Algorithms for monotone operators
Abstract problems
Splitting methods

Descent algorithms
Forward-Backward
Acceleration

Continuous (convex) optimisation

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Lecture 4: Splitting algorithms, Acceleration, FISTA

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Abstract methods for Monotone operators

General problem:

$$0 \in Ax \quad \text{or} \quad 0 \in Ax + Bx$$

where A, B are maximal monotone operators (which may or may not be subgradients).

Explicit methods

Generalization of gradient descent:

$$x^{k+1} = x^k - \tau p^k \, , p^k \in A x^k .$$

Issue: Even if A is single-valued and Lipschitz continuous, then this might not.

Example: $A = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$. Then,

$$x^k = \begin{pmatrix} 1 & -\tau \\ \tau & 1 \end{pmatrix}^k x^0 .$$

The eigenvalues of this matrix are $1 + \pm\tau i$ with modulus $\sqrt{1+\tau^2}$ and the iteration always diverges (unless $x^0 = 0$).

Explicit methods

So one needs a stronger condition on A. We recall that the gradient descent works for convex functions with Lipschitz gradient, and the proof relies on the co-coercivity.

Theorem

Let A maximal monotone be μ-co-coercive (in particular, single-valued):

$$\langle Ax - Ay, x - y\rangle \geq \mu |Ax - Ay|^2.$$

Assume there exists a solution to $Ax = 0$. Then the iteration $x^{k+1} = x^k - \tau Ax^k$ converges to x^* with $Ax^* = 0$ if $0 < \tau < 2\mu$.

The proof relies on proving that $I - \tau A$ is an averaged operator.

Explicit methods

Proof:

$$
\begin{aligned}
&|(I-\tau A)x-(I-\tau A)y|^2 \\
&\qquad = |x-y|^2 - 2\tau\langle x-y, Ax-Ay\rangle + \tau^2|Ax-Ay|^2 \\
&\qquad\qquad \le |x-y|^2 - \tau(2\mu-\tau)|Ax-Ay|^2 .
\end{aligned}
$$

This shows that if $0 \le \tau \le 2\mu$, $I-\tau A$ is 1-Lipschitz (nonexpansive). Hence for $\tau < 2\mu$,

$$
I-\tau A = (1-\tfrac{\tau}{2\mu})I + \tfrac{\tau}{2\mu}(I-(2\mu)A)
$$

is averaged. By The K-M Theorem, the iterates weakly converge, as $k\to\infty$, to a fixed point of $(I-\tau A)$ (if it exists). If $\tau = 0$ this is not interesting, if $0<\tau<2\mu$, then it is a zero of A, which exists by assumption.

Explicit method without co-coercivity?

Extragradient method (Korpelevich, 1976)

In case B is just L-Lipschitz continuous, the following method was proposed in 1976 by G. M. Korpelevich:

$$\begin{cases} y^k = x^k - \tau B x^k \\ x^{k+1} = x^k - \tau B y^k \end{cases}$$

Theorem

If $\tau L < 1$, then the algorithm generates sequences x^k and y^k which (weakly) converge to a solution of $Bx \ni 0$, if there exists one. In addition, $|x^k - y^k| \to 0$.

Remark: the original paper has an additional projection step (for a convex constraint), the proof is almost identical.

Extragradient method

Proof: For this algorithm we cannot use out of the box a previous theorem. We compute, for x^* with $Bx^* \ni 0$,

$$|x^{k+1}-x^*|^2 = |x^k-x^*|^2+2\left\langle x^k - x^*, x^{k+1} - x^k\right\rangle+|x^{k+1}-x^k|^2 = |x^k-x^*|^2-2\tau\left\langle x^k - x^*, By^k\right\rangle+|x^{k+1}-x^k|^2.$$

We use then that $\left\langle x^k - x^*, By^k\right\rangle = \left\langle x^k - y^k + y^k - x^*, By^k - Bx^*\right\rangle \geq \left\langle x^k - y^k, By^k\right\rangle$ and deduce:

$$|x^{k+1}-x^*|^2 \leq |x^k-x^*|^2-2\tau\left\langle x^k - y^k, By^k\right\rangle+|x^{k+1}-x^k|^2 = |x^k-x^*|^2+2\left\langle x^k - y^k, x^{k+1} - x^k\right\rangle+|x^{k+1}-x^k|^2.$$

It follows:

$$\begin{aligned}|x^{k+1} - x^*|^2 &\leq |x^k - x^*|^2 + |x^{k+1} - y^k|^2 - |x^k - y^k|^2 \\ &= |x^k - x^*|^2 + |\tau By^k - \tau Bx^k|^2 - |x^k - y^k|^2 \leq |x^k - x^*|^2 - (1 - \tau^2 L^2)|y^k - x^k|^2.\end{aligned}$$

We deduce, when $\tau L < 1$, that $|x^k - x^*|$ is decreasing (Fejér-monotonicity of the sequence), that $|x^k - y^k| \to 0$ (and therefore also $|x^{k+1} - y^k|$ and $|x^{k+1} - x^k|$) and can continue as in the proof of KM's theorem.

