An introduction to nonsmooth optimisation

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Outline

Descent methods

Gradient descent

Subgradient descent

Projected gradient descent

Douglas-Rachford splitting

Alternating Direction Method of Multipliers (ADMM)

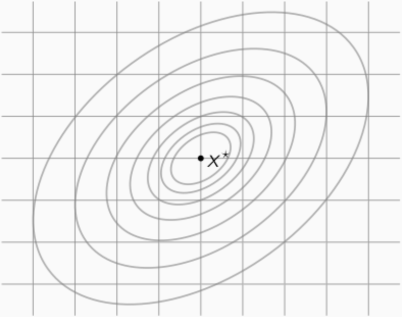
Primal-Dual splitting

Unconstrained smooth optimisation

We first consider minimising

$$\min_{x \in \mathbb{R}^n} F(x)$$

where $F : \mathbb{R}^n \to \mathbb{R}$ is a proper, convex and differentiable function.



Unconstrained smooth optimisation

We first consider minimising

$$\min_{x \in \mathbb{R}^n} F(x)$$

where $F : \mathbb{R}^n \to \mathbb{R}$ is a proper, convex and differentiable function.

- Assume that the set of minimisers is nonempty,

$$\operatorname{argmin}(F) = \left\{ x \in \mathbb{R}^n \; ; \; F(x) = \min_{x \in \mathbb{R}^n} F(x) \right\} \neq \emptyset$$

- $x_* \in \operatorname{argmin}(F)$ has no closed form expression in general.
- We will consider iterative algorithms which start at a point x_0 and build a sequence x_k which converge to a minimiser.

General iterative method

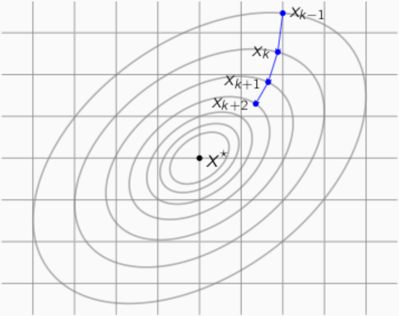
Initialization $x_0 \in \mathrm{dom}(F)$

while *stopping criterion not satisfied* **do**

choose step-size $\gamma_k > 0$ and a search direction d_k

Update $x_{k+1} = x_k - \gamma_k d_k$

end

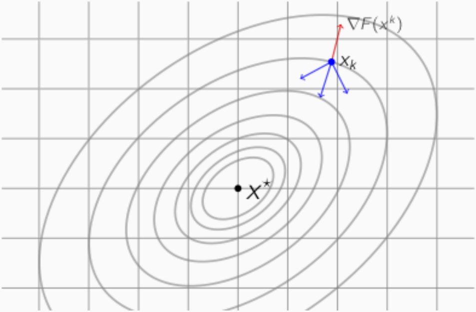


Choice of d_k to enforce descent

Descent methods

An algorithm is called a descent method if $F(x_{k+1}) < F(x_k)$.

- $\varphi_k(\gamma) \overset{\text{def.}}{=} F(x_k + \gamma d_k)$ is a decreasing function
- So, for d_k to be a descent direction, we need $\varphi_k'(0) = \langle \nabla F(x_k), d_k \rangle < 0$.



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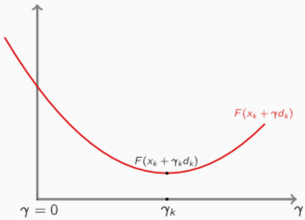

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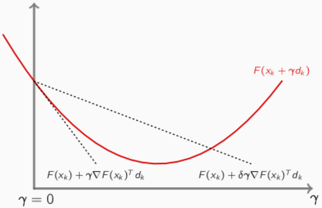
3. Backtracking: Given direction d_k, choose $\delta \in (0,1)$ and $\beta \in (0,1)$ and let $\gamma = 1$.

$$\text{while } F(x_k + \gamma d_k) > F(x_k) + \delta\gamma\langle \nabla F(x_k),\, d_k\rangle \,:\; \gamma = \beta\gamma.$$



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- Optimality condition: $\|\nabla F(x_k)\| \leqslant \varepsilon$.

Outline

Gradient descent

The method of steepest descent or gradient descent chooses $d_k = -\nabla F(x_k)$. If x_k is not a stationary point, then $\nabla F(x_k) \neq 0$ and

$$\langle \nabla F(x_k),\, d_k \rangle = -\left\| \nabla F(x_k) \right\|^2 < 0$$

Gradient descent

Initialization $x_0 \in \mathrm{dom}(F)$

while *stopping criterion not satisfied* **do**

  choose step-size $\gamma_k > 0$

  Update $x_{k+1} = x_k - \gamma_k \nabla F(x_k)$

end

NB: method may not converge if γ_k is too large.

