



Non-smooth convex optimization. Lower
bounds. Subgradient method.

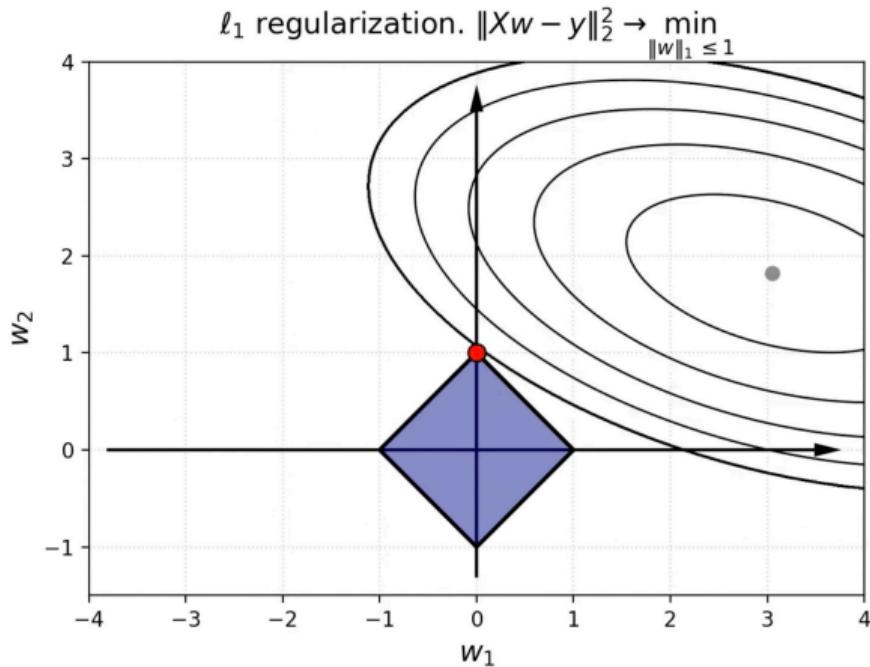
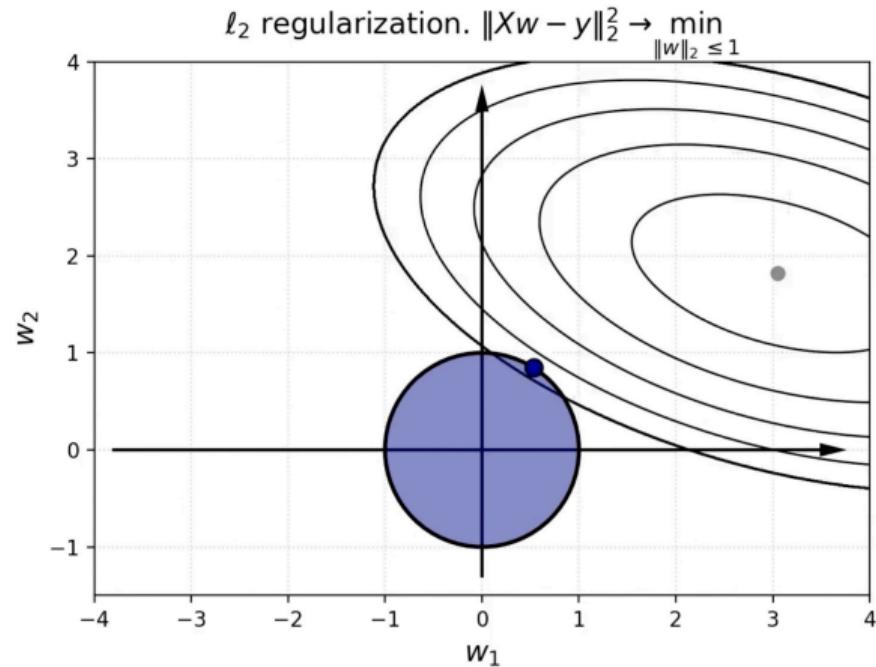
Daniil Merkulov

Optimization methods. MIPT

Non-smooth problems

ℓ_1 -regularized linear least squares

ℓ_1 induces sparsity



@fminxyz

Norms are not smooth

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

A classical convex optimization problem is considered. We assume that $f(x)$ is a convex function, but now we do not require smoothness.