Extragradient method

One also needs to check that a fixed point is a solution! A fixed point satisfies: $y = x - \tau Bx$, $x = x - \tau By$. Hence one has $y - x = \tau(By - Bx)$ so that $|y - x| \leq \tau L|y - x|$. If $\tau L < 1$ then $y - x = 0$ and $Bx = 0$. $\square$

Proximal point algorithm

Now we consider the “implicit descent”:

$$x^{k+1} \in x^k - \tau A x^{k+1}$$

This is precisely which is solved by

$$x^{k+1} = (I + \tau A)^{-1} x^k = J_{\tau A} x^k$$

which is well-posed for A is maximal monotone.
This iteration is known as the *proximal point algorithm*. It obviously converges to a fixed point as the operator is $(1/2)$-averaged (if the fixed point, that is a point with $Ax = 0$, exists).

Proximal point algorithm
Overrelaxation

The reflexion $R_{\tau A} = 2(I + \tau A)^{-1} - I$ is 1-Lipschitz and one can generalize as follows:

$$x^{k+1} = (1 - \theta_k)x^k + \theta_k R_{\tau A} x^k = x^k + 2\theta_k \left((I + \tau A)^{-1} x^k - x^k \right) = x^k - 2\theta_k \tau A_\tau x^k,$$

for $0 < \underline{\theta} \le \theta_k \le \overline{\theta} < 1$.
We still get convergence.

Proximal point algorithm

Theorem (PPA Algorithm)

Let $x^0 \in \mathcal{X}$, $\tau_k \geq \underline{\tau} > 0$, $0 \leq \underline{\lambda} \leq \lambda_k \leq \overline{\lambda} \leq 2$, *and let*

$$x^{k+1} = x^k + \lambda_k((I + \tau_k A)^{-1} x^k - x^k). \tag{1}$$

If there exists x *with* $Ax \ni 0$, *then* x^k *weakly converges to a zero of* A.

We could also consider (summable) errors. (See Bauschke-Combettes for variants, Eckstein-Bertsekas for a proof with errors.)

Proof. The proof follows the lines of the proof of the KM Theorem.

We observe that obviously, $|x^{k+1} - x|^2 \leq |x^k - x|^2$ for each $k \geq 0$ and for each x with $Ax \ni 0$. But we can be more precise. One has:

Proximal point algorithm

$$
\begin{aligned}
|x^{k+1}-x|^2 &= |x^k-x|^2+\lambda_k^2|J_{\tau_k A}x^k-x^k|^2+2\lambda_k\left\langle x^k-x, J_{\tau_k A}x^k-x^k\right\rangle \\
&= |x^k-x|^2+\lambda_k^2|J_{\tau_k A}x^k-x^k|^2 \\
&\quad +\lambda_k\left(|J_{\tau_k A}x^k-x|^2-|x^k-x|^2-|J_{\tau_k A}x^k-x^k|^2\right).
\end{aligned}
$$

As $J_{\tau_k A}$ is firmly non-expansive:

$$
|J_{\tau_k A}x^k-x|^2+|(I-J_{\tau_k A})x^k-(I-J_{\tau_k A})x|^2\le|x^k-x|^2
$$

where in addition $(I-J_{\tau_k A})x=0$ so that $|(I-J_{\tau_k A})x^k-(I-J_{\tau_k A})x|^2=|x^k-J_{\tau_k A}x^k|^2$. Hence:

$$
\begin{aligned}
|x^{k+1}-x|^2 &\le |x^k-x|^2+\lambda_k^2|J_{\tau_k A}x^k-x^k|^2-2\lambda_k|J_{\tau_k A}x^k-x^k|^2 \\
&= |x^k-x|^2-\lambda_k(2-\lambda_k)|J_{\tau_k A}x^k-x^k|^2.
\end{aligned}
$$

