle < 0$. By continuity, this inequality holds in a neighborhood of τ''. □

Theorem 2.3 (Zoutendijk)**.** *Assume that $J : \mathbb{E} \to \mathbb{R}$ is continuously differentiable, and the Armijo- and curvature-conditions are both satisfied with $0 < c_1 < c_2 < 1$ for each k. In addition, J is μ-Lipschitz differentiable on $\{u \in \mathbb{E} : J(u) \leq J(u^0)\}$. Then $\sum_{k=0}^{\infty} \frac{\left| \left\langle \nabla J(u^k), d^k \right\rangle \right|^2}{\|d^k\|^2} < \infty$.*

Proof. From the curvature condition, we have $\left\langle \nabla J(u^{k+1}) - \nabla J(u^k), d^k \right\rangle \geq (c_2 - 1) \left\langle \nabla J(u^k), d^k \right\rangle$. Since ∇J is μ-Lipschitz, $\left\langle \nabla J(u^{k+1}) - \nabla J(u^k), d^k \right\rangle \leq \tau^k \mu \|d^k\|^2$. Altogether we have $\tau^k \geq \frac{(c_2-1)\left\langle \nabla J(u^k), d^k \right\rangle}{\mu \|d^k\|^2}$. Using the Armijo condition, we have $J(u^{k+1}) \leq J(u^k) - \frac{c_1(1-c_2)\left| \left\langle \nabla J(u^k), d^k \right\rangle \right|^2}{\mu \|d^k\|^2}$. Summing up this inequality from $k = 0$ to ∞, we have $\sum_{k=0}^{\infty} \frac{\left| \left\langle \nabla J(u^k), d^k \right\rangle \right|^2}{\|d^k\|^2} < \infty$. □

Lemma 2.4. *Assume that $J : \mathbb{E} \to \mathbb{R}$ is μ-Lipschitz differentiable. Then $\forall u, v \in \mathbb{E}$:*

$$|J(v) - J(u) - \langle \nabla J(u), v - u \rangle| \leq \frac{\mu}{2} \|v - u\|^2.$$

Proof. Since $J(v) = J(u) + \int_0^1 \langle \nabla J(u + t(v-u)), v - u \rangle \, dt = J(u) + \langle \nabla J(u), v - u \rangle$ $+ \int_0^1 \langle \nabla J(u + t(v-u)) - \nabla J(u), v - u \rangle \, dt$, we have $|J(v) - J(u) - \langle \nabla J(u), v - u \rangle|$ $= \left| \int_0^1 \langle \nabla J(u + t(v-u)) - \nabla J(u), v - u \rangle \, dt \right| \leq \int_0^1 |\langle \nabla J(u + t(v-u)) - \nabla J(u), v - u \rangle| dt$ $\leq \int_0^1 \|\nabla J(u + t(v-u)) - \nabla J(u)\| \|v - u\| dt \leq \int_0^1 t\mu \|v - u\|^2 dt = \frac{\mu}{2} \|v - u\|^2$. □

Theorem 2.5 (convergence of gradient descent)**.** *Assume that $J : \mathbb{E} \to \mathbb{R}$ is μ-Lipschitz differentiable. Then the gradient descent iteration $u^{k+1} = u^k - \tau \nabla J(u^k)$ with $\tau \in (0, 1/\mu]$ yields $\lim_{k \to \infty} \nabla J(u^k) = 0$.*

Proof. First, note that $J(u^{k+1}) \leq J(u^k)\ \forall k$. Since J has finite infimum by assumption, $\lim_{k \to \infty} |J(u^{k+1}) - J(u^k)| = 0$. Due to the majorization property and $\mu \leq 1/\tau$, we have $J(u^{k+1}) \leq J(u^k) + \left\langle \nabla J(u^k), u^{k+1} - u^k \right\rangle + \frac{1}{2\tau} \|u^{k+1} - u^k\|^2 = J(u^k) - \frac{1}{2\tau} \|u^{k+1} - u^k\|^2$. Hence, we conclude $\|\nabla J(u^k)\| = \frac{1}{\tau} \|u^{k+1} - u^k\| \to 0$. □