Convergence of gradient descent

Let $F \in \mathcal{C}^1$, ∇F is L-Lipschitz and $\operatorname{argmin}(F) \neq \emptyset$. Let $\gamma_k \equiv \gamma$.

General case

Choosing fixed $\gamma \in (0, 2/L)$, $\nabla F(x_k) \to 0$.

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Convex case

Suppose that F is convex and let x_* be a minimiser. For $\gamma \in (0, 2/L)$,

$$F(x_k) - F(x_*) \leqslant \frac{\|x_0 - x_*\|^2}{\theta(k+1)}, \quad \text{where} \quad \theta = \gamma(1 - \gamma L/2). \tag{2.1}$$

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Strongly-convex case

If F is α-strongly convex, that is, $F(x) - \alpha \|x\|^2 /2$ is convex (if $F \in \mathcal{C}^2$, equivalent to $\nabla^2 F(x) \geqslant \alpha \mathrm{Id}$), then

$$\|x_{k+1} - x_*\| \leqslant \max(1 - \gamma\alpha, \gamma L - 1) \|x_k - x_*\|.$$

Best constant is $\gamma = 2/(L + \alpha)$:

$$\|x_k - x_*\| \leqslant q^k \|x_0 - x_*\| \quad \text{where} \quad q = (L - \alpha)/(L + \alpha) \in (0, 1).$$

Lower complexity bounds

Suppose that x_k is an element of

$$x_0 + \mathrm{Span}\{\nabla F(x_0), \nabla F(x_1), \ldots, \nabla F(x_{k-1})\}. \tag{2.2}$$

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Theorem 2.1 (Nesterov's lower complexity bound)

For any $n \geqslant 2$ and $x_0 \in \mathbb{R}^n$, $L > 0$ and $k < n$, there exists a convex one-time continuously differentiable function F with L-Lipschitz continuous gradient, such that for any algorithm satisfying (2.2), we have

$$F(x_k) - F(x_*) \geqslant \frac{L\,\|x_0 - x_*\|^2}{8(k+1)^2}$$

where x_* denotes a minimiser of F.

- This result is valid only when the number of iterations is smaller than the problem size.

Suppose that x_k is an element of

$$x_0 + \mathrm{Span}\{\nabla F(x_0), \nabla F(x_1), \ldots, \nabla F(x_{k-1})\}. \tag{2.2}$$

Theorem 2.1 (Lower complexity bound for strongly convex functions)

For any $x_0 \in \ell_2(\mathbb{N})$ and $\gamma, L > 0$, there exists a γ-strongly convex one times continuously differentiable function f with L-Lipschitz gradient such that for any algorithm satisfying (2.2), we have for all k

$$f(x_k) - f(x_*) \geqslant \frac{\gamma}{2}\left(\frac{\sqrt{Q}-1}{\sqrt{Q}+1}\right)^{2k}\|x_0 - x_*\|^2.$$

where $Q = L/\gamma \geqslant 1$ is the condition number and x_* is a minimiser of f.

Accelerated gradient descent

Initialization $x_0 = \bar{x}_0 \in \mathrm{dom}(F)$ and $\lambda_0 = 0$

while *stopping criterion not satisfied* **do**

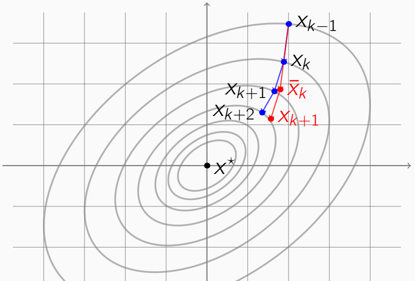
choose step-size $\gamma_k > 0$

Update $x_{k+1} = \bar{x}_k - \gamma_k \nabla F(\bar{x}_k)$

$\lambda_k = \frac{1+\sqrt{1+4\lambda_{k-1}^2}}{2}$ and $a_k = \frac{1-\lambda_k}{\lambda_{k+1}}$

$\bar{x}_{k+1} = x_{k+1} + a_k(x_{k+1} - x_k)$

end



If F is L-Lipschitz gradient, then by choosing $\gamma_k = 1/L$, AGD achieves $\mathcal{O}(1/k^2)$ convergence rate

Outline

Nonsmooth optimisation

Let $R : \mathbb{R}^n \to (-\infty, +\infty]$ be proper, convex and lower semi-continuous, but non-differentiable. Assume that $\mathrm{argmin}(R) \neq \emptyset$ and consider

$$\min_{x \in \mathbb{R}^n} R(x). \tag{3.1}$$

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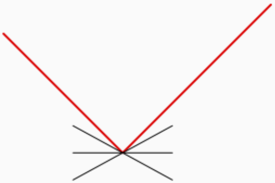
Recall: the subdifferential of R at x is the set

$$\partial R(x) = \{p \in \mathbb{R}^n \; ; \; R(y) - R(x) \geqslant \langle p, y - x \rangle, \quad \forall y \in \mathbb{R}^n\} .$$



$$\partial \|x\|_1 = \begin{cases} 1 & x > 0 \\ -1 & x < 0 \\ [-1, 1] & x = 0 \end{cases} .$$

Note that $\partial R(x) = \{\nabla R(x)\}$ when R is differentiable at x.