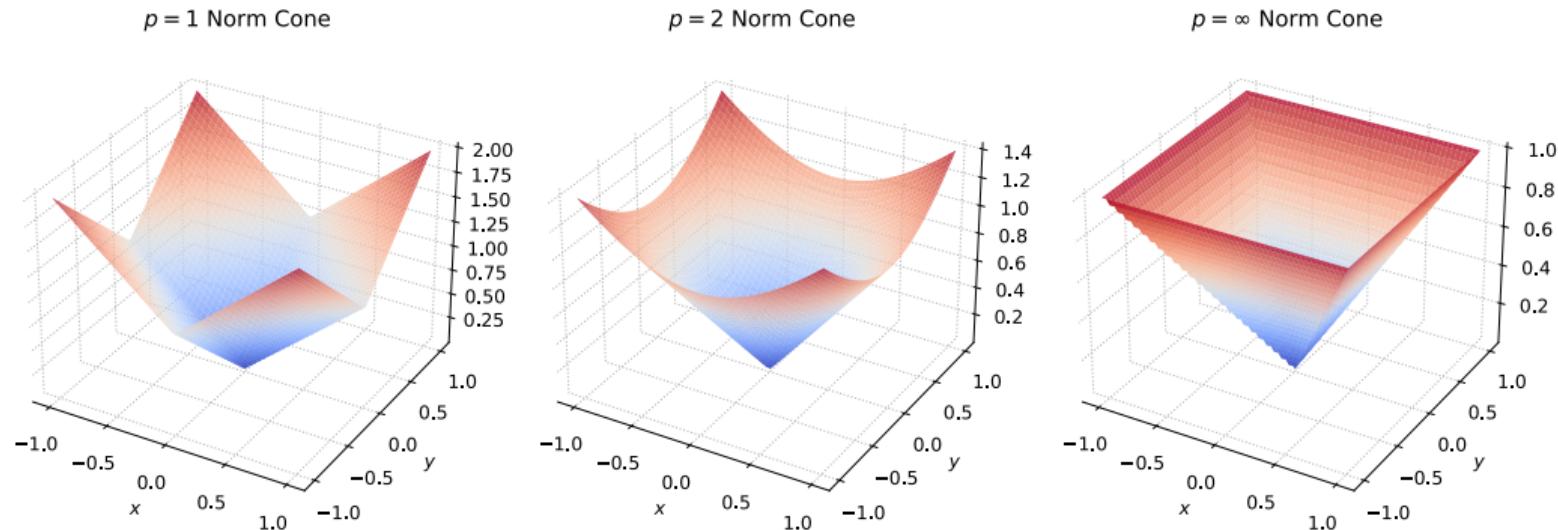
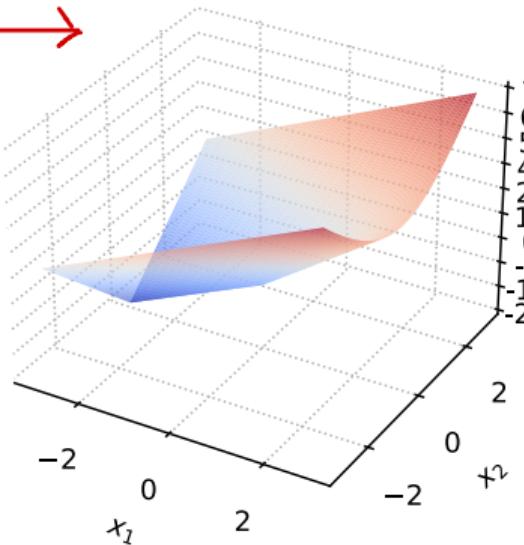
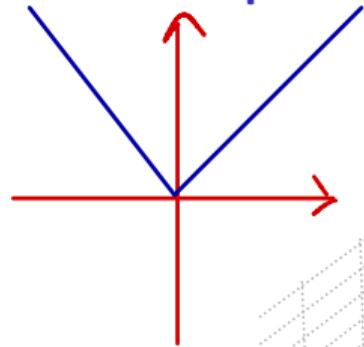
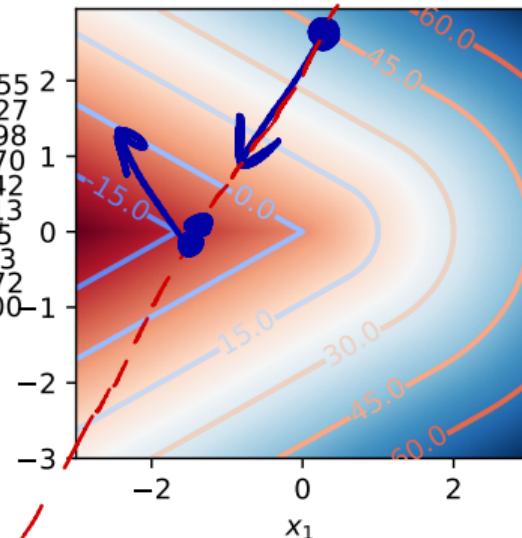