Proximal Point Algorithm

Letting $c = \underline{\lambda}(2 - \overline{\lambda}) > 0$, we deduce that $(x^k)_k$ is Fejér-monotone with respect to $\{x : Ax \ni 0\}$ and that

$$c \sum_{k=0}^{n} |J_{\tau_k A} x^k - x^k|^2 + |x^{n+1} - x|^2 \leq |x^0 - x|^2$$

for all $n \geq 0$, in particular $|J_{\tau_k A} x^k - x^k| \to 0$ (as well as, by the scheme, $x^{k+1} - x^k$).
We would like to deduce convergence as in the proof of KM's Theorem. Yet, with varying τ_k, it is not obvious that a limit point $\bar{x}$ of a subsequence x^{k_l} is a fixed point (of what?).
But one proves that $Ax \ni 0$ using the maximal-monotonicity of A. If $x' \ni \mathcal{X}$, $y' \in Ax'$, denoting $e_k := J_{\tau_k A} x^k - x^k \to 0$ we have:

$$A(x^k + e^k) \ni -\frac{e_k}{\tau_k},$$

so that

$$\left\langle y' + \frac{e^k}{\tau_k}, x' - x^k - e^k \right\rangle \geq 0.$$

In the limit along the subsequence x^{k_l}, we find $\langle y', x' - \bar{x} \rangle \geq 0$, so that $A\bar{x} \ni 0$. The rest of the proof relies on Opial's lemma and is as in the proof of the KM Theorem.

Splitting methods

Forward-Backward splitting

We can now mix the implicit and explicit algorithms: Let A, B be maximal-monotone, with B μ-co-coercive. We define the *forward-backward* splitting algorithm as:

$$x^{k+1} = (I + \tau A)^{-1}(I - \tau B)x^k$$

If $0 < \tau < 2\mu$, the algorithm is the composition of two averaged operator $\rightarrow$ converges weakly to a fixed point if it exists:

$$(I + \tau A)^{-1}(I - \tau B)x = x \Leftrightarrow x - \tau Bx \in x + \tau Ax \Leftrightarrow Ax + Bx \ni 0.$$

(As B is continuous, this is equivalent to $(A + B)x \ni 0$. Hence, if $A + B$ has a zero, this algorithm converges to a zero of $A + B$.)

Douglas-Rachford splitting

Introduced under the following form in a paper of Lions and Mercier (79):

$$x^{k+1} = J_{\tau A}(2J_{\tau B} - I)x^k + (I - J_{\tau B})x^k$$

Theorem

Let $x^0 \in \mathcal{X}$. Then $x^k \rightharpoonup x$ such that $w = J_{\tau B}x$ is a solution of $Aw + Bw \ni 0$ (if it exists).

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Theorem

Let $x^0 \in \mathcal{X}$. Then $x^k \rightharpoonup x$ such that $w = J_{\tau B}x$ is a solution of $Aw + Bw \ni 0$ (if it exists).

To prove this, we express the iterations in terms of the reflexion opeators:

$$J_{\tau A} = \frac{1}{2}I + \frac{1}{2}R_{\tau A}, \quad J_{\tau B} = \frac{1}{2}I + \frac{1}{2}R_{\tau B}.$$

Douglas-Rachford splitting

One has then

$$J_{\tau A}(2J_{\tau B} - I)x + (I - J_{\tau B})x = \left(\frac{I + R_{\tau A}}{2}(R_{\tau B}) + \frac{I - R_{\tau B}}{2} \right)(x)$$
$$= \frac{I + R_{\tau A} \circ R_{\tau B}}{2}(x)$$

It follows that the iterates are of an averaged operator (with $1/2$).
A fixed points satisfies:

$$x = J_{\tau A}(2J_{\tau B} - I)x + (I - J_{\tau B})x \Leftrightarrow w := J_{\tau B}x = J_{\tau A}(2w - x)$$
$$\Leftrightarrow w + \tau Aw \ni 2w - x \Leftrightarrow \tau Aw \ni w - x$$

Now since $w + \tau Bw \ni x$, this is $\tau Aw + \tau Bw \ni 0$, which shows the theorem. $\square$

Douglas-Rachford splitting

and Peaceman-Rachford splitting

Remark: In addition: one can consider an "over-relaxed" iteration with operator:

$$(1-\theta)I + \theta R_{\tau A} \circ R_{\tau B} = I + 2\theta(J_{\tau A}(2J_{\tau B} - I) - J_{\tau B}).$$

for $0 < \theta < 1$. The case $\theta = 1$ is called the "Peaceman-Rachford" splitting and converges under some conditions on A, B.