Subgradient descent

Initialization $x_0 \in \mathrm{dom}(R)$

while *stopping criterion not satisfied* **do**

choose step-size $\gamma_k > 0$ and a subgradient $g_k \in \partial R(x_k)$

Update $x_{k+1} = x_k - \gamma_k g_k$

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In general, if x_* is a solution

$$\begin{aligned}\|x_{i+1} - x_*\|^2 &= \|x_i - x_*\|^2 + \|\gamma_i g_i\|^2 - 2\gamma_i \langle g_i, x_i - x_* \rangle \\ &\leqslant \|x_i - x_*\|^2 + \|\gamma_i g_i\|^2 - 2\gamma_i (R(x_i) - R(x_*))\end{aligned}$$

So, summing from $i = 0, \ldots, k$ and rearranging, we have

$$\sum_{i=0}^{k} \gamma_i (R(x_i) - R(x_*)) \leqslant \|x_0 - x_*\|^2 + \sum_{i=0}^{k} \gamma_i^2 \|g_i\|^2 - \|x_{k+1} - x_*\|^2$$

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If R is L-Lipschitz,

$$2 \min_{i=0}^{k} (R(x_i) - R(x_*)) \leqslant \frac{\|x_0 - x_*\|^2 + L \sum_{i=0}^{k} \gamma_i^2}{2 \sum_{i=0}^{k} \gamma_i}$$

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- No convergence if γ_k is fixed. Note also that this is not a descent method.

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- In general choose $\sum_i \gamma_i^2 < \infty$ and $\sum_i \gamma_i = +\infty$, so γ_i converges to 0.
- Choosing $\gamma_i \equiv C/\sqrt{k+1}$ for k iterations, then

$$\min_{i=0}^{k} (R(x_i) - R(x_*)) \leqslant \frac{\|x_0 - x_*\|^2 + LC^2}{2C\sqrt{k+1}}.$$

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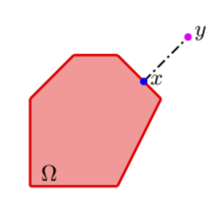
Projection onto sets

Indicator function: Let $\Omega \subseteq \mathbb{R}^n$

$$\iota_\Omega(x) = \begin{cases} +\infty & x \notin \Omega \\ 0 & x \in \Omega. \end{cases}$$



Projection onto Ω:

$$\mathcal{P}_\Omega(y) \stackrel{\text{def.}}{=} \operatorname{argmin}_{x \in \Omega} \|x - y\| .$$

Projected gradient descent

Constrained smooth optimisation

Let $F \in \mathcal{C}^1$ with L-Lipschitz gradient and let $\Omega \subset \mathbb{R}^n$ be a closed convex set, and consider

$$\min_{x \in \Omega} F(x). \tag{4.1}$$

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Projected gradient descent method

Initialization $x_0 \in \Omega$

while *stopping criterion not satisfied* **do**

choose step-size $\gamma_k \in (0, 2/L)$

Update $x_{k+1/2} = x_k - \gamma_k \nabla F(x_k)$

Project $x_{k+1} = \mathcal{P}_\Omega(x_{k+1/2})$

end

- Hyperplane: $\Omega = \{x : a^T x = b\},\ a \neq 0$

$$\mathcal{P}_\Omega = x + \frac{b - a^T x}{\|a\|^2} a.$$

- Affine subspace: $\Omega = \{x : Ax = b\}$ with $A \in \mathbb{R}^{m \times n},\ \operatorname{rank}(A) = m < n$

$$\mathcal{P}_\Omega = x + A^T (AA^T)^{-1} (b - Ax).$$

- Half space: $\Omega = \{x : a^T x \leqslant b\},\ a \neq 0$

$$\mathcal{P}_\Omega = x + \frac{b - a^T x}{\|a\|^2} a \quad \text{if } a^T x > b \qquad \text{and} \quad x \quad \text{if } a^T x \leqslant b.$$

- Nonnegative orthant: $\Omega = \mathbb{R}^n_+$

$$\mathcal{P}_\Omega = \left(\max\{0, x_i\}\right)_i.$$

Composite optimisation problem

Composite optimisation

$$\min_{x\in\mathbb{R}^n} \Phi(x) \stackrel{\text{def.}}{=} F(x) + R(x). \tag{4.2}$$

where $F \in \mathcal{C}^1$ has L-Lipschitz gradient and R is proper, convex, lower semi-continuous but nonsmooth.