Proposition 2.6. *Let C be a nonempty, closed, convex subset of $\mathbb{E}$, $\Phi : C \to \mathbb{E}$, and $\alpha \in (0, 1)$. Then the following statements are equivalent:*

1. *Φ is α-averaged.*
2. *$(1 - \frac{1}{\alpha})I + \frac{1}{\alpha}\Phi$ is nonexpansive.*
3. *$\forall u, v \in C : \|\Phi(u) - \Phi(v)\|^2 \le \|u - v\|^2 - \frac{1-\alpha}{\alpha}\|(I - \Phi)(u) - (I - \Phi)(v)\|^2$.*
4. *$\forall u, v \in C : \|\Phi(u) - \Phi(v)\|^2 + (1 - 2\alpha)\|u - v\|^2 \le 2(1 - \alpha)\langle u - v, \Phi(u) - \Phi(v)\rangle$.*

Proof. By the definition of the averaged operator, $\Phi = (1 - \alpha)I + \alpha\Psi$ for some nonexpansive operator $\Psi : C \to \mathbb{E}$, or $\Psi = (1 - \frac{1}{\alpha})I + \frac{1}{\alpha}\Phi$. Hence, (1) $\Leftrightarrow$ (2) follows.

(2) $\Leftrightarrow \Psi = (1-\frac{1}{\alpha})I+\frac{1}{\alpha}\Phi$ is nonexpansive $\Leftrightarrow \|\Psi(u)-\Psi(v)\| \le \|u-v\| \Leftrightarrow \alpha^2\|u-v\|^2 \ge \|((\alpha-1)I+\Phi)(u)-((\alpha-1)I+\Phi)(v)\|^2 = \|\Phi(u)-\Phi(v)\|^2+(\alpha-1)^2\|u-v\|^2+2(\alpha-1)\langle u - v, \Phi(u) - \Phi(v)\rangle$ $\Leftrightarrow$ (4).

Note that $-2\langle u - v, \Phi(u) - \Phi(v)\rangle = \|(I - \Phi)(u) - (I - \Phi)(v)\|^2 - \|u - v\|^2 - \|\Phi(u) - \Phi(v)\|^2$. Hence, (4) $\Leftrightarrow \|\Phi(u) - \Phi(v)\|^2 + (1 - 2\alpha)\|u - v\|^2 \le (1 - \alpha)\|(I - \Phi)(u) - (I - \Phi)(v)\|^2 - (1 - \alpha)\|u - v\|^2 - (1 - \alpha)\|\Phi(u) - \Phi(v)\|^2 \Leftrightarrow$ (3). □

Theorem 2.7 (Baillon-Haddad)**.** *Let $J : \mathbb{E} \to \mathbb{R}$ be a convex, continuously differentiable function. Then ∇J is a nonexpansive operator iff ∇J is firmly nonexpansive.*

Proof. (if) Obvious.

(only if) Define $H(\cdot) := \frac{1}{2}\|\cdot\|^2 - J(\cdot)$. Note that H is continuously differentiable and $\nabla H = I - \nabla J$. Since ∇J is nonexpansive, we have $\forall u, v : \langle\nabla H(v) - \nabla H(u), v - u\rangle \ge \|v - u\|(\|v - u\| - \|\nabla J(v) - \nabla J(u)\|) \ge 0$.

This implies $\forall u, v : H(v)-H(u) = \int_0^1 \langle\nabla H(u + t(v - u)), v - u\rangle\, dt \ge \int_0^1 \langle\nabla H(u), v - u\rangle\, dt = \langle\nabla H(u), v - u\rangle$. Furthermore, $H(v) \ge H(u)+\langle\nabla H(u), v - u\rangle \Rightarrow \frac{1}{2}\|v\|^2-J(v) \ge \frac{1}{2}\|u\|^2-J(u)+\langle u - \nabla J(u), v - u\rangle \Rightarrow J(v) - J(u) - \langle\nabla J(u), v - u\rangle \le \frac{1}{2}\|v\|^2 - \frac{1}{2}\|u\|^2 + \langle u, u - v\rangle = \frac{1}{2}\|v - u\|^2$.

