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ON THE SPLITTING METHODS AND THE PROXIMAL POINT ALGORITHM FOR MAXIMAL MONOTONE OPERATORS

Corina L. Chiriac

To Professor Dan Pascali, at his 70's anniversary

Abstract

The theory of maximal set-valued monotone operators provides a powerful general framework for the study of convex programming and variational inequalities. A fundamental algorithm for finding a root of a monotone operator is the proximal point algorithm.

A lot of papers have been dedicated to this subject. Two principal classes of splitting methods are Peaceman-Rachford, and Douglas-Rachford algorithms. Eckstein has presented a generalized form of the proximal point algorithm – created by synthesizing the work of Rockafellar with that of Golshtein and Tretyakov – and has shown how it gives rise to a new method, generalized Douglas-Rachford splitting. Some results, about a connection between the proximal algorithm and Douglas-Rachford splitting will be given.

We give a proof that Douglas-Rachford splitting is an application of the proximal point algorithm. Using this fact we prove that Peaceman-Rachford splitting is equivalent to applying the generalized proximal point algorithm.

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Introduction.

For many maximal monotone operators T, the evaluation of inverses for operators of the form $I + \lambda T$, where $\lambda > 0$, may be difficult. Now suppose that we can choose two maximal monotone operators W and V such that $W + V = T$, but J_W^λ and J_V^λ are easier to evaluate than J_T^λ. A *splitting*

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algorithm is a method that employs the resolvents J_W^λ, J_V^λ of W and V, but does not use the resolvent J_T^λ of the original operator T. Here we consider theDouglas -Rachford scheme of Lions and Mercier [9].

We shall present a result, which establishes a relation between two well-known algorithms: proximal point algorithm and Douglas-Rachford splitting algorithm.

Preliminary results.

We enumerate some concepts and main results, which will be used to get our results.

Let H be a real Hilbert space with inner product $(\cdot,\cdot)$ and associated norm $||\cdot||$. We consider a multi-valued operator $T : H \to 2^H$. First we recall some properties of the monotone and maximal monotone operators.

Theorem 1 (Minty [10]). *A monotone operator $T : H \to 2^H$ is maximal if and only if $R(I+T) = H$.*

For alternative proofs of Theorem 1,or stronger related theorems, see [12],[2] or [7].

Given any operator A, let J_A denote the operator $(I + A)^{-1}$. Given any positive scalar λ and an operator$T$, $J_T^\lambda = (I + \lambda T)^{-1}$ is called the *resolvent* of T. An operator $B : H \to 2^H$ is said to be *nonexpansive* if

$$||y\prime - y|| \leq ||x\prime - x|| \text{ for all } [x, y], [x\prime, y\prime] \in G(B).$$

Note that nonexpansive operators are necessarily single-valued and Lipschitz continuous (see [11]).

An operator $C : H \to 2^H$ is said to be *firmly nonexpansive* if

$$||y\prime - y|| \leq (x\prime - x, y\prime - y) \text{ for all } [x, y], [x\prime, y\prime] \in G(C).$$

The following lemma summarizes some well-known properties of firmly nonexpansive operators.

Lemma 2 (Rockafellar [13]). *Let $T : H \to 2^H$ be an operator. The following statements are hold:*

(i) *All firmly nonexpansive operators are nonexpansive.*

(ii) *T is firmly nonexpansive if and only if $2T - I$ is nonexpansive.*

(iii) *T is firmly nonexpansive if and only if it is of the form $\frac{1}{2}(U+I)$, where U is nonexpansive.*

(iv) *T is firmly nonexpansive if and only* if *$I - T$ is firmly nonexpansive.*

We now give a critical theorem. The "only if" part of the following theorem has been well-known for some time (see [13]), but the "if" part has appeared in

[4]. The purpose here is to stress the complete symmetry that exists between (maximal) monotone operators and (full-domained) firmly nonexpansive operators over any Hilbert space.

Theorem 3 (Eckstein [5]). *Let λ be any positive scalar. An operator $T : H \to 2^H$ is monotone if and only if its resolvent $J_T^\lambda = (I + \lambda T)^{-1}$ is firmly nonexpansive. Furthermore, T is maximal monotone if and only if J_T^λ is firmly nonexpansive and $D(J_T^\lambda) = H$.*

Corollary 4. *An operator T is firmly nonexpansive if and only if $T^{-1} - I$ is monotone. T is firmly nonexpansive with full domain if and only if $T^{-1} - I$ is maximal monotone.*

Corollary 5. *For any $\lambda > 0$, the resolvent J_T^λ of a monotone operator T is single-valued. If T is also maximal, then J_T^λ is defined on all of H.*

Corollary 6 (The Representation Lemma). *Let λ >0 and let $T : H \to 2^H$ be monotone. Then every element $z \in H$ can be written in at most one way as $x + \lambda y$, where $y \in Tx$. If T is maximal, then every element $z \in H$ can be written in exactly one way as $x + \lambda y$, where $y \in Tx$.*

Corollary 7. *The correspondence from an operator T into $(I + T)^{-1}$ is a bijection between the collection of maximal monotone operators on H and the collection of firmly nonexpansive operators on H.*

Remark 8. Corollary 7 reminds us a result of Minty [10], but it is not identical (Minty did not use the concept of firm nonexpansiveness; see also [6]).

