Proofs in SS'17 Convex Optimization Lectures*

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1 Convex Analysis

Theorem 1.1 (separation of convex sets)**.** *Let C_1, C_2 be nonempty convex subsets in $\mathbb{E}$ such that $C_1 \cap C_2 = \emptyset$ and C_1 is open. Then there exists a hyperplane separating C_1 and C_2, i.e. $\exists v \in \mathbb{E},\ v \neq 0,\ \alpha \in \mathbb{R}$ such that*

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

Proof. (i) Claim: Let $C \subset \mathbb{E}$ be closed, convex set, and $w \in \mathbb{E}\backslash C$. Then $\exists v \in \mathbb{E},\ v \neq 0,\ \alpha \in \mathbb{R}$ s.t. $\langle v, w \rangle > \alpha \geq \langle v, u \rangle\ \forall u \in C$.

Consider the projection of w onto C, i.e. set $u^* := \arg\min_{u \in C} \frac{1}{2}\|u - w\|^2$ or, equivalently, let $\langle u - u^*, u^* - w \rangle \geq 0\ \forall u \in C$.

Now set $v := w - u^* \neq 0$. Then $\forall u \in C$, 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 $\alpha := \sup\{\langle v, u \rangle : u \in C\}$. Note $\alpha < \infty$ since $\langle v, u \rangle \leq \langle v, u^* \rangle\ \ \forall u \in C$. Thus $\langle v, w \rangle > \alpha \geq \langle v, u \rangle\ \ \forall u \in C$, which proves the claim.

(ii) Assume $C_2 = \{\bar{w}\}$ with $\bar{w} \in C_1$. Since $\mathbb{E}\backslash C_1$ is closed, $\exists w^k \in \mathbb{E}\backslash C_1$ s.t. $w^k \to \bar{w}$. For each w^k, by (i), $\exists v^k \in \mathbb{E}$ with $\|v^k\| \equiv 1$ s.t. $\left\langle v^k, w^k \right\rangle \leq \left\langle v^k, u^1 \right\rangle\ \ \forall u^1 \in C_1$. Hence $v^k \to \bar{v} \in \mathbb{E}$ along a subsequence s.t. $\|\bar{v}\| = 1$ and $\langle \bar{v}, \bar{w} \rangle \leq \left\langle \bar{v}, u^1 \right\rangle\ \ \forall u^1 \in C_1$.

(iii) Consider C_2 as a general convex subset of $\mathbb{E}$. Set $C := C_2 - C_1 = \{u^2 - u^1 : u^1 \in C_1,\ u^2 \in C_2\}$. Note that C is a convex, open set, and $0 \in C$. By (ii), $\exists \bar{v}$ with $\bar{v} = 1$ s.t. $\left\langle -\bar{v}, u^2 - u^1 \right\rangle \geq \langle -\bar{v}, 0 \rangle = 0$ or, equivalently, $\left\langle \bar{v}, u^1 \right\rangle \geq \left\langle \bar{v}, u^2 \right\rangle\ \ \forall u^1 \in C_1,\ u^2 \in C_2$. Set $\alpha := \sup\{\left\langle \bar{v}, u^2 \right\rangle : u^2 \in C_2\}$, then we conclude that $\left\langle \bar{v}, u^1 \right\rangle \geq \alpha \geq \left\langle \bar{v}, u^2 \right\rangle\ \forall u^1 \in C_1,\ u^2 \in C_2$. ☐

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

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

Let $M := \sup\{J(v) : v \in B_\epsilon(u)\} < \infty$. By convexity of J, $\forall v \in B_\epsilon(u) : J(v) \geq 2J(u) - J(2u - v) \geq 2J(u) - M$. Thus, $\|J\|_{B_\epsilon(u)} := \sup\{|J(v)| : v \in B_\epsilon(u)\} \leq M + 2|J(u)|$.