Note that the constrained smooth problem can be rewritten as

$$\min_{x\in\mathbb{R}^n} F(x) + \iota_\Omega(x).$$

From projection to proximal mapping

Proximal mapping

Let R be proper, convex, lower semicontinuous and bounded from below. Its proximal mapping is defined by

$$\mathrm{prox}_{\gamma R}(y) \stackrel{\text{def.}}{=} \operatorname{argmin}_{x \in \mathbb{R}^n} \ \gamma R(x) + \frac{1}{2} \|x - y\|^2 .$$

Note that this is precisely the projection operator $\mathcal{P}_\Omega$ when $R = \iota_\Omega$.

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Optimality condition denote $y_+ \stackrel{\text{def.}}{=} \mathrm{prox}_{\gamma R}(y)$,

$$\begin{aligned} 0 \in \gamma\partial R(y_+) + y_+ - y \quad &\Longleftrightarrow \quad y \in (\mathrm{Id} + \gamma\partial R)(y_+) \\ &\Longleftrightarrow \quad y_+ = (\mathrm{Id} + \gamma\partial R)^{-1}(y). \end{aligned}$$

Proximal gradient descent

Initialization $x_0 \in \mathrm{dom}(\Phi)$

while *stopping criterion not satisfied* **do**

  choose step-size $\gamma_k \in (0, 2/L)$

  Update $x_{k+1/2} = x_k - \gamma_k \nabla F(x_k)$

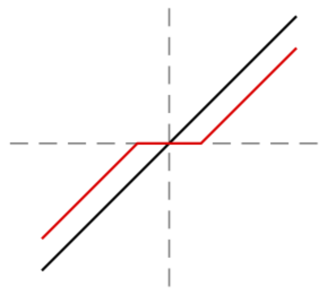
  Project $x_{k+1} = \mathrm{prox}_{\gamma_k R}(x_{k+1/2})$

end

Example

Soft-threshold: $R(x) = |x|$,

$$\operatorname{prox}_{\gamma R}(y) = \mathcal{T}_\gamma(y) = \begin{cases} y - \gamma : y > \gamma, \\ \quad 0 : y \in [-\gamma, \gamma], \\ y + \gamma : y < -\gamma. \end{cases}$$



Example

Consider the Lasso problem where for $y \in \mathbb{R}^m$ and a matrix $K \in \mathbb{R}^{n \times m}$,

$$R(x) = \lambda \|x\|_1 \quad \text{and} \quad F(x) = \frac{1}{2} \|Kx - y\|^2$$

- $\nabla F(x) = K^*(Kx - y)$
- $L = \|K^* K\|$
- The proximal mapping of γR is the soft-thresholding operator $\mathcal{T}_\gamma$

The iterates are therefore, for $\gamma_k \in (0, 1/\|K^* K\|]$:

$$x_{k+1} = \mathcal{T}_{\lambda \gamma_k}(x_k - \gamma_k(K^*(Kx_k - y)))$$

Specialised to the ℓ_1 case, this is sometimes known as the iterative soft thresholding algorithm (ISTA).

Interpretation

This is also known as Forward-Backward splitting:

$$x_{k+1} = \mathrm{prox}_{\gamma R}(x_k - \gamma \nabla F(x_k))$$

- forward: gradient descent set in F
- backward: implicit step in R

Interpretation

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$$x_{k+1} = \mathrm{prox}_{\gamma R}(x_k - \gamma \nabla F(x_k))$$

- forward: gradient descent set in F
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By definition of prox,

$$\begin{aligned} x_{k+1} &= \mathrm{argmin}_x \{ \frac{1}{2} \|x - (x_k - \gamma \nabla F(x_k))\|^2 + \gamma R(x) \} \\ &= \mathrm{argmin}_x \{ \frac{1}{2} \|x - x_k\|^2 + \gamma \langle x - x_k, \nabla F(x_k)) \rangle + \gamma R(x) \} \\ &= \mathrm{argmin}_x \{ F(x_k) + \langle x - x_k, \nabla F(x_k)) \rangle + \frac{1}{2\gamma} \|x - x_k\|^2 + R(x) \} \end{aligned}$$

So, x_{k+1} minimises $R(x)$ plus majorisation of $F(x)$ at x_k if $\gamma \leqslant \frac{1}{L}$

Convergence properties

FB is a descent method.