Define $D_J(w, u) := J(w) - J(u) - \langle\nabla J(u), w - u\rangle, \forall w, u \in \mathbb{E}$. The above result says $\frac{1}{2}\|w - u\|^2 \ge D_J(w, u), \forall w, u$. Fix u temporarily and let $d(\cdot) = D_J(\cdot, u)$. Then d is convex, $d(\cdot) \ge 0$, $\nabla d(\cdot) = \nabla J(\cdot) - \nabla J(u)$, and $D_J(\cdot, u) = D_d(\cdot, u)$. Therefore, we have $\frac{1}{2}\|w - v\|^2 \ge D_d(w, v) = d(w)-d(v)-\langle\nabla d(v), w - v\rangle = d(w)-d(v)-\langle\nabla J(v) - \nabla J(u), w - v\rangle$. Set $w = v-\nabla J(v)+\nabla J(u)$, then we have $D_J(v, u) = d(v) \ge d(w) + \frac{1}{2}\|\nabla J(v) - \nabla J(u)\|^2 \ge \frac{1}{2}\|\nabla J(v) - \nabla J(u)\|^2$.

Analogously, we can show $D_J(u, v) \ge \frac{1}{2}\|\nabla J(u)-\nabla J(v)\|^2$. Hence, $\langle\nabla J(v) - \nabla J(u), v - u\rangle = D_J(u, v) + D_J(v, u) \ge \|\nabla J(v) - \nabla J(u)\|^2$. Hence, ∇J is firmly nonexpansive by Proposition 2.6. □

Corollary 2.8. *Assume $G : \mathbb{E} \to \mathbb{R}$ is convex and μ-Lipschitz differentiable, and $\tau = 2\alpha/\mu$ with $\alpha \in (0, 1)$. Then $I - \tau\nabla G$ is α-averaged.*

Proof. Since $\frac{1}{\mu}\nabla G$ is nonexpansive, by the Baillon-Haddad theorem, $\frac{1}{\mu}\nabla G$ is firmly nonexpansive, i.e., $\exists\Psi : \mathbb{E} \to \mathbb{E}$ nonexpansive s.t. $\frac{1}{\mu}\nabla G = \frac{1}{2}I + \frac{1}{2}\Psi$. Hence, $I - \tau\nabla G = (1 - \frac{\tau\mu}{2})I - \frac{\tau\mu}{2}\Psi = (1 - \alpha)I + \alpha(-\Psi)$, i.e., $I - \tau\nabla G$ is α-averaged. □

Theorem 2.9 (composition of averaged operators)**.** *Let C be a nonempty, closed, convex subset of $\mathbb{E}$. For each $i \in \{1, ..., m\}$, let $\alpha_i \in (0, 1)$ and $\Phi_i : C \to C$ be an α_i-averaged operator. Then*

$$\Phi = \Phi_m \circ ... \circ \Phi_1$$

is α-averaged with

$$\alpha = \frac{m}{m-1+\dfrac{1}{\max_{1\le i\le m}\alpha_i}}.$$

Proof. Let $\kappa_i := \alpha_i/(1-\alpha_i)$ for each i, and $\kappa := \max_i \kappa_i$. For arbitrarily fixed $u, v \in C$, we derive