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 $t \leq \|w - v\|/\|z - v\| \leq 2\|w - v\|/\epsilon$ 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 $u \in \operatorname{ri}\operatorname{dom} J$ and n be the dimension of the affine hull of $\operatorname{dom} J$, then $\exists\{\alpha^i\}_{i=1}^{n+1} \subset (0, 1),\ \{u^i\}_{i=1}^{n+1} \subset \operatorname{dom} J$ 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. ☐

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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 $J(\alpha\bar{u} + (1-\alpha)u^*) \leq J(u^*) - \alpha(J(u^*) - J(\bar{u}))\ \forall \alpha \in [0,1]$. 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 ∂J is a monotone operator, i.e. $\forall u^1, u^2 \in \operatorname{dom} J,\ \xi^1 \in \partial J(u^1),\ \xi^2 \in \partial J(u^2)$:*

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

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

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

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

Theorem 1.7. *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, $\exists (\xi, -\alpha) \in \mathbb{E}\times\mathbb{R}$ s.t. $(\xi, -\alpha) \neq (0,0)$, $\alpha \geq 0$ by our choice, and $\langle (\xi, -\alpha), (u - v, J(u) - J(v)) \rangle \geq 0\ \forall v \in \operatorname{dom} J$. In fact, we must have $\alpha > 0$ since otherwise $\xi = 0$. Thus, we conclude that $\xi/\alpha \in \partial J(u)$.

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

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

(iv) convexity. Let $v \in \mathbb{E}$ be arbitrarily given, $\xi, \eta \in \partial J(u)$. Then we have

$$J(v) \geq J(u) + \langle \xi, v - u \rangle,$$
$$J(v) \geq J(u) + \langle \eta, v - u \rangle.$$

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

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. $\xi^* \in \partial J(u^*)$ whenever*

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

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

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 all $u \in \operatorname{dom} J$, $p \in \operatorname{dom} J^*$, we have $J(u) + J^*(p) \geq \langle u, p \rangle$. The equality holds iff $p \in \partial J(u)$.*

Proof. $J(u) + J^*(p) \geq \langle u, p \rangle$ follows directly from the definition of convex conjugate; $p \in \partial J(u)$ is the sufficient and necessary condition for: $u = \arg\min_{v \in \mathbb{E}} J(v) - \langle v, p \rangle$. □

Theorem 1.11. *Assume $J : \mathbb{E} \to \overline{\mathbb{R}}$ and $J^{**} = (J^*)^*$ is 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 $\langle p, u \rangle - J^*(p) \leq J(u)$ by Theorem 1.10, we assert $J^{**}(\cdot) \leq J(\cdot)$.

(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 $d := \frac{1}{2}(J(\bar{u}) - J^{**}(\bar{u})) > 0$. Since $(\bar{u}, J(\bar{u}) - d) \notin \operatorname{epi} J$ and $\operatorname{epi} J$ is closed, by Theorem 1.1, $\exists (\bar{p}, -1) \in \mathbb{E} \times \mathbb{R}$ s.t. $\langle (\bar{p}, -1), (\bar{u}, J(\bar{u}) - d) \rangle \geq \langle (\xi, -1), (u, \alpha) \rangle \;\forall (u, \alpha) \in \operatorname{epi} J$. In particular, $\langle \bar{p}, \bar{u} \rangle - J(\bar{u}) + d \geq \langle \bar{p}, u \rangle - J(u) \;\forall u$. 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 $J^{**}(\bar{u}) \geq J(\bar{u})$ 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 1.12. *Assume that $J : \mathbb{E} \to \overline{\mathbb{R}}$ is proper, convex, and lsc. Then J is μ-strongly convex iff J^* has $\frac{1}{\mu}$-Lipschitz gradient.*

Proof. 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

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

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 $\|u-v\| \leq \frac{1}{\mu}\|p-q\|$. □

Theorem 1.13 (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 $\Phi(\cdot) := \inf_u\{F(Ku+\cdot) + G(u)\}$. Since $\forall v^1, v^2 \in \mathbb{R}^m,\ \forall \alpha \in [0,1] : \alpha\Phi(v^1) + (1-\alpha)\Phi(v^2) = \inf_{u^1}\{\alpha F(Ku^1+v^1) + \alpha G(u^1)\} + \inf_{u^2}\{(1-\alpha)F(Ku^2+v^2) + (1-\alpha)G(u^2)\} = \inf_{u^1,u^2}\{\alpha F(Ku^1+v^1) + (1-\alpha)F(Ku^2+v^2) + \alpha G(u^1) + (1-\alpha)G(u^2)\} \geq \inf_u\{\alpha F(Ku+v^1) + (1-\alpha)F(Ku+v^2) + G(u)\} \geq \inf_u\{F(Ku+\alpha v^1 + (1-\alpha)v^2) + G(u)\} = \Phi(\alpha v^1 + (1-\alpha)v^2)$, 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 $M < \infty$. Hence, by Theorem 1.2, Φ is locally Lipschitz at 0, and $\Phi(0) = \Phi^{**}(0) = \sup_p -\Phi^*(p)$, where $\Phi^*(p) = \sup_v\{\langle p, v\rangle - \inf_u\{F(Ku+v) + G(u)\}\} = \sup_{v,u}\{\langle p, v+Ku\rangle + \langle -K^\top p, u\rangle - F(Ku+v) - G(u)\} = F^*(p) + G^*(-K^\top p)$. Thus, $\mathcal{P}^* = \mathcal{D}^*$ is proven.