- For $\gamma_k \equiv \gamma \in (0, 1/L]$, x_k converges to a minimiser and

$$\Phi(x_k) - \Phi(x_*) \leqslant \frac{1}{2\gamma k} \|x_0 - x_*\|^2 .$$

- If F and R are strongly convex with parameters μ_F, μ_R and $\mu \overset{\text{def.}}{=} \mu_F + \mu_R > 0$, then

$$\Phi(x_k) - \Phi(x_*) \leqslant \omega^k \frac{(1 + \gamma\mu_R)}{2\gamma} \|x_0 - x_*\|^2 ,$$

  where $\omega = (1 - \gamma\mu_F)/(1 + \gamma\mu_R)$.

The convergence rate matches that of gradient descent, although faster convergence rates can be obtained by

- incorporating Nesterov acceleration. This is called FISTA (fast iterative soft thresholding).
- Another (very effective) acceleration technique for FB is the restarted-FISTA scheme.

Other examples of proximal operators

Quadratic function $R(x) = \frac{1}{2}x^T Ax + b^T x + c,\ A \succeq 0$

$$\mathrm{prox}_{\gamma R}(y) = (\mathrm{Id} + \gamma A)^{-1}(y - \gamma b).$$

Euclidean norm $R(x) = \|x\|$

$$\mathrm{prox}_{\gamma R}(y) = \begin{cases} (1 - \frac{\gamma}{\|y\|})y : \|y\| > \gamma, \\ 0 : o.w. \end{cases}$$

Nuclear norm $R(x) = \sum_i \sigma_i$

$$\mathrm{prox}_{\gamma R}(y) = U\mathcal{T}_\gamma\left(\Sigma\right)V^T.$$

Calculus rules for proximal operators

Quadratic perturbation $H(x) = R(x) + \frac{\alpha}{2}\|x\|^2 + \langle x, u\rangle + \beta,\ \alpha \geqslant 0$

$$\mathrm{prox}_H = \mathrm{prox}_{R/(\alpha+1)}\left(\frac{x-u}{\alpha+1}\right).$$

Translation $H(x) = R(x-z)$

$$\mathrm{prox}_H = z + \mathrm{prox}_R(x-z).$$

Scaling $H(x) = R(x/\rho)$

$$\mathrm{prox}_H = \rho\, \mathrm{prox}_{R/\rho^2}\left(\frac{x}{\rho}\right).$$

Reflection $H(x) = R(-x)$

$$\mathrm{prox}_H = -\mathrm{prox}_R(-x).$$

Composition $H = R \circ L$ with L being bijective bounded linear mapping such that $L^{-1} = L^*$,

$$\mathrm{prox}_H = L^* \circ \mathrm{prox}_R \circ L.$$

Outline

Two nonsmooth terms

We now let $F, G \in \Gamma_0(\mathbb{R}^n)$ and consider

$$\min_x F(x) + G(x) \tag{5.1}$$

Define the reflection operator:

$$\mathrm{rprox}_F \stackrel{\text{def.}}{=} 2\mathrm{prox}_F - \mathrm{Id}.$$

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Douglas-Rachford splitting

Initialization $x_0 \in \mathrm{dom}(\Phi)$, $\gamma > 0$, $\mu \in (0, 2)$

while *stopping criterion not satisfied* **do**

$$x_k = \mathrm{prox}_{\gamma F}(z_k)$$

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(ii)
$$\begin{aligned}
\mathrm{prox}_{\gamma G}(x) &= \mathrm{argmin}_z \left\{ \|z - x\|_2^2 \; ; \; Az = b \right\} \\
&= x + \mathrm{argmin}_y \left\{ \|y\|_2^2 \; ; \; A(y + x) = b \right\} \\
&= x + A^\dagger (b - Ax).
\end{aligned}$$

Intuition for the Douglas-Rachford iterates

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The fixed point formulation

$$x_* = \mathrm{prox}_{\gamma F}(z_*) \quad \text{and} \quad z_* = z_* + \mu \left(\mathrm{prox}_{\gamma G}(2x_* - z_*) - x_*\right)$$

leads to the fixed point iterations

$$\begin{aligned} x_k &= \mathrm{prox}_{\gamma F}(z_k) \\ z_{k+1} &= z_k + \mu \left(\mathrm{prox}_{\gamma G}(2x_k - z_k) - x_k\right) \end{aligned}$$

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Substituting the first line into the second line gives:

$$\begin{aligned} z_{k+1} &= z_k + \mu \left(\mathrm{prox}_{\gamma G}(\mathrm{rprox}_{\gamma F}(z_k)) - \mathrm{prox}_{\gamma F}(z_k)\right) \\ &= (1 - \frac{\mu}{2})z_k + \frac{\mu}{2}\ \mathrm{rprox}_{\gamma G}(\mathrm{rprox}_{\gamma F}(z_k)) \end{aligned}$$

Outline

Alternating Direction Method of Multipliers (ADMM)

We now consider the following constrained optimisation problem:

$$\min_{x,y} F(x) + G(y) \quad \text{such that} \quad Ax + By = \zeta, \tag{6.1}$$

where $F, G \in \Gamma_0(\mathbb{R}^n)$.