Figure 1: Norm cones for different p -norms are non-smooth

Wolfe's example



Wolfe's example



ReLU (x)

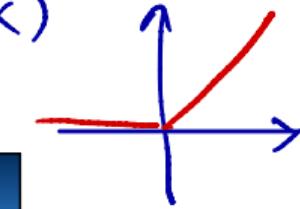


Figure 2: Wolfe's example. Open in Colab

Субградиентный
метод

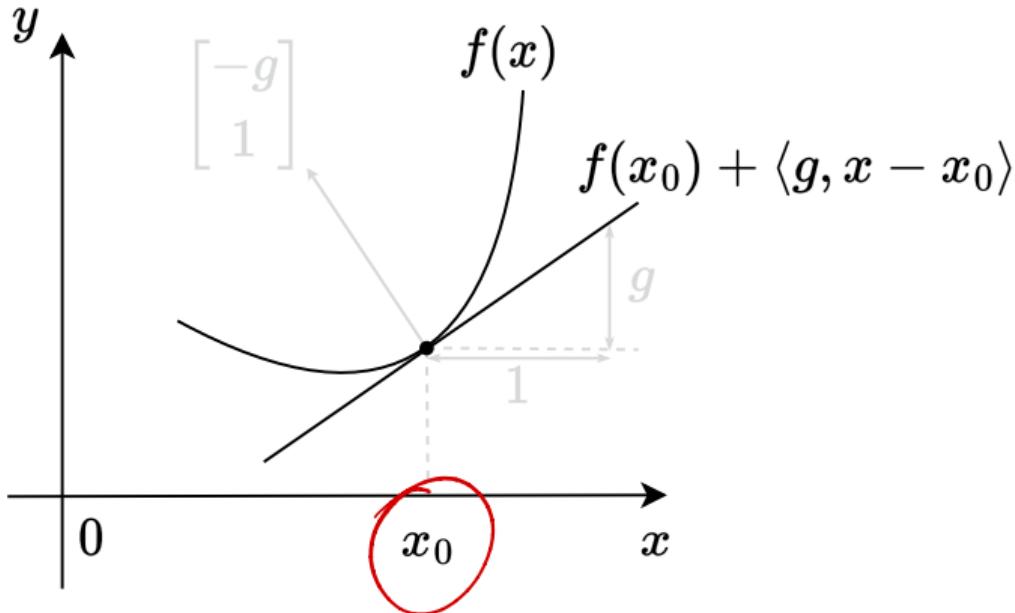


Subgradient calculus

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

$$g_k \in \partial f(x_k)$$

Convex function linear lower bound



An important property of a continuous convex function $f(x)$ is that at any chosen point x_0 for all $x \in \text{dom } f$ the inequality holds:

$$f(x) \geq f(x_0) + \langle g, x - x_0 \rangle$$

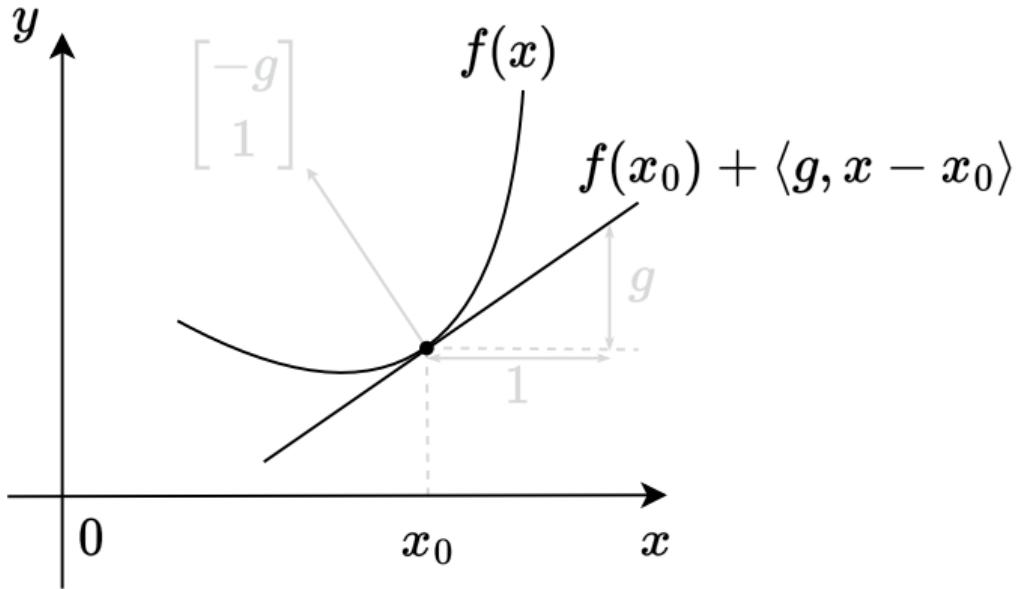
$$\langle g, x - x_0 \rangle \leq f(x) - f(x_0)$$

$$\langle g, x_0 - x \rangle \geq f(x_0) - f(x)$$

$$g \in \partial f(x_0)$$

Figure 3: Taylor linear approximation serves as a global lower bound for a convex function

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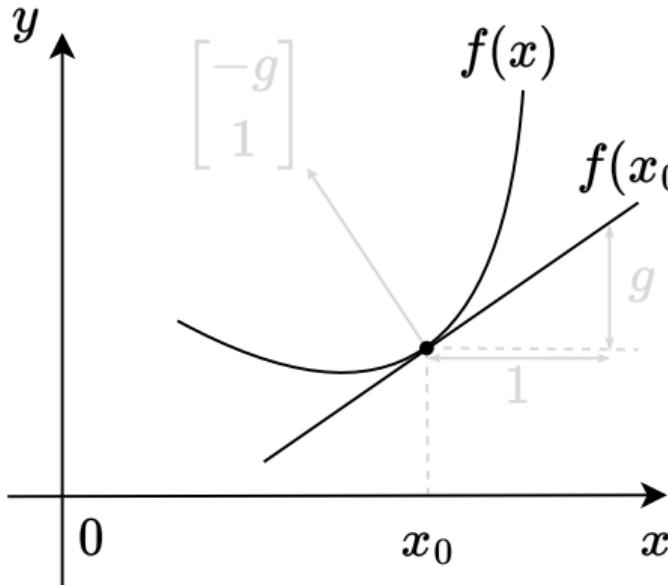
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for some vector g , i.e., the tangent to the function's graph is the *global* estimate from below for the function.