A *root* or *zero* of an operator T is a point x such that

$$0 \in Tx.$$

Let $zer(T) = T^{-1}(0)$ denote the set of all such points. The zeroes of a monotone operator are precisely the fixed points of its resolvents. In other words the following result is true:

Lemma 9. *Given any maximal monotone operator* T*, real number* λ >0*, and $x \in H$, we have $0 \in Tx$ if and only if $J_T^\lambda(x) = x$.*

Decomposition: Douglas-Rachford splitting methods

We shall consider the Douglas-Rachford scheme of Lions and Mercier [9].

Let us fix some$\lambda > 0$ and two maximal monotone operators W and V. The sequence $\{z^k\}$ is said to *obey the Douglas-Rachford recursion for* λ*,*W *and* V if

$$z^{k+1} = J_W^\lambda (2J_V^\lambda - I)z^k + (I - J_V^\lambda)z^k.$$

Let $[x^k, v^k] \in G(V)$ be, for all $k \geq 0$, the unique element such that $x^k + \lambda v^k = z^k$(by Corollary 6). Then, for all k, one has

$$(I - J_V^\lambda)z^k = x^k + \lambda v^k - x^k = \lambda v^k,$$

$$(2J_V^\lambda - I)z^k = 2x^k - (x^k + \lambda v^k) = x^k - \lambda v^k.$$

Similarly, if $[y^k, u^k] \in G(W)$, then $J_W^\lambda (y^k + \lambda u^k) = y^k$.

In view of these identities, one may give the following alternative prescription for finding z^{k+1} from z^k:

(i) Find the unique $[y^{k+1}, u^{k+1}] \in G(W)$ such that $y^{k+1} + \lambda u^{k+1} = x^k - \lambda v^k$.

(ii) Find the unique $[x^{k+1}, v^{k+1}] \in G(V)$ such that $x^{k+1} + \lambda v^{k+1} = y^{k+1} + \lambda v^k$.

The analysis is centered on the operator

$$S_{W,V}^\lambda = J_W^\lambda \circ (2J_V^\lambda - I) + (I - J_V^\lambda),$$

where "$\circ$" denotes mapping composition.

Thus the Douglas-Rachford recursion can be written as

$$z^{k+1} = S_{W,V}^\lambda (z^k).$$

Lions and Mercier [9] showed that $S_{W,V}^\lambda$ is firmly nonexpansive, from which they obtained the convergence of $\{z^k\}$. Their analysis can be extended by exploiting the connection between firm nonexpansiveness and maximal monotonicity.

Consider the operator

$$Q_{W,V}^\lambda = (S_{W,V}^\lambda)^{-1} - I.$$

Using the above algorithmic description (i)-(ii), we obtain the following expression for the graph of $S_{W,V}^\lambda$

$$G(S^{\lambda}_{W,V}) = \{[x+\lambda v, y+\lambda v] | [x,v] \in G(V), [y,u] \in G(W), y+\lambda u = x-\lambda v\}.$$

A simple computation provides an expression for $Q^{\lambda}_{W,V} = (S^{\lambda}_{W,V})^{-1} - I$,wiyh its graph:

$$G(Q^{\lambda}_{W,V}) = \{[y+\lambda v, x-y] | [x,v] \in G(V), [y,u] \in G(W), y+\lambda u = x-\lambda v\}.$$

Given any Hilbert space H, a scalar $\lambda > 0$, and the operators W and V on H, we define $Q^{\lambda}_{W,V}$ to be the *splitting operator* of W and V with respect to λ. The following theorem establishes the maximal monotonicity of $Q^{\lambda}_{W,V}$:

Theorem 10. *If W and V are monotone then $Q^{\lambda}_{W,V}$ is monotone. If W and V are maximal monotone then $Q^{\lambda}_{W,V}$ is maximal monotone.*

Combining Theorems 10 and 3 , we have the key Lions-Mercier result.