$$\begin{aligned}
&\|(I-\Phi)(u)-(I-\Phi)(v)\|^2/m \\
=&\|(I-\Phi_1)(u)-(I-\Phi_1)(v)+[(I-\Phi_2)\circ\Phi_1](u)-[(I-\Phi_2)\circ\Phi_1](v)+... \\
&+[(I-\Phi_m)\circ\Phi_{m-1}\circ...\circ\Phi_1](u)-[(I-\Phi_m)\circ\Phi_{m-1}\circ...\circ\Phi_1)](v)\|^2/m \\
\le&\|(I-\Phi_1)(u)-(I-\Phi_1)(v)\|^2+\|[(I-\Phi_2)\circ\Phi_1](u)-[(I-\Phi_2)\circ\Phi_1](v)\|^2+... \\
&+\|[(I-\Phi_m)\circ\Phi_{m-1}\circ...\circ\Phi_1](u)-[(I-\Phi_m)\circ\Phi_{m-1}\circ...\circ\Phi_1)](v)\|^2 \\
\le&\kappa_1(\|u-v\|^2-\|\Phi_1(u)-\Phi_1(v)\|^2)+\kappa_2(\|\Phi_1(u)-\Phi_1(v)\|^2-\|[\Phi_2\circ\Phi_1](u)-[\Phi_2\circ\Phi_1](v)\|^2) \\
&+...+\kappa_m([\Phi_{m-1}\circ...\circ\Phi_1](u)-[\Phi_{m-1}\circ...\circ\Phi_1](v)\|^2-\|[\Phi_m\circ...\circ\Phi_1](u)-[\Phi_m\circ...\circ\Phi_1](v)\|^2 \\
\le&\kappa(\|u-v\|^2-\|\Phi(u)-\Phi(v)\|^2).
\end{aligned}$$

Since (1) $\Leftrightarrow$ (3) in Proposition 2.6, Φ is α-averaged with $\frac{1-\alpha}{\alpha} = \frac{1}{m\kappa}$, or equivalently $\alpha = \frac{m}{m+1/\kappa}$. □

Theorem 2.10 (Krasnoselskii)**.** *Let C be a nonempty, closed, convex subset of $\mathbb{E}$, and $u^{k+1} = \Phi(u^k)$ for $k = 0, 1, 2, ...$ where $\Phi : C \to C$ satisfies:*

1. *Φ is α-averaged for some $\alpha \in (0, 1)$.*
2. *Φ has at least one fixed point.*

Then $\{u^k\}$ converges to a fixed point of Φ.

Proof. Let $\bar{u} \in C$ be an arbitrary fixed point of Φ. Since Φ is α-averaged, we have $\forall k$: $\|u^{k+1}-\bar{u}\|^2 = \|\Phi(u^k)-\Phi(\bar{u})\|^2 \le \|u^k-\bar{u}\|^2 - \frac{1-\alpha}{\alpha}\|(I-\Phi)(u^k)-(I-\Phi)(\bar{u})\|^2 = \|u^k-\bar{u}\|^2 - \frac{1-\alpha}{\alpha}\|(I-\Phi)(u^k)\|^2$. Summing up this inequality for all indices in $l \in [0, k]$, we have

$$\|u^{k+1}-\bar{u}\|^2 \le \|u^0-\bar{u}\|^2 - \frac{1-\alpha}{\alpha}\sum_{l=0}^{k}\|(I-\Phi)(u^l)\|^2.$$

This yields: (i) $\|u^k-\bar{u}\| \searrow c \ge 0$; (ii) $\sum_{k=0}^{\infty}\|(I-\Phi)(u^k)\|^2 < \infty$.

By (i), $\{u^k\}$ is uniformly bounded. Let $\{u^{k'}\}$ be any convergent subsequence of $\{u^k\}$ s.t. $\lim_{k'\to\infty} u^{k'} = u^* \in C$. By (ii), $\|(I-\Phi)(u^*)\| = \lim_{k'\to\infty}\|(I-\Phi)(u^{k'})\| = 0$, i.e., u^* is a fixed point of Φ.

Finally, we show the limit u^* is unique for any convergent subsequence of $\{u^k\}$. Assume that another subsequence of $\{u^k\}$, say $\{u^{k''}\}$, converges to $u^{**} \in C$. Then both $\lim_{k\to\infty}\|u^k-u^*\|^2$ and $\lim_{k\to\infty}\|u^k-u^{**}\|^2$ exist, and therefore $2\langle u^k, u^{**}-u^*\rangle = \|u^k-u^*\|^2 - \|u^k-u^{**}\|^2 - \|u^*\|^2 + \|u^{**}\|^2 \to c' \in \mathbb{R}$. Passing $k \to \infty$ along subindices $\{k'\}$ and $\{k''\}$ respectively, we have $2\langle u^*, u^{**}-u^*\rangle = 2\langle u^{**}, u^{**}-u^*\rangle = c'$ and hence $\|u^*-u^{**}\|^2 = 0$. Thus, we have shown that $\lim_{k\to\infty} u^k = u^*$. □

