STEEPEST DESCENT METHOD FOR
LOCALLY ACCRETIVE MAPPINGS

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ABSTRACT.

1. Introduction

Let $E$ be a real normed linear space, $K \subseteq E$. A mapping $A : K \to E$ is called strongly pseudocontractive if there exists $t > 1$ such that the inequality

$$
\|x - y\| \leq \|(1 + t)(x - y) - rt(Ax - Ay)\|
$$

holds for all $x, y \in K$ and $r > 0$. If $t = 1$ then $A$ is called pseudocontractive. The map $A$ is called locally strongly pseudocontractive if each point of $K$ has a neighbourhood $N$ for which (1) holds for each $x, y \in N$ and some $t > 1$. Pseudocontractive operators have been studied by various authors (see e.g., [1], [2], [4], [8-12], [14], [16], [17], [18], [19], [21], [22], [28], [29], [30], [32-33], [37]). Interest in such mappings stems mainly from the fact that they are firmly connected with the important class of nonlinear accretive operators. A mapping $U$ with domain $D(U)$ and range $R(U)$ in $E$ is called accretive (see e.g., [2], [15]) if the inequality

$$
\|x - y\| \leq \|x - y + t(Ux - Uy)\|
$$

holds for each $x, y \in D(U)$ and all $t > 0$.

The accretive operators were introduced independently by Browder [3] and Kato [15]. If $E = H$, a Hilbert space, one of the earliest problems in the theory of accretive operators was to solve the equation $x + Ux = f$ for $x$, given an element $f$ of $H$ and an accretive operator $U$. We remark here that in
Hilbert spaces, accretive operators are also called monotone. In [3], Browder proved that if $U$ is locally Lipschitzian and accretive then $U$ is $m$-accretive, that is, $(I + U)$ is surjective. This result was subsequently generalized by Martin [20] to the continuous accretive operators.

The firm connection between the pseudocontractive mappings and the accretive operators is that a mapping $U$ is pseudocontractive if and only if $(I - U)$ is accretive [3, Proposition 1]. Consequently, the mapping theory for accretive operators is closely related to the fixed point theory of pseudocontractive operators.

It is well known (see for example, [4]) that many physically significant problems can be modelled in terms of an initial value problem of the form

$$\begin{align*}
\frac{dx}{dt} &= -Ux \\
x(0) &= x_0
\end{align*}$$

where $U$ is either accretive or strongly accretive. Typical examples of how such evolution equations arise are found in models involving either the heat, the wave or the Schrödinger equation. Let $N(U)$ denote the kernel of $U$. We observe that members of $N(U)$ are, in fact, the equilibrium points of the system (2). Consequently, considerable effort has been devoted to developing constructive techniques for the determination of the kernels of accretive operators (see e.g., [5], [6], [7], [8-12], [13], [14], [22], [23-25], [27], [28], [29], [30], [32, 33], [35], [36], [37]). Moreover, since a continuous accretive operator can be approximated well by a sequence of strongly accretive ones, particular attention has been devoted to constructive techniques for the kernels of strongly accretive operators. In this connection, but in Hilbert space, Vainberg [35] and Zarantonello [39] introduced the steepest descent method:

$$x_{n+1} = x_n - c_n Ux_n, \quad x_0 \in H, \quad n = 0, 1, 2, \ldots$$

and proved that if $U = I + T$ where $T$ is a monotone Lipschitz map and $c_n = \lambda, n = 0, 1, 2, \ldots; \lambda$ a constant, then the sequence $(x_n)$ defined by (3) converges strongly to an element of $N(U)$. This result has been generalized and extended to more general Banach spaces (see e.g., [5], [8-12], [2], [23-26], [28], [29], [32], [33], [37]). Recently, the author proved the following theorem:
THEOREM 1 ([8]). Suppose $K$ is a nonempty closed bounded and convex subset of $L^p$, $p \geq 2$, and $T : K \to K$ is a Lipschitz strongly pseudocontractive mapping of $K$ into itself. Let $\{c_n\}$ be a real sequence satisfying:

(i) $0 < c_n < 1$ for all $n \geq 1$,
(ii) $\sum_{n=1}^{\infty} c_n = \infty$; and 
(iii) $\sum_{n=0}^{\infty} c_n^2 < \infty$.