The **augmented Lagrangian** formulation is

$$\min_{x,y} \sup_{\psi} F(x) + G(y) - \langle \psi, Ax + By - \zeta \rangle + \frac{\gamma}{2} \|Ax + By - \zeta\|^2 \tag{6.2}$$

Note that the two formulations are equivalent since the supremum is $+\infty$ if $Ax + By \neq \zeta$.

The ADMM iterations: alternate between descents on x, y and ascent on ψ

$$\min_{x,y} \sup_{\psi} F(x) + G(y) - \langle \psi,\, Ax + By - \zeta \rangle + \frac{\gamma}{2} \|Ax + By - z\|^2 \tag{6.3}$$

ADMM

Initialization $y_0, \psi_0,\, \gamma > 0$

while *stopping criterion not satisfied* **do**

$$x_{k+1} \in \operatorname{argmin}_x F(x) + G(y_k) - \langle \psi_k,\, Ax + By_k - \zeta \rangle + \frac{\gamma}{2} \|Ax + By_k - \zeta\|^2$$

$$y_{k+1} \in \operatorname{argmin}_y F(x_{k+1}) + G(y) - \langle \psi_k,\, Ax_{k+1} + By - \zeta \rangle + \frac{\gamma}{2} \|Ax_{k+1} + By - \zeta\|^2$$

$$\psi_{k+1} = \psi_k + \gamma(\zeta - Ax_{k+1} - By_{k+1})$$

end

The ADMM iterations: alternate between descents on x, y and ascent on ψ

$$\min_{x,y} \sup_{\psi} F(x) + G(y) - \langle \psi,\, Ax + By - \zeta \rangle + \frac{\gamma}{2} \left\| Ax + By - z \right\|^2 \tag{6.3}$$

ADMM

Initialization $y_0, \psi_0,\ \gamma > 0$

while *stopping criterion not satisfied* **do**

$x_{k+1} \in \operatorname{argmin}_x F(x) - \langle \psi_k,\, Ax \rangle + \frac{\gamma}{2} \left\| Ax + By_k - \zeta \right\|^2$

$y_{k+1} \in \operatorname{argmin}_y G(y) - \langle \psi_k,\, By \rangle + \frac{\gamma}{2} \left\| Ax_{k+1} + By - \zeta \right\|^2$

$\psi_{k+1} = \psi_k + \gamma(\zeta - Ax_{k+1} - By_{k+1})$

end

Consider the Lasso example again:

$$\min_{x,y} \lambda \|y\|_1 + \frac{1}{2} \|Kx - b\|^2 \text{ such that } x - y = 0.$$

Let

- $F(x) = \frac{1}{2} \|Kx - b\|^2$, $G(y) = \lambda \|y\|_1$
- $A = \mathrm{Id}$, $B = -\mathrm{Id}$ and $\zeta = 0$.

The ADMM iterates are:

$$\begin{aligned} x_{k+1} &= (\gamma \mathrm{Id} + K^* K)^{-1}(K^* b + \gamma y_k + \psi_k) \\ y_{k+1} &= \mathcal{T}_{\lambda/\gamma}(x_{k+1} - \psi_k/\gamma) \\ \psi_{k+1} &= \psi_k + \gamma(y_{k+1} - x_{k+1}). \end{aligned}$$

Equivalence to Douglas-Rachford

Recall that ADMM solves the problem:

$$\min_{x,y} F(x) + G(y) \text{ s.t. } Ax + By = \zeta.$$

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The dual problem is

$$\begin{aligned}
&\max_{p} \min_{x,y} F(x) + G(y) + \langle p, \zeta - Ax - By\rangle \\
&= \max_{p} \min_{x} \left(-\langle A^* p, x\rangle + F(x)\right) + \min_{y} \left(-\langle B^* p, y\rangle + G(y)\right) + \langle p, \zeta\rangle \\
&= \max_{p} -F^*(A^* p) - G^*(B^* p) + \langle p, \zeta\rangle
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\end{aligned}$$

Equivalence

ADMM is equivalent to applying DR on the dual problem

$$\min_p \tilde{F}^*_\zeta(p) + \tilde{G}^*(p)$$

where $\tilde{G}^*(p) \overset{\text{def.}}{=} G^*(B^* p)$ and $\tilde{F}^*_\zeta(p) \overset{\text{def.}}{=} F^*(A^* p) - \langle p, \zeta \rangle$.