Descent algorithms: Forward-backward descent

In case $A = \partial g$, $B = \nabla f$, g, f convex, lsc, f with L-Lipschitz gradient, the forward-backward splitting solves $\partial g(x) + \nabla f(x) \ni 0$: then x is a minimizer of the composite minimization problem:

$$\min_x F(x) := f(x) + g(x).$$

We consider the operator:

$$\bar{x} \mapsto \hat{x} = T_\tau \bar{x} := \mathrm{prox}_{\tau g}(\bar{x} - \tau\nabla f(\bar{x})) = (I + \tau\partial g)^{-1}(\bar{x} - \tau\nabla f(\bar{x})).$$

It corresponds to one explicit descent step for f followed by an implicit descent step for g.
[Also "composite" gradient descent, where $(T_\tau(x) - x)/\tau$ is the "composite" gradient of $f + g$, *cf* Nesterov, 2005]

Forward-Backward descent with fixed step ("ISTA")

We choose $x^0 \in \mathcal{X}$ and let $x^{k+1} = T_\tau x^k$ for fixed k. Then we have seen that if $\tau < 2/L$, the methods converges to a fixed point of T_τ which is a minimizer of F. In this case we can additionally show, at least for $\tau \le 1/L$:

$$F(x^k) - F(x^*) \le \frac{1}{2\tau k}|x^* - x^0|^2$$

while in case f is μ_f convex and/or g is μ_g convex ($\mu_f, \mu_g \ge 0$, $\mu_f + \mu_g > 0$) one shows:

$$F(x^k) - F(x^*) + \frac{1+\tau\mu_g}{2\tau}|x^k - x^*|^2 \le \omega^k \frac{1+\tau\mu_g}{2\tau}|x^0 - x^*|^2.$$

where $\omega = (1-\tau\mu_f)/(1+\tau\mu_g) < 1$.

Proof: descent inequality

Let $\hat{x} = T_\tau \bar{x}$: then for all $x \in \mathcal{X}$,

$$F(x) + (1 - \tau\mu_f)\frac{|x - \bar{x}|^2}{2\tau} \geq \frac{1 - \tau L}{\tau}\frac{|\hat{x} - \bar{x}|^2}{2} + F(\hat{x}) + (1 + \tau\mu_g)\frac{|x - \hat{x}|^2}{2\tau}.$$

In particular, if $\tau L \leq 1$,

$$F(x) + (1 - \tau\mu_f)\frac{|x - \bar{x}|^2}{2\tau} \geq F(\hat{x}) + (1 + \tau\mu_g)\frac{|x - \hat{x}|^2}{2\tau}.$$

The proof relies on the fact that $\hat{x}$ is obtained as a minimizer of

$$\min_x f(\bar{x}) + \langle \nabla f(\bar{x}), x - \bar{x}\rangle + g(x) + \frac{1}{2\tau}|x - \bar{x}|^2$$

which is $(\mu_g + \frac{1}{\tau})$-convex.

Descent inequality

Proof: One has

$$
\begin{aligned}
f(\bar{x}) + \langle \nabla f(\bar{x}), x - \bar{x}\rangle + g(x) + \frac{1}{2\tau}|x-\bar{x}|^2 \\
\geq f(\bar{x}) + \langle \nabla f(\bar{x}), \hat{x} - \bar{x}\rangle + g(\hat{x}) + \frac{1}{2\tau}|\hat{x}-\bar{x}|^2 + (\mu_g + \tfrac{1}{\tau})\frac{1}{2}|x-\bar{x}|^2
\end{aligned}
$$

Now, on the one hand we have:

$$F(x) = f(x) + g(x) \geq f(\hat{x}) + \langle \nabla f(\bar{x}), x - \bar{x}\rangle + \frac{\mu_f}{2}|x-\bar{x}|^2 + g(x)$$

and on the other hand because ∇f is L-Lipschitz we have

$$f(\bar{x}) + \langle \nabla f(\bar{x}), \hat{x} - \bar{x}\rangle + g(\hat{x}) \geq f(\hat{x}) - \frac{L}{2}|\hat{x}-\bar{x}|^2 + g(\hat{x}) = F(\hat{x}) - \frac{L}{2}|\hat{x}-\bar{x}|^2.$$

Combining these three inequalities we get the descent inequality:

$$F(x) + (1-\tau\mu_f)\frac{|x-\bar{x}|^2}{2\tau} \geq F(\hat{x}) + (1+\tau\mu_g)\frac{|x-\hat{x}|^2}{2\tau}.$$