Then the sequence $\{x_n\}_{n=0}^{\infty}$ generated by $x_1 \in K$,

(4) $x_{n+1} = x_n - c_n Ax_n, \quad n \geq 1$

converges strongly to a solution of the equation $Ax = 0$ where $A = I - T$.

Several authors have generalized and extended Theorem 1 in various directions. In [32], Schu extended the theorem to the class of continuous strongly pseudocontractive maps in real Banach spaces with property $(U, \alpha, m + 1, m)$ (see e.g., [32] for definition). These Banach spaces include the $L^p$ spaces, $p \geq 2$; and in [33] he extended the theorem to the class of uniformly continuous maps in smooth Banach spaces. Bethke [1] obtained a slight generalization of the theorem still in $L^p$ spaces, $p \geq 2$; the author [10] and also Osilike [22] extended the theorem to the class of continuous strongly pseudocontractive maps on real uniformly smooth Banach spaces. Other generalizations can be found in Xu, Zhang and Roach [30]. The most general result for the global convergence of (4) for strongly accretive maps seems to be the main result of Xu and Roach [28] (see also a result of the author, [12]). A natural problem of interest (see e.g., [14], [37]) is to prove convergence theorems for approximating solutions of $Ax = 0$ when $A$ is locally accretive and a solution is known to exist.

It is our purpose in this paper to prove that in real $q$-uniformly smooth Banach spaces (defined below) the steepest descent approximation method (4) converges strongly to a solution of the equation $Ax = 0$ (when one exists) for locally strongly accretive operators, $A$. In particular, our result (Theorem 2) will extend Theorem 1 to real $q$ uniformly smooth Banach spaces (which include the $L^p$ spaces, $1 < p < \infty$) and to the class of locally strongly pseudocontractive maps (see our Remarks 1 and 2). Furthermore, since Banach spaces with property $(U, \alpha, m + 1, m)$ are $q$-uniformly smooth, Theorem 2 also extends the result of Schu (Theorem 1 of [32]) to these more general Banach spaces and to operators which are continuous and locally strongly pseudocontractive, while Theorem 4 extends Theorem 2 of [32]
to the class of *locally* Lipschitz continuous and *strongly* pseudocontractive maps. In addition, we shall prove a theorem (Theorem 3) on the convergence of the iteration process (4) to a solution of the equation \( x + Ux = f \) where \( U \) is a continuous *locally* accretive map on a real \( q \)-uniformly smooth Banach space. This result is related to the results of Bruck [5], the author [9] and Carbone [6].

2. Preliminaries

Let \( E \) be a Banach space. We shall denote by \( J \) the normalised duality mapping from \( E \) to \( 2^E \) given by

\[
Jx = \{ f^* \in E^* : \| f^* \|^2 = \| x \|^2 = \langle x, f^* \rangle \}
\]

where \( \langle \cdot, \cdot \rangle \) denotes the generalized duality pairing. If \( E \) is uniformly convex then \( J \) is single-valued, and is uniformly continuous on bounded sets. In the sequel we shall denote single-valued normalized duality map by \( j \).

Now, with \( p > 1 \), following [38], we shall associate the generalized duality map \( J_p \) from \( E \) to \( E^* \) defined by

\[
J_p(x) = \{ f^* \in E^* : \langle x, f^* \rangle = \| x \|^p, \quad \text{and} \quad \| f^* \| = \| x \|^{p-1} \}
\]

In particular, \( J_2 \) is the usual normalized duality map on \( E \). It is known (see e.g., [38]) that

\[
(5) \quad J_p(x) = \| x \|^{p-2} J(x) \quad \text{for} \quad x \neq 0.
\]

Let \( E \) be a Banach space with \( \dim E \geq 2 \). The *modulus of smoothness* \( \rho_\varepsilon(\tau) \), \( \tau > 0 \), of \( E \) is defined by

\[
\rho_\varepsilon(\tau) = \sup\{ (\| x + y \| + \| x - y \|)/2 - 1 : x, y \in E, \ \| x \| = 1, \ \| y \| = \tau \}.
\]