Equivalence to Douglas-Rachford

To prove the equivalence between ADMM and DR, we will rewrite the ADMM iterates in terms of $\xi_k \overset{\text{def.}}{=} Ax_k$, $\eta_k \overset{\text{def.}}{=} By_k$ and the functions $\tilde{G}^*$ and $\tilde{F}^*_\zeta$.

We will make use of the following lemma:

Lemma 1

Suppose that F^* is continuous as A^*p and G^* is continuous at B^*q. Define

$$\tilde{F}(\xi) = \min_{Ax=\xi} F(x) \quad \text{and} \quad \tilde{G}(\eta) = \min_{By=\eta} G(y)$$

Then,

- *the minimums are achieved (thanks to Fenchel Rockafellar duality).*
- $\tilde{G}^*(q) = G^*(B^*q)$ *and* $\tilde{F}^*(p) = F^*(A^*p)$.

Moreover, defining $\tilde{F}^*_\zeta(p) = \tilde{F}^*(p) - \langle \zeta, p \rangle$, *we have*

$$\mathrm{prox}_{\gamma \tilde{F}^*_\zeta}(x) = \mathrm{prox}_{\gamma \tilde{F}^*}(x + \gamma\zeta).$$

Step 1: rewrite the iterates in terms of $\xi_k \stackrel{\text{def.}}{=} Ax_k$ and $\eta_k \stackrel{\text{def.}}{=} By_k$

On ξ_k

Recall the iteration on x_k is

$$x_{k+1} \in \operatorname{argmin}_x F(x) - \langle \psi_k, \xi \rangle + \frac{\gamma}{2} \|\xi + \eta_k - \zeta\|^2 \text{ s.t. } Ax = \xi$$

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So, $\xi_{k+1} = Ax_{k+1}$ satisfies

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Therefore,

$$0 \in \partial \tilde{F}(\xi_{k+1}) - \psi_k + \gamma(\xi_{k+1} + \eta_k - \zeta)$$

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Moreau's identity

Let f be proper, convex and lower semicontinuous and let f^* be its convex conjugate. Then for $\gamma > 0$, $\frac{1}{\gamma}\mathrm{prox}_{\gamma f^*}(\gamma x) + \mathrm{prox}_{f/\gamma}(x) = x$

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(ii) $\eta_{k+1} = \mathrm{prox}_{\tilde{G}/\gamma}(v_{k+1}/\gamma)$ implies

$$\mathrm{prox}_{\gamma\tilde{G}^*}(v_{k+1}) \stackrel{\text{Moreau}}{=} v_{k+1} - \gamma\eta_{k+1} \stackrel{\substack{\text{3rd admm}\\ \text{iteration}}}{=} \psi_{k+1} \tag{6.5}$$

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Note also that $\frac{1}{2}v_k = \frac{1}{2}\psi_k + \frac{1}{2}\gamma\eta_k \stackrel{\text{def. } u_k}{=} \frac{1}{2}u_k + \gamma\eta_k \implies \gamma\eta_k = \frac{1}{2}v_k - \frac{1}{2}u_k$

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(ii) $\eta_{k+1} = \mathrm{prox}_{\tilde{G}/\gamma}(v_{k+1}/\gamma)$ implies

$$\mathrm{prox}_{\gamma\tilde{G}^*}(v_{k+1}) \stackrel{\text{Moreau}}{=} v_{k+1} - \gamma\eta_{k+1} \stackrel{\substack{\text{3rd admm}\\ \text{iteration}}}{=} \psi_{k+1} \tag{6.5}$$

Note also that $\frac{1}{2}v_k = \frac{1}{2}\psi_k + \frac{1}{2}\gamma\eta_k \stackrel{\text{def. } u_k}{=} \frac{1}{2}u_k + \gamma\eta_k \implies \gamma\eta_k = \frac{1}{2}v_k - \frac{1}{2}u_k$

(i) $v_{k+1} \stackrel{(6.4)}{=} \gamma\eta_k + \mathrm{prox}_{\gamma\tilde{F}^*_\zeta}(u_k) = \frac{1}{2}v_k + \frac{1}{2}\mathrm{rprox}_{\gamma\tilde{F}^*_\zeta}(u_k)$

(ii) $2\mathrm{prox}_{\gamma\tilde{G}^*}(v_{k+1}) - v_{k+1} \stackrel{(6.5)}{=} v_{k+1} - 2\gamma\eta_{k+1} \stackrel{(6.5)}{=} \psi_{k+1} - \gamma\eta_{k+1} \stackrel{\text{def. of } u_{k+1}}{=} u_{k+1}.$