- If $f(x)$ is differentiable, then $g = \nabla f(x_0)$

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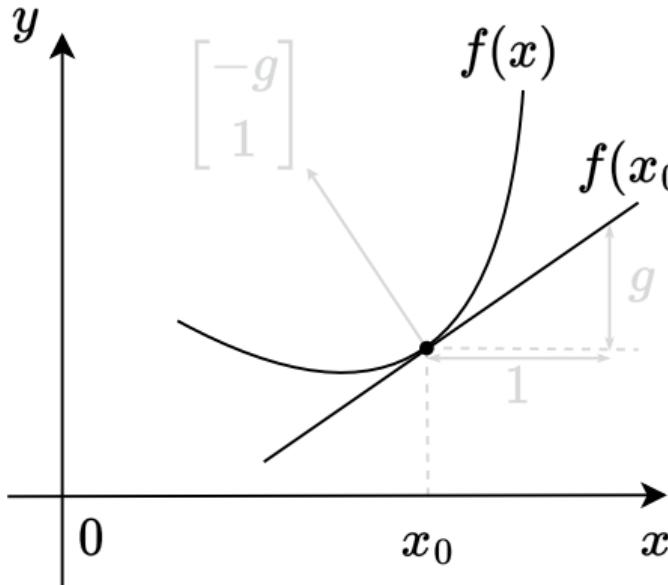
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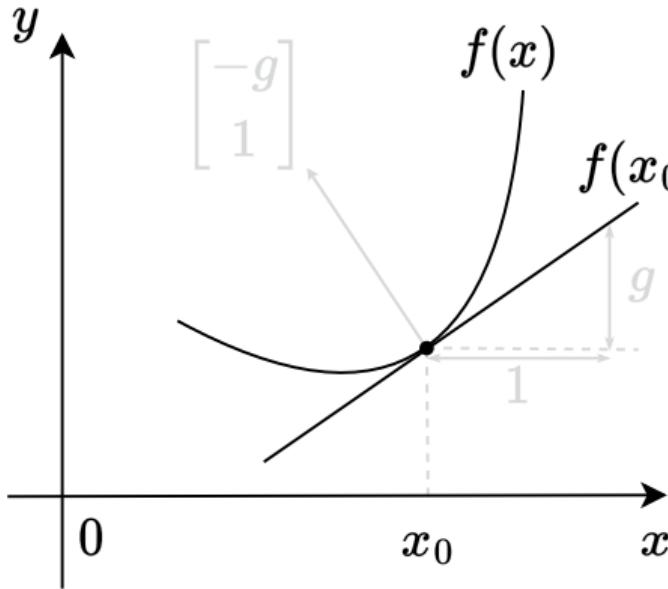
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We do not want to lose such a lovely property.

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Subgradient and subdifferential

A vector g is called the **subgradient** of a function $f(x) : S \rightarrow \mathbb{R}$ at a point x_0 if $\forall x \in S$:

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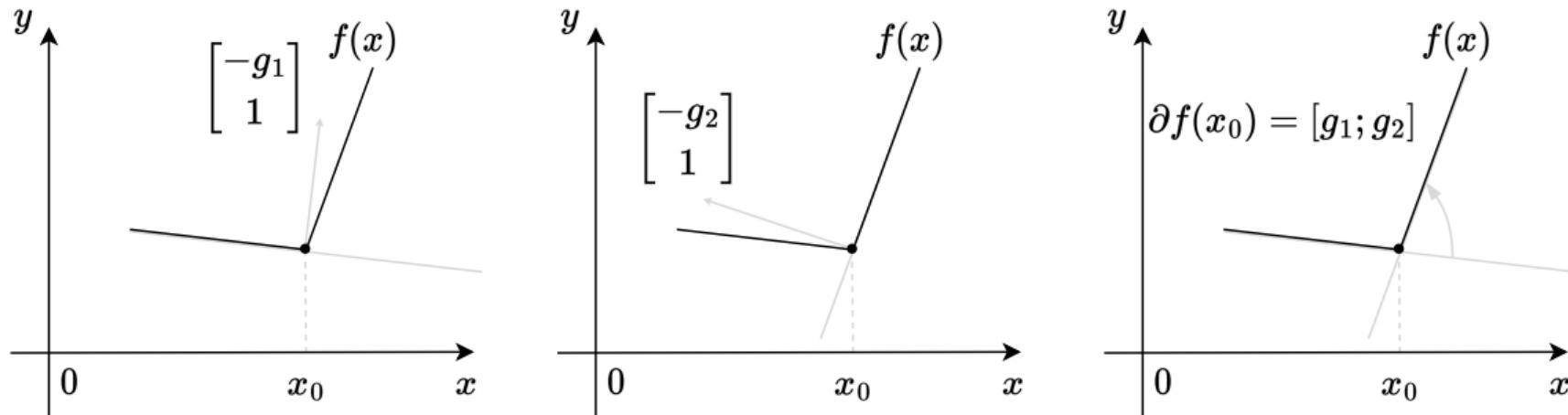