The Banach space \( E \) is uniformly smooth (see e.g., [34]) if

\[
\lim_{\tau \to 0} \rho_\varepsilon(\tau)/\tau = 0,
\]

and \( E \) is called \( q \)-uniformly smooth (see e.g., [38]) if there exists a constant \( c > 0 \) such that

\[
\rho_\varepsilon(\tau) \leq c \tau^q, \quad \text{for} \quad 0 < \tau < \infty.
\]

It is known (see e.g., [38], [34]) that

\[
L_p \quad \text{is} \quad \begin{cases} 
\text{\( p \)-uniformly smooth if} & 1 < p \leq 2 \\
\text{\( 2 \)-uniformly smooth if} & p \geq 2.
\end{cases}
\]

A Banach space \( E \) is called smooth (see e.g., [34], p.60) if, for every \( x \in E \) with \( \| x \| = 1 \), there exists a unique \( f^* \in E^* \) such that \( \| f^* \| = f^*(x) = 1 \). In [38], the following result which will be needed in the sequel is proved.
LEMMA 1 ([38]). Let \( q > 1 \) be a real number and \( E \) be a smooth Banach space. Then the following are equivalent:

(i) \( E \) is \( q \)-uniformly smooth;
(ii) There is a constant \( c > 0 \) such that for every \( x, y \in E \), the following inequality holds:

\[
\|x + y\|_q \leq \|x\|_q + q \langle y, J_q(x) \rangle + c \|y\|_q
\]

A mapping \( U \) is called locally strongly accretive if each point in the domain of \( U \) has a neighbourhood \( N \) for which there exist a constant \( k > 0 \) and \( j(x - y) \in J(x - y) \) such that

\[
\langle Ux - Uy, j(x - y) \rangle \geq k\|x - y\|^2.
\]

holds for \( x, y \in N \).

The following lemma has been proved:

LEMMA 2 ([37]). Let \( E \) be a real Banach space, \( K \) a subset of \( E \) and \( U : K \to E \). Then \( U \) is locally strongly pseudocontractive if and only if \( (I - U) \) is a locally strongly accretive.

3. Main results

In the sequel, \( c \) will denote the constant appearing in inequality (6). We prove the following theorems.

THEOREM 2. Let \( E \) be a real \( q \)-uniformly smooth Banach space. Suppose \( T \) is a continuous locally strongly accretive map with open domain \( D(T) \) in \( E \) and that \( Tx = 0 \) has a solution \( x^* \) in \( D(T) \). Then there exist a neighbourhood \( B \) in \( D(T) \) of \( x^* \) and a real number \( r_1 > 0 \) such that for any \( r > r_1 \) and some real sequence \( \{c_n\} \), any initial guess \( x_1 \in B \), the sequence \( \{x_n\} \) generated from \( x_1 \) by

\[
x_{n+1} = x_n - c_n T x_n, \quad n \geq 1,
\]

remains in \( D(T) \) and converges strongly to \( x^* \) with

\[
\|x_n - x^*\| = O(n^{-(q-1)/q}).
\]
Proof. Since $T$ is locally strongly accretive, there exists a neighborhood $U$ of $x^*$ such that for each $x \in U$,

$$\langle Tx - Tx^*, j(x - x^*) \rangle \geq k\|x - x^*\|^2.$$ 

Accretiveness of $T$ on $U$ implies $T$ is locally bounded at each interior point of $U$ (see e.g., Rockafellar [31], Reich [26]). So, we can choose $B = B_d(x^*)$, the closed ball of radius $d > 0$, $B \subseteq U$ so that $T(B)$ is bounded and $T$ is strongly accretive on $B$. Let $D$ be a constant such that $2d + \text{diam}(T(B)) \leq D$. Let $r_1 = [c^{1/q}D]^q/(q-1)(dk)-q/(q-1)$. Then $r_1 > 0$ and for $r \geq r_1$,

$$D \leq r^{(q-1)/q}dk c^{-q^{-1}}. \tag{9}$$

Let $c_n = \frac{1}{k(n+r)}$, $d_n = \frac{1}{k(n+r-1)^{1/q}q^{-1}}$. Observe that $(1 - k c_n)^q d_n^q + c_n^q = d_n^q$. Starting with an initial guess $x_1 \in B$, define the sequence $\{x_n\}_{n=1}^\infty$ inductively by (8).