Theorem 2.11 (Krasnoselskii-Mann). *Let C be a nonempty, closed, convex subset of $\mathbb{E}$, and $u^{k+1} = (1-\tau^k)u^k + \tau^k\Psi(u^k)$ for $k = 0, 1, 2, ...$ where $\{\tau^k\} \subset [0,1]$* s.t.

$$\sum_{k=0}^{\infty} \tau^k(1-\tau^k) = \infty,$$

and $\Psi : C \to C$ satisfies:

1. *Ψ is nonexpansive.*
2. *Ψ has at least one fixed point.*

Then $\{u^k\}$ converges to a fixed point of Ψ.

Proof. Let $\bar{u} \in C$ be an arbitrary fixed point of Ψ. Then $\forall k : \|u^{k+1} - \bar{u}\|^2 = \|(1-\tau^k)(u^k - \bar{u}) + \tau^k(\Psi(u^k) - \bar{u})\|^2 = (1-\tau^k)\|u^k - \bar{u}\|^2 + \tau^k\|\Psi(u^k) - \bar{u}\|^2 - \tau^k(1-\tau^k)\|\Psi(u^k) - u^k\|^2 \leq \|u^k - \bar{u}\|^2 - \tau^k(1-\tau^k)\|\Psi(u^k) - u^k\|^2$. Summing up this inequality for all indices in $l \in [0,k]$, we have

$$\|u^{k+1} - \bar{u}\|^2 \leq \|u^0 - \bar{u}\|^2 - \sum_{l=0}^{k} \tau^k(1-\tau^k)\|(I-\Psi)(u^l)\|^2.$$

This yields: (i) $\|u^k - \bar{u}\| \searrow c \geq 0$; (ii) $\sum_{k=0}^{\infty} \tau^k(1-\tau^k)\|(I-\Psi)(u^k)\|^2 < \infty$.

(ii) further implies $\liminf_{k\to\infty} \|(I-\Psi)(u^k)\| = 0$. Otherwise $\exists \bar{k} \in \mathbb{N},\ \epsilon > 0,$ s.t. $\forall k \geq \bar{k} : \|(I-\Psi)(u^k)\| \geq \epsilon$, and hence $\infty > \sum_{k=0}^{\infty} \tau^k(1-\tau^k)\|(I-\Psi)(u^k)\|^2 \geq \sum_{k=\bar{k}}^{\infty} \tau^k(1-\tau^k)\|(I-\Psi)(u^k)\|^2 \geq \epsilon^2\tau^k(1-\tau^k) = \infty$ yields a contradiction. Moreover, $\|(I-\Psi)(u^{k+1})\| = \|(1-\tau^k)(u^k - \Psi(u^k)) + (\Psi(u^k) - \Psi(u^{k+1}))\| \leq (1-\tau^k)\|u^k - \Psi(u^k)\| + \|u^{k+1} - u^k\| = \|(I-\Psi)(u^k)\|$. Altogether, we obtain $\lim_{k\to\infty} \|(I-\Psi)(u^k)\| = 0$.

The remainder of the proof is identical to that for Theorem 2.10. ☐

Lemma 2.12 (demiclosedness principle). *Let C be a nonempty, closed, convex subset of a real Hilbert space $\mathbb{H}$, and $\Phi : C \to \mathbb{H}$ be nonexpansive. For any sequence $\{u^k\} \subset C$* s.t. *$\{u^k\}$ weakly converges to $u \in C$ and $u^k - \Phi(u^k)$ strongly converges to $v \in \mathbb{H}$, we have $u - \Phi(u) = v$.*