Rates of convergence for the FB splitting

We consider the case $\mu_f + \mu_g = 0$. The descent rule with $x = x^*$ shows that:

$$F(x^{k+1}) + \frac{1}{2\tau}|x^{k+1} - x^*|^2 \leq F(x^*) + \frac{1}{2\tau}|x^k - x^*|^2$$

while for $x = x^k$ we get:

$$F(x^{k+1}) + \frac{1}{2\tau}|x^{k+1} - x^k|^2 \leq F(x^k)$$

We deduce that for $N \geq 1$,

$$N(F(x^N) - F(x^*)) \leq \sum_{k=0}^{N-1} F(x^{k+1}) - F(x^*) + \frac{1}{2\tau}|x^N - x^*|^2 \leq + \frac{1}{2\tau}|x^0 - x^*|^2.$$

FISTA: acceleration for the FB splitting

Due in this form to Beck and Teboulle (2009), see also Nesterov (1983, 2004 "Introductory lectures...")

Algorithm: FISTA with fixed steps:

Choose $x^0 = x^{-1} \in \mathcal{X}$ and $t_0 \geq 0$

for all $k \geq 0$ **do**

$$y^k = x^k + \beta_k(x^k - x^{k-1})$$
$$x^{k+1} = T_\tau y^k = \mathrm{prox}_{\tau g}(y^k - \tau \nabla f(y^k))$$

where

$$t_{k+1} = \frac{1+\sqrt{1+4t_k^2}}{2} \geq \frac{k+1}{2},$$
$$\beta_k = \frac{t_k - 1}{t_{k+1}},$$

end for

FISTA: strongly convex case

In case $\mu = \mu_f + \mu_g > 0$ is known, then the previous method is not optimal. One should choose:

$$t_{k+1} = \frac{1 - qt_k^2 + \sqrt{(1 - qt_k^2)^2 + 4t_k^2}}{2},$$
$$\beta_k = \frac{t_k - 1}{t_{k+1}} \frac{1 + \tau\mu_g - t_{k+1}\tau\mu}{1 - \tau\mu_f},$$

where $q = \tau\mu/(1 + \tau\mu_g) < 1$, or alternatively the fixed overrelaxation parameter: $\beta = \frac{\sqrt{1+\tau\mu_g} - \sqrt{\tau\mu}}{\sqrt{1+\tau\mu_g} + \sqrt{\tau\mu}}$.

FISTA: rate

Theorem

If $\sqrt{q}t_0 \le 1$, $t_0 \ge 0$, then the sequence (x^k) produced the algorithm satisfies

$$F(x^k) - F(x^*) \le \min\left\{\frac{(1-\sqrt{q})^k}{t_0^2}, \frac{4}{(k+1)^2}\right\}\left(t_0^2(F(x^0) - F(x^*)) + \frac{1+\tau\mu_g}{2\tau}|x^0 - x^*|^2\right)$$

if $t_0 \ge 1$, and

$$F(x^k) - F(x^*) \le \min\left\{(1+\sqrt{q})(1-\sqrt{q})^k, \frac{4}{(k+1)^2}\right\}\left(t_0^2(F(x^0) - F(x^*)) + \frac{1+\tau\mu_g}{2\tau}|x^0 - x^*|^2\right)$$

if $t_0 \in [0,1]$, where x^* is a minimiser of F.

Common choices are $t_0 = 0$, $t_0 = 1$. The rate is "optimal".

FISTA: proof

Again we prove first $\mu_f + \mu_g = 0$.
In that case, the algorithm has the form $x^{k+1} = T_\tau y^k$ for some y^k which we will specify later. One has for all x:

$$F(x^{k+1}) + \frac{|x - x^{k+1}|^2}{2\tau} \le F(x) + \frac{|x - y^k|^2}{2\tau}$$

The idea is to choose x as a convex combination of a minimizer x^* [or any point] and the old point x^k, and use the convexity to deduce a "better" decrease. Here we choose (as it will make the computation much quicker) $x = ((t-1)x^k + x^*)/t$, $t \ge 1$, and we find:

$$\begin{aligned} F(x^{k+1}) - F(x^*) + \frac{|(t-1)x^k + x^* - tx^{k+1}|^2}{2t^2\tau} &\le F(\frac{(t-1)x^k + x^*}{t}) - F(x^*) + \frac{|(t-1)x^k + x^* - ty^k|^2}{2t^2\tau} \\ &\le \frac{t-1}{t}(F(x^k) - F(x^*)) + \frac{|(t-1)x^k + x^* - ty^k|^2}{2t^2\tau}. \end{aligned}$$