Claim For all $n \geq 1$, $x_n$ is well defined and

$$\|x_n - x^*\| \leq d_n d r^{(q-1)/q} k.$$

The proof of this claim is by induction. For $n = 1$, $x_n$ is clearly in $B$. Suppose now that the claim has been proved for a particular choice of $n$. Then,

$$\|x_n - x^*\| \leq d_1 d r^{(q-1)/q} k = d, \text{ so } x_n \in B.$$

Thus, $x_n$ is well defined by (8). Using (5), (6), (7) and the induction hypothesis, we obtain:

$$\|x_{n+1} - x^*\|^q = \|(1 - c_n)(x_n - x^*) + c_n(Sx_n - Sx^*)\|^q, \tag{10}$$

where $Sx := x - Tx$ for each $x \in B$. Observe that $x^*$ is a solution of $Tx = 0$ and only if it is a fixed point of $S$. Moreover,

$$\langle Sx_n - Sx^*, J_q(x_n - x^*) \rangle = \langle x_n - x^* - (Tx_n - Tx^*), J_q(x_n - x^*) \rangle$$

$$= \|x_n - x^*\|^q - \langle Tx_n - Tx^*, J_q(x_n - x^*) \rangle$$

$$\leq (1 - k) \|x_n - x^*\|^q.$$
Hence, from (10), using (6):

\[
\begin{align*}
\|x_{n+1} - x^*\|^q &\leq (1 - c_n)^q \|x_n - x^*\|^q \\
&+ q \, c_n (1 - c_n)^{q-1} (Sx_n - Sx^*, J_q (x_n - x^*)) + c \, c_n^q \|Sx_n - Sx^*\|^q \\
&\leq \left[(1 - c_n)^q + q (1 - k) c_n (1 - c_n)^{q-1}\right] \|x_n - x^*\|^q \\
&+ c \, c_n^q \|Sx_n - Sx^*\|^q,
\end{align*}
\]

For \(x \in (0, 1)\), consider the function

\[f(x) = (1 + x)^q, \quad q > 1\]

Then, there exists \(\xi \in (0, x)\) such that

\[
f(x) = f(0) + x f'(0) + x^2 \frac{f''(\xi)}{2} = 1 + x q + \frac{x^2}{2} f''(\xi).
\]

Observe that \(f''(\xi) \geq 0\). Set \(x = (1 - k) c_n (1 - c_n)^{-1}\) in (i) to get,

\[
\left[1 + \frac{(1 - k) c_n}{1 - c_n}\right]^q = 1 + \frac{q (1 - k) c_n}{(1 - c_n)} + \frac{(1 - k)^2 c_n^2}{2} \frac{f''(\xi)}{(1 - c_n)^2}
\]

which simplifies to

\[
[1 - c_n + (1 - k) c_n]^q
\]

\[
= (1 - c_n)^q + q (1 - k) c_n (1 - c_n)^{q-1} + \frac{1}{2} (1 - k)^2 c_n^2 (1 - c_n)^{q-2} f''(\xi)
\]

and implies (since \(f''(\xi) \geq 0\)):

\[
(1 - c_n)^q + q (1 - k) c_n (1 - c_n)^{q-1} \leq [1 - c_n + (1 - k) c_n]^q = (1 - k c_n)^q
\]

Hence, using this inequality, (11) yields:

\[
\|x_{n+1} - x^*\|^q \leq (1 - k c_n)^q \|x_n - x^*\|^q + c \, c_n^q \|Sx_n - Sx^*\|^q.
\]

Observe that \(\|Sx_n - Sx^*\| \leq D\) so that

\[
\|x_{n+1} - x^*\|^q \leq (1 - k c_n)^q \|x_n - x^*\|^q + c \, c_n^q D^q
\]

which implies, by induction hypothesis

\[
\|x_{n+1} - x^*\|^q \leq [(1 - k c_n)^q d_n^q + c_n^q] d^q \, r^{q-1} \, k^q = d_{n+1}^q \, r^{q-1} \, k^q \, d^q
\]

so that

\[
\|x_{n+1} - x^*\| \leq d_{n+1} \, k \, r^{(q-1)/q},
\]