Figure 4: Subdifferential is a set of all possible subgradients

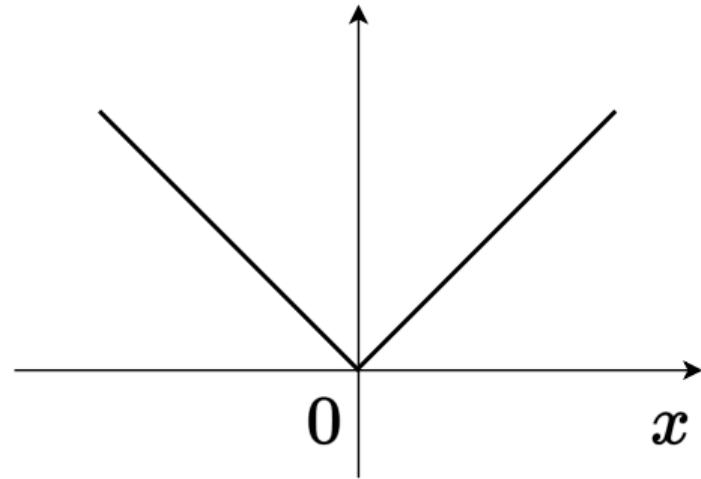
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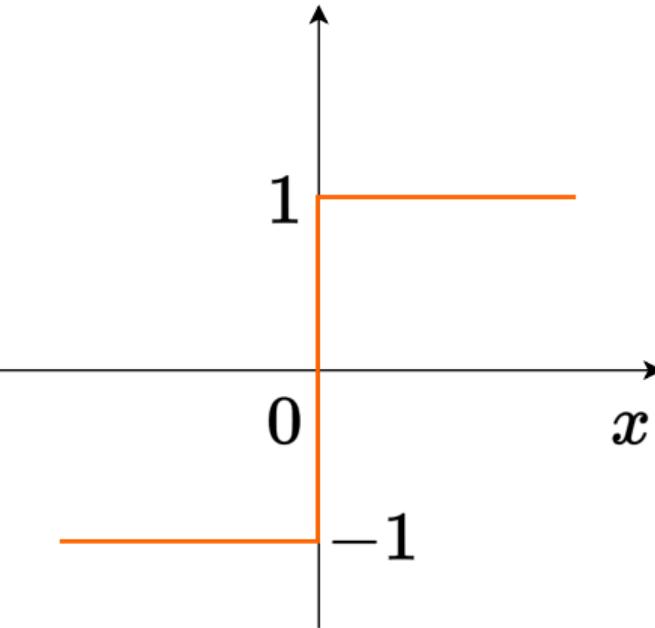
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Let $f : S \rightarrow \mathbb{R}$ be a function defined on the set S in a Euclidean space \mathbb{R}^n . If $x_0 \in \text{ri}(S)$ and f is differentiable at x_0 , then either $\partial f(x_0) = \emptyset$ or $\partial f(x_0) = \{\nabla f(x_0)\}$. Moreover, if the function f is convex, the first scenario is impossible.

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Proof

1. Assume, that $s \in \partial f(x_0)$ for some $s \in \mathbb{R}^n$ distinct from $\nabla f(x_0)$. Let $v \in \mathbb{R}^n$ be a unit vector. Because x_0 is an interior point of S , there exists $\delta > 0$ such that $x_0 + tv \in S$ for all $0 < t < \delta$. By the definition of the subgradient, we have

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$$\langle \nabla f(x_0), v \rangle = \lim_{t \rightarrow 0; 0 < t < \delta} \frac{f(x_0 + tv) - f(x_0)}{t} \geq \langle s, v \rangle$$

2. From this, $\langle s - \nabla f(x_0), v \rangle \geq 0$. Due to the arbitrariness of v , one can set

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3. Furthermore, if the function f is convex, then according to the differential condition of convexity $f(x) \geq f(x_0) + \langle \nabla f(x_0), x - x_0 \rangle$ for all $x \in S$. But by definition, this means $\nabla f(x_0) \in \partial f(x_0)$.