Proof. Since $\{u^k\}$ weakly converges to u^* and C is weakly closed (for being convex and strongly closed), we have $u \in C$ and $\Phi(u)$ is well defined. By the nonexpansiveness of Φ, we derive

$$\begin{aligned}
&\|u - \Phi(u) - v\|^2 = \|u^k - \Phi(u) - v\|^2 - \|u^k - u\|^2 - 2\left\langle u^k - u, u - \Phi(u) - v\right\rangle \\
&= \|u^k - \Phi(u^k) - v\|^2 + 2\left\langle u^k - \Phi(u^k) - v, \Phi(u^k) - \Phi(u)\right\rangle + \|\Phi(u^k) - \Phi(u)\|^2 - \|u^k - u\|^2 \\
&\quad - 2\left\langle u^k - u, u - \Phi(u) - v\right\rangle \\
&\leq \|u^k - \Phi(u^k) - v\|^2 + 2\left\langle u^k - \Phi(u^k) - v, \Phi(u^k) - \Phi(u)\right\rangle - 2\left\langle u^k - u, u - \Phi(u) - v\right\rangle \to 0.
\end{aligned}$$

Note that, in the last inequality above, $\Phi(u^k) - \Phi(u) = (\Phi(u^k) - u^k + v) + (u^k - \Phi(u) - v)$ weakly converges to $u - \Phi(u) - v$ and is, therefore, bounded. ☐

Theorem 2.13 (local quadratic convergence of proximal Newton). *The proximal Newton method converges locally quadratically to the (global) minimizer u^* if $\nabla^2 G(u^*)$ is spd.*

Proof. Note that $0 \in \partial F(u^*) + \nabla G(u^*)$. Let u^k be in a small neighborhood of u^* where $\nabla^2 G(\cdot) \succeq \mu I$ and $\nabla^2 G$ is L-Lipschitz for some constants $\mu, L > 0$. Note that $u^{k+1} = u^k + d^k = [\partial F + \nabla^2 G(u^k)]^{-1} \nabla^2 G(u^k)(u^k - [\nabla^2 G(u^k)]^{-1} \nabla G(u^k))$, and $[\partial F + \nabla^2 G(u^k)]^{-1} \nabla^2 G(u^k)$ is firmly nonexpansive under the scaled norm $\|\cdot\|_{\nabla^2 G(u^k)}$. Hence, the conclusion follows from

$$\begin{aligned}
&\sqrt{\mu}\|u^{k+1} - u^*\| \le \|u^{k+1} - u^*\|_{\nabla^2 G(u^k)} \\
&= \|[\partial F + \nabla^2 G(u^k)]^{-1} \nabla^2 G(u^k)(u^k - [\nabla^2 G(u^k)]^{-1} \nabla G(u^k)) \\
&\quad - [\partial F + \nabla^2 G(u^k)]^{-1} \nabla^2 G(u^k)(u^* - [\nabla^2 G(u^k)]^{-1} \nabla G(u^*))\|_{\nabla^2 G(u^k)} \\
&\le \|(u^k - [\nabla^2 G(u^k)]^{-1} \nabla G(u^k)) - (u^* - [\nabla^2 G(u^k)]^{-1} \nabla G(u^*))\|_{\nabla^2 G(u^k)} \\
&\le \frac{1}{\sqrt{\mu}} \|\nabla^2 G(u^k)(u^k - u^*) - (\nabla G(u^k) - \nabla G(u^*))\| \\
&\le \frac{L}{2\sqrt{\mu}} \|u^k - u^*\|^2.
\end{aligned}$$

□

Theorem 2.14. *Assume* $\forall k : \mu I \preceq \nabla^2 J(\widetilde{u}^k) \preceq LI$ *for some constants* $\mu, L > 0$. *If* $\theta \ge \max\{|1 - \sqrt{\tau\mu}|, |1 - \sqrt{\tau L}|\}^2$, *then* $\mathrm{sr}(A^k) = \sqrt{\theta}\ \forall k$.