completing the induction process. Since \(d_n = O(n^{-(q-1)/q})\), the error estimate of the theorem has also been established. This completes the proof.
Corollary 1. Let $E$ be a real $q$-uniformly smooth Banach space. Suppose $U$ is a continuous locally strongly pseudocontractive map with open domain $D(U)$ in $E$ and that $U$ has a fixed point in $D(U)$. Then there exist a neighbourhood $B$ in $D(U)$ of $x^*$ and a real number $r_1 > 0$ such that for any $r > r_1$ and some real sequence $\{c_n\}$, any initial guess $x_1 \in B$, the sequence $\{x_n\}$ generated from $x_1$ by

$$x_{n+1} = x_n - c_n(I - U)x_n \quad n \geq 1,$$

remains in $D(U)$ and converges strongly to $x^*$ with

$$\|x_n - x^*\| = O(n^{-(q-1)/q}).$$

Proof. Follows immediately from Lemma 2 and Theorem 1.

Remark 1. In [14], the author claimed to have generalized Theorem 1 to locally Lipschitzian and strongly pseudocontractive operators in $L_p$ spaces, $p \geq 2$. He stated that if the mapping $U : D(U) \to E(E = L_p, p \geq 2)$ is locally Lipschitzian and strongly pseudocontractive, then there exists a closed region $B(x^*)$ containing a solution $x^*$ of the equation $Tx = y$ such that, for arbitrary $x_0 \in B(x^*)$, the process $x_{n+1} = x_n + \lambda(y - Tx_n)$ for a suitable $\lambda$ converges strongly to the solution $x^*$. However, as has already rightly been observed (MR. 92h:47090) the author fails to prove the existence of the region $B(x^*)$ where the iteration process is well defined. Moreover, there are several other inconsistencies in this result (see e.g., MR. 92h:47090).

Remark 2. In [37], the author claimed to have extended Theorem 1 to general uniformly smooth Banach spaces $E$ and to the class of local strongly pseudocontractive operators. He published the following theorem:

Theorem XW ([37]). Let $K$ be a subset of a uniformly smooth Banach space $E$ and $U : K \to E$ be a local pseudocontractive mapping. If $F(U) = \{x \in K : Ux = x\} \neq \emptyset$ and the range of $U$ is bounded, then $\{x_n\} \subseteq K$ generated by $x_1 \in K$,

$$x_{n+1} = x_n - c_n(I - U)x_n$$

with $\{c_n\} \subseteq (0, 1]$, satisfying: $\sum_{n=1}^{\infty} c_n = \infty$, $c_n \to 0$, converges strongly to $x^* \in F(U)$ and $F(U)$ is a singleton set.

We remark immediately that the sequence $\{x_n\}$ in Theorem XW is not even well defined, as can be seen from the following easy example.
**Counter-example to Theorem XW.** Take $E = \ell_2$, $K = \{x \in \ell_2 : \|x\| \leq 1\}$. Define $U : K \to E$ by

$$U(x_1, x_2, x_3, \ldots) = (-4x_1, -4x_2, -4x_3, \ldots)$$

for arbitrary $(x_1, x_2, x_3, \ldots) \in K$. Then,

(i) $E$ is clearly uniformly smooth;
(ii) $Ux = x$ if and only if $x = 0$. Hence $F(U) \neq \emptyset$.
(iii) $\|Ux\| \leq 4$ for each $x \in K$. Hence, the range of $U$ is bounded
(iv) $(I - U)x - (I - U)y, j(x - y)) = 5\|x - y\|^2$ for each $x, y \in K$.

Now, choose $c_n = \frac{1}{n+1}$, $n = 1, 2, \cdots$ and $x_1 = (1, 0, 0, \ldots) \in K$. Then $x_2 = (-\frac{3}{2}, 0, 0, \ldots) \notin K$, and so $x_3$ is not defined. In fact, the above choice of $x_1$ is not crucial. For example, for any $\lambda \in (\frac{2}{3}, 1)$, $x_1 = (\lambda, 0, 0, \ldots) \in K$ and $x_2 = (-\frac{2\lambda}{3}, 0, 0, \ldots) \notin K$. Again $x_3$ is not defined. Other choices are obviously possible. This completes the counter-example.

We now prove the following theorem on the convergence of the steepest descent method to a solution of the equation $x + Tx = f$ for a locally accretive operator $T$ in $q$-uniformly smooth Banach spaces.