Subdifferential calculus

■ Moreau - Rockafellar theorem (subdifferential of a linear combination)

Let $f_i(x)$ be convex functions on convex sets S_i , $i =$

$\overline{1, n}$. Then if $\bigcap_{i=1}^n \text{ri}(S_i) \neq \emptyset$ then the function

$f(x) = \sum_{i=1}^n a_i f_i(x)$, $a_i > 0$ has a subdifferential

$\partial_S f(x)$ on the set $S = \bigcap_{i=1}^n S_i$ and

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i Dubovitsky - Milutin theorem (subdifferential of a point-wise maximum)

Let $f_i(x)$ be convex functions on the open convex set $S \subseteq \mathbb{R}^n$, $x_0 \in S$, and the pointwise maximum is defined as $f(x) = \max_i f_i(x)$. Then:

$$\partial_S f(x_0) = \text{conv} \left\{ \bigcup_{i \in I(x_0)} \partial_{S_i} f_i(x_0) \right\}, \quad I(x) = \{i \in [1, n] : f_i(x) = \max_j f_j(x)\}$$

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- $\partial(f(Ax + b))(x) = A^T \partial f(Ax + b)$, f - convex function
- $z \in \partial f(x)$ if and only if $x \in \partial f^*(z)$.

Subgradient Method

Algorithm

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The idea is very simple: let's replace the gradient $\nabla f(x_k)$ in the gradient descent algorithm with a subgradient g_k at point x_k :

$$x_{k+1} = x_k - \alpha_k g_k,$$

where g_k is an arbitrary subgradient of the function $f(x)$ at the point x_k , $g_k \in \partial f(x_k)$

субградиентный метод
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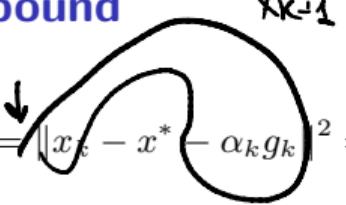
Note that the **subgradient method is not guaranteed to be a descent method**; the negative subgradient need not be a descent direction, or the step size may cause $f(x_{k+1}) > f(x_k)$.

That is why we usually track the best value of the objective function

$$f_k^{\text{best}} = \min_{i=1, \dots, k} f(x_i).$$

$$f(\bar{x}_k) = f\left(\frac{1}{k} \sum_{i=0}^{k-1} x_i\right)$$

Convergence bound

$$\|x_{k+1} - x^*\|^2 = \|x_k - x^* - \alpha_k g_k\|^2 =$$


Convergence bound

Метод проекции
субградиента:

$$\|x_{k+1} - x^*\|^2 = \|x_k - x^* - \alpha_k g_k\|^2 = \\ = \|x_k - x^*\|^2 + \alpha_k^2 \|g_k\|^2 - 2\alpha_k \langle g_k, x_k - x^* \rangle$$

$$x_{k+1} = \Pi_S(x_k - \alpha_k g_k)$$

$$\|x_{k+1} - x^*\| = \|\Pi_S(x_k - \alpha_k g_k) - \Pi_S(x^*)\| \quad x^* = \Pi_S(x^*)$$

$$\|x_k - \alpha_k g_k - x^*\|$$

Convergence bound

$$\begin{aligned}\|x_{k+1} - x^*\|^2 &= \|x_k - x^* - \alpha_k g_k\|^2 = \\ &= \|x_k - x^*\|^2 + \alpha_k^2 \|g_k\|^2 - 2\alpha_k \langle g_k, x_k - x^* \rangle \\ &\leq \|x_k - x^*\|^2 + \alpha_k^2 \|g_k\|^2 - 2\alpha_k (f(x_k) - f(x^*))\end{aligned}$$

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$$f(x^*) \geq f(x_k) + \langle g_k, x^* - x_k \rangle$$

$$\langle g_k, x_k - x^* \rangle \geq f(x_k) - f(x^*)$$

$$-\alpha_k \langle g_k, x_k - x^* \rangle \leq \alpha_k (f(x_k) - f(x^*))$$

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$$2\alpha_k (f(x_k) - f(x^*)) \leq \|x_k - x^*\|^2 - \|x_{k+1} - x^*\|^2 + \alpha_k^2 \|g_k\|^2$$