Corollary 11. *If W and V are maximal monotone, then $S^{\lambda}_{W,V} = (I + Q^{\lambda}_{W,V})^{-1}$ is firmly nonexpansive and is defined on all of H.*

There is also a relationship between the zeroes of $Q^{\lambda}_{W,V}$ and those of $W+V$.

Theorem 12. *Given $\lambda > 0$ and the operators W and V on H,*we have:

$$zer(Q^{\lambda}_{W,V}) = Z_{\lambda} = \{x+\lambda v | v \in Vx, -v \in Wx\} \subset \{x+\lambda v | x \in zer(W+V), v \in Vx\}.$$

In conclusion, given any zero z of $Q^{\lambda}_{W,V}$, $J^{\lambda}_{V}(z)$ is a zero of $W+V$. Thus one may imagine finding a zero of$W+V$ by using the proximal point algorithm on $Q^{\lambda}_{W,V}$ and then applying the operator J^{λ}_{V} to the result. In fact, this is precisely what the Douglas-Rachford splitting method does.

Theorem 13. *The Douglas-Rachford iteration*

$$z^{k+1} = J^{\lambda}_{W}(2J^{\lambda}_{V} - I)z^k + (I - J^{\lambda}_{V})z^k$$

is equivalent to applying proximal point algorithm to the maximal monotone operator $Q^{\lambda}_{W,V}$ with the proximal point stepsizes λ_k fixed at 1, and exact evaluation of the resolvents.

In conclusion the Douglas-Rachford splitting method is a special case of the proximal point algorithm as applied to the splitting operator $Q^{\lambda}_{W,V}$.

Generalized Proximal Point Algorithm

We present a scheme due to Golshtein and Tretyakov [6], which generalizes proximal point algorithm. They consider iterations of the form

$$z^{k+1} = (I - \rho_k)z^k + \rho_k J_T^{\lambda}(z^k),$$

(1)
where $\{\rho_k\}_{k=0}^{\infty} \subset (0, 2)$ is a sequence of *over*-or *under-relaxation* factors.
Golshtein and Tretyakov also allow resolvents to be evaluated approximatively, but, unlike Rockafellar, do not allow the stepsize λ to vary with k, restrict H to be finite-dimensional, and do not consider the case in which $zer(T) = \emptyset$. The following theorem combines the results of Rockafellar and Golshtein-Tretyakov.

Theorem 14 (Eckstein [5]). *Let$T$ be a maximal monotone operator on H, and let $\{z^k\}$ be such that*

$$z^{k+1} = (I - \rho_k)z^k + \rho_k w^k \textit{ for all } k \geq 0,$$

where

$$||w^k - (I + \lambda_k T)^{-1}(z^k)|| \leq \varepsilon_k \textit{ for all } k \geq 0,$$

and $\{\varepsilon_k\}$, $\{\rho_k\}$, $\{\lambda_k\} \subset [0, +\infty)$ *are sequences such that*

$$\mathrm{E}_1 = \sum{}_{k=0}^{\infty}\varepsilon_k < \infty,\ \Delta_1 = \inf_{k \geq 0} \rho_k > 0,\ \Delta_2 = \sup_{k \geq 0} \rho_k < 2,$$
$$\overline{\lambda} = \inf_{k \geq 0} \lambda_k > 0.$$

Such a sequence $\{z^k\}$ is said to be conform to the generalized proximal point algorithm. If T possesses a zero, then $\{z^k\}$ converges weakly to a zero of T. If T has no zeroes, then $\{z^k\}$ is an unbounded sequence.

We make some **remarks**:
- Theorem 14 states also that, in a general Hilbert space, the proximal point algorithm produces an unbounded sequence when applied to a maximal monotone operator that has no zeroes.

- In view of Theorems 14 and 12, we immediately obtain the following Lions-Mercier convergence result:
If $W + V$ has a zero, then the Douglas-Rachford splitting method produces a sequence $\{z^k\}$ weakly convergent to a limit z of the form $x + \lambda v$, where $x \in zer(W + V)$, $v \in Vx$,and $-v \in Wx$.

- Using Remark 15, we deduce the following result:

Suppose W and V are maximal monotone operators and $zer(W+V)=\emptyset$. Then the sequence $\{z^k\}$ produced by Douglas-Rachford splitting is unbounded.

We intend **to establish a relation between the Peaceman-Rachford algorithm and the generalized proximal point algorithm presented above.**

The following result will be used in the next presentation. We adapt a theorem, which was stated and proved in [1], in view of our goal.