As for the optimality condition, note that $\forall (u,p) : \mathcal{G}(u,p) = F(Ku) + G(u) + G^*(-K^\top p) + F^*(p) = F(Ku) + F^*(p) - \langle Ku, p\rangle + G(u) + G^*(-K^\top p) - \langle -K^\top p, u\rangle \geq 0$. 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 1.14 (Moreau identity). *Let $\tau > 0$ and $J : \mathbb{E} \to \overline{\mathbb{R}}$ be proper, convex, and lsc. Then the following identity holds:*

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

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

Theorem 1.15. *Let $F, G : \mathbb{E} \to \overline{\mathbb{R}}$ be proper, convex, and lsc. Then*

$$(F \Box G)^*(\cdot) = F^*(\cdot) + G^*(\cdot).$$

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

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 the curvature conditions are both satisfied with $0 < c_1 < c_2 < 1$ for each k. In addition, $\nabla J(\cdot)$ is μ-Lipschitz on $\{u \in \mathbb{E} : J(u) \leq J(u^0)\}$. Then we have $\sum_{k=0}^{\infty} \frac{\left| \left\langle \nabla J(u^k), d^k \right\rangle \right|^2}{\|d^k\|^2} < \infty$.*

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 $J : \mathbb{E} \to \mathbb{R}$ is convex with μ-Lipschitz gradient. 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 $J : \mathbb{E} \to \mathbb{R}$ is convex with μ-Lipschitz gradient. 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 a (finite) minimum 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, $\langle \nabla J(v) - \nabla J(u), v-u\rangle = D_J(u,v) + D_J(v,u) \ge \|\nabla J(v) - \nabla J(u)\|^2$ and ∇J is firmly nonexpansive by Proposition 2.6. ☐

Corollary 2.8. *Assume that $G : \mathbb{E} \to \mathbb{R}$ is a convex, differentiable function with μ-Lipschitz ∇G, $\tau = 2\alpha/\mu$, and $\alpha \in (0,1)$, 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

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

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

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

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 $\forall k$: $\|u^{k+1}-\bar{u}\|^2 = \|\Phi(u^k)-\Phi(\bar{u})\|^2 \leq \|u^k-\bar{u}\|^2 - \frac{1-\alpha}{\alpha}\|(I-\Phi)(u^k)-(I-\Phi)(\bar{u})\|^2 = \|u^k-\bar{u}\|^2 - \frac{1-\alpha}{\alpha}\|(I-\Phi)(u^k)\|^2$. Summing up this inequality for all indices in $l \in [0, k]$, we have

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

This yields: (i) $\|u^k-\bar{u}\| \searrow c \geq 0$; (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 $u - \Phi(u) - v$. □

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

Proof. Note that $0 \in \partial F(u^*) + \nabla G(u^*)$. Let u^k be in a small neighborhood of u^* where $\nabla^2 G(\cdot) \succeq cI$ and $\nabla^2 G$ is L-Lipschitz continuous for some constants $c, L > 0$. 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

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

□

Theorem 2.14. *Assume* $\forall k : \ell I \preceq \nabla^2 J(\widetilde{u}^k) \preceq LI$ *for some constants* $\ell, L > 0$. *If* $\theta \ge \max\{|1-\sqrt{\tau\ell}|, |1-\sqrt{\tau L}|\}^2$, *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 $\theta \ge \left(1-\sqrt{\tau\lambda_i^k}\right)^2$, $\forall i$. Thus, $|1+\theta-\tau\lambda_i^k|^2-4\theta\le 0$ and therefore both roots have the same magnitude $\sqrt{\theta}$. □