Proof. For each k, let $\nabla^2 J(\widetilde{u}^k) = U^k \Lambda^k (U^k)^\top$ be the eigendecomposition of the spd matrix $\nabla^2 J(\widetilde{u}^k)$, where V^k is orthogonal and $\Lambda^k = \mathrm{diag}\{\lambda_i^k\}$. Then we have

$$\begin{bmatrix} U^k & 0 \\ 0 & U^k \end{bmatrix} \begin{bmatrix} (1+\theta)I - \tau\nabla^2 J(\widetilde{u}^k) & -\theta I \\ I & 0 \end{bmatrix} \begin{bmatrix} U^k & 0 \\ 0 & U^k \end{bmatrix}^\top = \begin{bmatrix} (1+\theta)I - \tau\Lambda^k & -\theta I \\ I & 0 \end{bmatrix}, \tag{2}$$

whose eigenvalues consists of those eigenvalues of 2-by-2 blocks:

$$\begin{bmatrix} 1+\theta-\tau\lambda_i^k & -\theta \\ 1 & 0 \end{bmatrix},$$

i.e., the roots of $t^2 - (1+\theta-\tau\lambda_i^k)t + \theta = 0$. By the assumption, we have $1 - \sqrt{\theta} \le \sqrt{\tau\lambda_i^k} \le 1 + \sqrt{\theta}$, which implies $|1+\theta-\tau\lambda_i^k|^2 - 4\theta \le 0$. Therefore, both roots have the same magnitude $\sqrt{\theta}$. □

Proposition 2.15. *Assume* S, T *are spd matrices, and* $\widehat{K} = T^{-1/2} K S^{-1/2}$. *Then*

$$M_{S,T} = \begin{bmatrix} S & -K^\top \\ -K & T \end{bmatrix} \succ 0 \iff \widehat{M}_{S,T} = \begin{bmatrix} I & -\widehat{K}^\top \\ -\widehat{K} & I \end{bmatrix} \succ 0 \iff \|T^{-1/2} K S^{-1/2}\| < 1.$$

Proof. Note that

$$\begin{aligned}
\begin{bmatrix} S^{1/2} & 0 \\ 0 & T^{1/2} \end{bmatrix} \begin{bmatrix} I & -\widehat{K}^\top \\ -\widehat{K} & I \end{bmatrix} \begin{bmatrix} S^{1/2} & 0 \\ 0 & T^{1/2} \end{bmatrix} &= \begin{bmatrix} S & -K^\top \\ -K & T \end{bmatrix} \\
&= \begin{bmatrix} I & -K^\top T^{-1} \\ 0 & I \end{bmatrix} \begin{bmatrix} S - K^\top T^{-1} K & 0 \\ 0 & T \end{bmatrix} \begin{bmatrix} I & 0 \\ -T^{-1}K & I \end{bmatrix}.
\end{aligned}$$

Hence

$$\begin{aligned}
&\widehat{M}_{S,T} \succ 0 \iff M_{S,T} \succ 0 \iff S - K^\top T^{-1} K \succ 0 \iff I - S^{-1/2} K^\top T^{-1} K S^{-1/2} \succ 0 \\
&\iff (T^{-1/2} K S^{-1/2})^\top T^{-1/2} K S^{-1/2} \prec I \iff \|T^{-1/2} K S^{-1/2}\| < 1.
\end{aligned}$$

□

Proposition 2.16. *Given matrix K, define*

$$S = \operatorname{diag}(\{s_j\}),\ s_j = \sum_i |K_{ij}|^{2-\theta},\ T = \operatorname{diag}(\{t_i\}),\ t_i = \sum_j |K_{ij}|^{\theta},$$

where $\theta \in [0, 2]$. Then S and T satisfy $M_{S,T} = \begin{bmatrix} S & -K^\top \\ -K & T \end{bmatrix} \succeq 0$.

Proof. For an arbitrary vector (u, p), we have

$$\begin{aligned} \begin{bmatrix} u \\ p \end{bmatrix}^\top \begin{bmatrix} S & -K^\top \\ -K & T \end{bmatrix} \begin{bmatrix} u \\ p \end{bmatrix} &= \sum_{i,j} |K_{ij}|^{2-\theta} |u_j|^2 + \sum_{i,j} |K_{ij}|^{\theta} |p_i|^2 - 2 \sum_{i,j} K_{ij} u_j p_i \\ &\geq \sum_{i,j} \left| |K_{ij}|^{(2-\theta)/2} u_j - |K_{ij}|^{\theta/2} p_i \right|^2 \geq 0. \end{aligned}$$

Hence the conclusion follows. □