**Theorem 3.** Let $E$ be a real $q$-uniformly smooth Banach space. Suppose $T$ is a continuous locally accretive map with open domain $D(T)$ in $E$ and that $f \in R(I + T)$. Suppose the equation $x + Tx = f$ has a solution $x^* \in D(T)$. Then there exist a neighbourhood $B \subseteq D(T)$ of $x^*$ and a real number $r_1 > 0$ such that for any $r > r_1$, any initial guess $x_1 \in B$, the sequence $\{x_n\}_{n=1}^{\infty}$ generated from $x_1$ by

$$x_{n+1} = x_n - c_n(I - f + T)x_n, \quad n = 1, 2, \ldots, \tag{12}$$

for some real sequence $\{c_n\}_{n=1}^{\infty}$ remains in $D(T)$ and converges strongly to $x^*$ with

$$\|x_n - x^*\| = O(n^{-(q-1)/q}).$$

**Proof.** Let $x^*$ denote a solution of the equation $x + Tx = f$. So, as in the proof of Theorem 2, we can choose $B = B_d(x^*)$, the closed unit ball of radius $d > 0$, $B \subseteq D(T)$ so that $T(B)$ is bounded and $T$ is accretive on $B$. Let

$$r_1 = \left[C^{1/q} \text{diam } T(B)\right]^{q/(q-1)} d^{-q/(q-1)}.$$
Then \( r > 0 \) and \( \text{diam} \ T(B) \leq r^{(q-1)/q} d \ c^{-q} \) for \( r \geq r_1 \). Let \( c_n = \frac{1}{n+r}, d_n = \frac{1}{(n+r)^{q-1}/q} \) so that \((1 - c_n)^q d_n^q + c_n^q = d_{n+1}^q\). Starting with an initial guess \( x_1 \in B \), define the sequence \( \{x_n\}_{n=1}^{\infty} \) inductively by (12). As in the proof of Theorem 2, \( \{x_n\} \) is well defined by (12). We now prove

\[
\|x_n - x^*\| \leq d_n d \ r^{(q-1)/q}.
\]

Now, using an induction argument as in the proof of Theorem 2, we have,

\[
\|x_{n+1} - x^*\|^q \leq (1 - c_n)^q \|x_n - x^*\|^q - q \ c_n (1 - c_n)^{q-1} \langle Tx_n - Tx^*, J_q(x_n - x^*) \rangle + c c_n^q \|Tx^* - Tx_n\|^q.
\]

Since \( c_n (1 - c_n) \geq 0 \) and \( T \) is accretive, it follows that

\[
\|x_{n+1} - x^*\|^q \leq (1 - c_n)^q \|x_n - x^*\|^q + c c_n^q \|Tx^* - Tx_n\|^q.
\]

Using the induction hypothesis and the fact that \( Tx_n \) and \( Tx^* \) belong to \( T(B) \), the last inequality yields:

\[
\|x_{n+1} - x^*\|^q \leq [(1 - c_n)^q d_n^q + c_n^q] d^q \ r^{(q-1)} = d_{n+1}^q \ d^q \ r^{(q-1)}
\]

so that \( \|x_{n+1} - x^*\| \leq d_{n+1} d \ r^{(q-1)/q} \), completing the induction argument and completing the proof of the theorem.

**Corollary 2.** Let \( E \) be a real \( q \)-uniformly smooth Banach space. Suppose \( U \) is continuous locally pseudocontractive map with open domain \( D(U) \) in \( E \) and that \( U \) has a fixed point \( x^* \) in \( D(U) \). Then there exist a neighbourhood \( B \) in \( D(U) \) of \( x^* \) and a real number \( r_1 > 0 \) such that for any \( r > r_1 \) and for some real sequence \( \{c_n\}_{n=1}^{\infty} \), any initial guess \( x_1 \in B \), the sequence \( \{x_n\}_{n=1}^{\infty} \) generated from \( x_1 \) by

\[
x_{n+1} = x_n - c_n (I - U) x_n, \quad n \geq 1,
\]

remains in \( D(U) \) and converges strongly to \( x^* \) with

\[
\|x_n - x^*\| = O(n^{-(q-1)/q}).
\]

**Proof.** Obvious, from Lemma 2 and Theorem 3.

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