Hence multiplying by t^2 and adding an index $k+1$ to t:

$$\begin{aligned} t_{k+1}^2(F(x^{k+1}) - F(x^*)) + \frac{|(t_{k+1}-1)x^k + x^* - t_{k+1}x^{k+1}|^2}{2\tau} \\ \le t_{k+1}(t_{k+1}-1)(F(x^k) - F(x^*)) + \frac{|(t_{k+1}-1)x^k + x^* - t_{k+1}y^k|^2}{2\tau}. \end{aligned}$$

FISTA: proof

We see here that the factor in front of $F(x^k)$ is strictly less than in front of $F(x^{k+1})$.

$$t_{k+1}^2(F(x^{k+1})-F(x^*))+\frac{|(t_{k+1}-1)x^k+x^*-t_{k+1}x^{k+1}|^2}{2\tau} \\ \le t_{k+1}(t_{k+1}-1)(F(x^k)-F(x^*))+\frac{|(t_{k+1}-1)x^k+x^*-t_{k+1}y^k|^2}{2\tau}.$$

This iteration can be iterated if the sequences t_k and y_k satisfy:

$$t_{k+1}(t_{k+1}-1)=t_k^2 \qquad (\le \text{ if } x^* \text{ is a minimizer})$$
$$(t_{k+1}-1)x^k+x^*-t_{k+1}y^k=(t_k-1)x^{k-1}+x^*-t_kx^k.$$

Then, indeed, we have

$$t_{k+1}^2(F(x^{k+1})-F(x^*))+\frac{|(t_{k+1}-1)x^k+x^*-t_{k+1}x^{k+1}|^2}{2\tau} \\ \le t_k^2(F(x^k)-F(x^*))+\frac{|(t_k-1)x^{k-1}+x^*-t_kx^k|^2}{2\tau}$$

and summing we obtain

$$t_N^2(F(x^N)-F(x^*))\le t_0^2(F(x^0)-F(x^*))+\frac{|(t_0-1)x^{-1}+x^*-t_0x^0|^2}{2\tau}$$

with by convention $y^0=x^0=x^{-1}$, and t_0 does not need to be ≥ 1 (only t_1).

FISTA: proof

To ensure:

$$t_{k+1}(t_{k+1} - 1) = t_k^2 \qquad\qquad (\leq \text{ if } x^* \text{ is a minimizer})$$

one can solve $t_{k+1}^2 - t_{k+1} - t_k^2 = 0$ and take

$$t_{k+1} = \frac{1 + \sqrt{1 + 4t_k^2}}{2}$$

(observe that if $t_0 \geq 0$, $t_1 \geq 1$), or one can also show that $t_k = (k + a - 1)/a$, $a \geq 2$, satisfies $t_{k+1} \geq 1$ and $t_{k+1}^2 - t_{k+1} \leq t_k^2$ for any $k \geq 0$.

FISTA: proof

To ensure:

$$t_{k+1}(t_{k+1}-1) = t_k^2 \qquad\qquad (\leq \text{ if } x^* \text{ is a minimizer})$$

one can solve $t_{k+1}^2 - t_{k+1} - t_k^2 = 0$ and take

$$t_{k+1} = \frac{1+\sqrt{1+4t_k^2}}{2}$$

(observe that if $t_0 \geq 0$, $t_1 \geq 1$), or one can also show that $t_k = (k+a-1)/a$, $a \geq 2$, satisfies $t_{k+1} \geq 1$ and $t_{k+1}^2 - t_{k+1} \leq t_k^2$ for any $k \geq 0$.

To ensure: $(t_{k+1}-1)x^k + x^* - t_{k+1}y^k = (t_k - 1)x^{k-1} + x^* - t_k x^k$ one has to take, simply,

$$y^k = x^k + \frac{t_k - 1}{t_{k+1}}(x^k - x^{k-1}).$$

FISTA: analysis

Observe that

$$\frac{1+\sqrt{1+4t_k^2}}{2} \geq \frac{1}{2} + t_k$$

hence if $t_1 = 1$, $t_k \geq (k+1)/2$. Then, the final bound shows, for $t_0 = 0$ and $\tau = 1/L$:

$$F(x^N) - F(x^*) \leq \frac{2L}{(k+1)^2}|x^0 - x^*|^2$$

which is "optimal".