Equivalence to Douglas-Rachford

The iterates are therefore

$$v_{k+1} = \frac{1}{2}v_k + \frac{1}{2}\mathrm{rprox}_{\gamma \tilde{F}^*_\zeta}(u_k)$$
$$u_{k+1} = \mathrm{rprox}_{\gamma \tilde{G}^*}(v_{k+1})$$

Equivalence to Douglas-Rachford

The iterates are therefore

$$\begin{aligned} v_{k+1} &= \frac{1}{2} v_k + \frac{1}{2} \mathrm{rprox}_{\gamma \tilde{F}^*_\zeta}(u_k) \\ u_{k+1} &= \mathrm{rprox}_{\gamma \tilde{G}^*}(v_{k+1}) \end{aligned}$$

This is precisely the Douglas-Rachford iterations

$$v_{k+1} = \frac{1}{2} v_k + \frac{1}{2} \mathrm{rprox}_{\gamma \tilde{F}^*_\zeta}(\mathrm{rprox}_{\gamma \tilde{G}^*}(v_k))$$

for the minimisation of

$$\begin{aligned} \Phi(p) &\overset{\text{def.}}{=} \tilde{F}^*_\zeta(p) + \tilde{G}^*(p) \\ &= F^*(A^* p) + G^*(B^* p) - \langle \zeta,\, p \rangle. \end{aligned}$$

Outline

Consider the problem

$$\min_x F(Kx) + G(x).$$

Primal-Dual splitting

Consider the problem

$$\min_x F(Kx) + G(x).$$

Then, by considering the Fenchel conjugate of

$$F(Kx) = \sup_y \langle Kx, y\rangle - F^*(y),$$

we have the saddle point problem

$$\min_x \sup_y \langle Kx, y\rangle - F^*(y) + G(x)$$

The primal dual splitting scheme essentially alternating between

- an implicit descent on x an implicit ascent on y

The optimality conditions of $\min_x \sup_y \langle Kx, y\rangle - F^*(y) + G(x)$ are

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Primal-Dual splitting

Initialization $x_0, y_0,\ \sigma, \tau > 0$

while *stopping criterion not satisfied* **do**

$$x_{k+1} = \mathrm{prox}_{\tau G}(x_k - \tau K^* y_k)$$

$$y_{k+1} = \mathrm{prox}_{\sigma F^*}(y_k + \sigma K(2x_{k+1} - x_k))$$

end

Convergence

If $\sigma\tau \|K\|^2 < 1$, (x_k, y_k) converges to a fixed point (x_*, y_*) which is a solution to the saddle point problem if a solution exists.

The primal-dual gap

For all x and y,

$$\begin{aligned}\min_{x'} \langle Kx', y\rangle - F^*(y) + G(x') &\leqslant \min_{x'} \max_{y'} \langle Kx', y'\rangle - F^*(y') + G(x') \\ &\leqslant \max_{y'} \langle Kx, y'\rangle - F^*(y') + G(x)\end{aligned}$$

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Defining the primal-dual gap as

$$\mathcal{G}(x, y) = \max_{y'}(\langle y', Kx\rangle - F^*(y') + G(x)) - \min_{x'}(\langle y, Kx'\rangle - F^*(y) + G(x')),$$

we have

$$\mathcal{G}(\bar{x}_n, \bar{y}_n) \leqslant \frac{C}{k}$$

where $\bar{x}_n = \frac{1}{n}\sum_{k=1}^n x_k$ and $\bar{y}_n \overset{\text{def.}}{=} \frac{1}{n}\sum_{k=1}^n x_k$.

Example

Example: Let D be the finite differences operator and $A \in \mathbb{R}^{m \times n}$.

$$\min_{x \in \mathbb{R}^n} \|Dx\|_1 + \frac{1}{2} \|Ax - b\|_2^2$$

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- For $\mathrm{prox}_{\tau G}$, note that $z = \mathrm{prox}_{\tau G}(x)$ satisfies
$$z \in \mathrm{argmin}_z \frac{1}{2} \|z - x\|^2 + \frac{\tau}{2} \|Az - b\|^2 \iff z = (\mathrm{Id} + \tau A^* A)^{-1} (\gamma A^* b + x)$$

Summary

There are two key ingredients to dealing with nonsmooth optimisation of the form

$$\min_x F(x) + \sum_i R_i(K_i x)$$

where F is smooth, R_i are non-smooth and K_i are linear operators.

1. Gradient descent
2. Proximal mapping

Key splitting methods:

- $F + R$ Forward-Backward splitting.
- $R_1 + R_2$ Douglas-Rachford splitting
- $R_1 + R_2(K\cdot)$ Primal-dual splitting, ADMM.