Theorem 18. *Assume that T is a maximal monotone operator on H and* $zer(T)$ be a nonempty set. *We consider that the following statements hold:*
(i) $0 < \underline{\lambda} \leq \lambda_k$ *for all* $k \in \mathbf{N}^*$,
(ii) $0 < \overline{\rho} \leq \rho_k \leq 2$ *for all* $k \in \mathbf{N}^*$.
Then the sequence $\{z^k\}$ generated by the rule (1) weakly converges to an element of $zer(T)$ and it is such that

$$\lim_{k\to\infty} ||z^k - z^{k-1}|| = 0.$$

In the following analysis, we use the *Peaceman-Rachford scheme* of Lions and Mercier [9]. Let us consider some $\lambda > 0$ and two maximal monotone operators W and V. The sequence $\{z^k\}$ is obtained by Peaceman-Rachford algorithm if

$$z^{k+1} = (2J_W^\lambda - I)(2J_V^\lambda - I)z^k.$$

(2)

Given any sequence satisfying (2), let $[z^k, v^k]$ be, for all $k \geq 0$, the unique element of $G(V)$ such that

$$x^k + \lambda v^k = z^k.$$

The existence and uniqueness of this element follow from Corollaries 5, 6. Then for all k, one has

$$(2J_V^\lambda - I)z^k = 2x^k - (x^k + \lambda v^k) = x^k - \lambda v^k$$

.

Similarly, if $[y^k, u^k] \in G(W)$, then

$$J_W^\lambda(y^k + \lambda u^k) = y^k.$$

Using these relations, we can give the following alternative scheme for finding z^{k+1} from z^k:

(i) Find the unique element $[y^{k+1}, u^{k+1}] \in G(W)$such that

$$y^{k+1} + \lambda u^{k+1} = x^k - \lambda v^k,$$

(ii) Find the unique element $[x^{k+1}, v^{k+1}] \in G(V)$ such that

$$x^{k+1} + \lambda v^{k+1} = y^{k+1} - \lambda v^{k+1}$$

From (2) we obtain

$$z^{k+1} = 2J_W^\lambda(2J_V^\lambda - I)z^k + 2(I - J_V^\lambda)z^k - z^k.$$

This relation suggests us to use the operator

$$S_{W,V}^\lambda = J_W^\lambda \circ (2J_V^\lambda - I) + (I - J_V^\lambda).$$

The Peaceman-Rachford recursion (2) can be written as follows:

$$z^{k+1} = 2S_{W,V}^\lambda(z^k) - z^k = (2S_{W,V}^\lambda - I)z^k$$

(3)

Consider the operator

$$Q_{W,V}^\lambda = (S_{W,V}^\lambda)^{-1} - I,$$

Since Theorem 10 implies that $Q_{W,V}^\lambda$ is maximal monotone, we can define the operator

$$P_{W,V}^\lambda = 2(I + Q_{W,V}^\lambda)^{-1} - I = 2(I + Q_{W,V}^\lambda)^{-1} + (1 - 2)I.$$

We rewrite (3) using $P^{\lambda}_{W,V}$, in the form

$$z^{k+1} = P^{\lambda}_{W,V}(z^k) = 2(I + Q^{\lambda}_{W,V}(z^k) + (1-2)z^k.$$

Theorem 19. *The Peaceman-Rachford iteration*

$$z^{k+1} = (2J^{\lambda}_W - I)(2J^{\lambda}_V - I)z^k$$

is equivalent to applying the generalized proximal point algorithm to the maximal monotone operator $Q^{\lambda}_{W,V}$ with the proximal point stepsizes λ_k fixed at 1 and the relaxation factors $\rho_k = 2$ for all $k \geq 1$.

Proof. The Peaceman-Rachford iteration is

$$z^{k+1} = P^{\lambda}_{W,V}(z^k),$$

which is just

$$z^{k+1} = (1-2)z^k + 2(I + Q^{\lambda}_{W,V})^{-1}(z^k),$$

that is the generalized proximal point scheme (1) with $\rho_k = 2$ for all $k \geq 1$.

In view of the Theorems 18 and 12, we immediately obtain the following result.

Corollary 20. *If $W + V$ has a zero, then the Peaceman-Rachford splitting method produces a sequence $\{z^k\}$ weakly convergent to a limit* z *of the form $x + \lambda v$, where $x \in zer(W + V)$, $v \in Vx$ and $-v \in Wx$.*

Proof. From the Theorem 18, we obtain that the sequence $\{z^k\}$ converges weakly to a limit $z \in zer(Q^{\lambda}_{W,V})$. Applying Theorem 12, we have

$$z = x + \lambda v,$$

where $x \in zer(W + V)$, $v \in Vx$ and $-v \in Wx$.

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"CORINA L. CHIRIAC
"George Baritiu" University, Brasov, Romania
corinalchiriac@yahoo.com