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$$2\alpha_k (f(x_k) - f(x^*)) \leq \|x_k - x^*\|^2 - \|x_{k+1} - x^*\|^2 + \alpha_k^2 \|g_k\|^2$$

Let us sum the obtained inequality for $k = 0, \dots, T-1$:

$$\sum_{k=0}^{T-1} 2\alpha_k (f(x_k) - f(x^*)) \leq \|x_0 - x^*\|^2 - \cancel{\|x_T - x^*\|^2} + \sum_{k=0}^{T-1} \alpha_k^2 \|g_k\|^2$$

Convergence bound

$$\begin{aligned}\|x_{k+1} - x^*\|^2 &= \|x_k - x^* - \alpha_k g_k\|^2 = \\ &= \|x_k - x^*\|^2 + \alpha_k^2 \|g_k\|^2 - 2\alpha_k \langle g_k, x_k - x^* \rangle \\ &\leq \|x_k - x^*\|^2 + \alpha_k^2 \|g_k\|^2 - 2\alpha_k (f(x_k) - f(x^*))\end{aligned}$$

$$2\alpha_k (f(x_k) - f(x^*)) \leq \|x_k - x^*\|^2 - \|x_{k+1} - x^*\|^2 + \alpha_k^2 \|g_k\|^2$$

Let us sum the obtained inequality for $k = 0, \dots, T - 1$:

$$\begin{aligned}\sum_{k=0}^{T-1} 2\alpha_k (f(x_k) - f(x^*)) &\leq \|x_0 - x^*\|^2 - \|x_T - x^*\|^2 + \sum_{k=0}^{T-1} \alpha_k^2 \|g_k\|^2 \\ &\leq \|x_0 - x^*\|^2 + \sum_{k=0}^{T-1} \alpha_k^2 \|g_k\|^2\end{aligned}$$

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$$\|x_0 - x^*\|_2^2 \leq R^2$$

$$\text{Thus } \|\alpha_k g_k\|_2 \leq G$$

Convergence bound

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Convergence bound

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Convergence bound

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- We use the notation $R = \|x_0 - x^*\|_2$

Convergence bound

- Finally, note:

$$\sum_{k=0}^{T-1} 2\alpha_k(f(x_k) - f(x^*)) \geq \sum_{k=0}^{T-1} 2\alpha_k(f_k^{\text{best}} - f(x^*)) = (f_k^{\text{best}} - f(x^*)) \sum_{k=0}^{T-1} 2\alpha_k$$

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- Which leads to the basic inequality:

$$f_k^{\text{best}} - f(x^*) \leq \frac{R^2 + G^2 \sum_{k=0}^{T-1} \alpha_k^2}{2 \sum_{k=0}^{T-1} \alpha_k}$$

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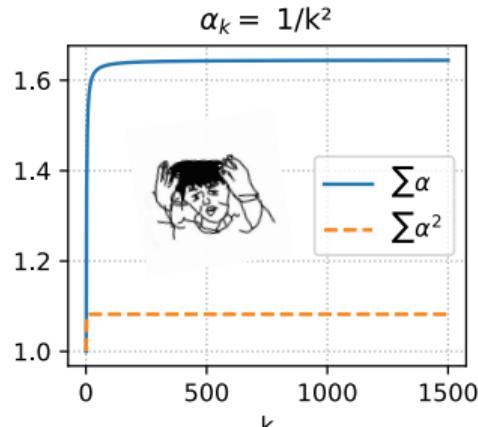
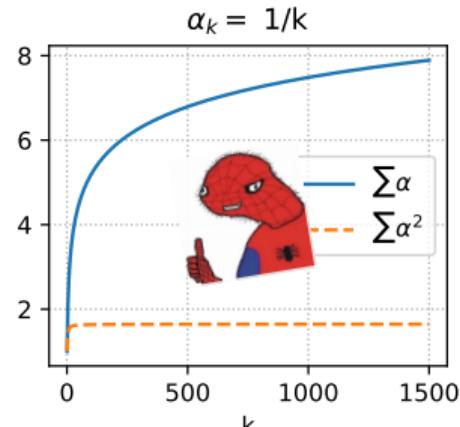
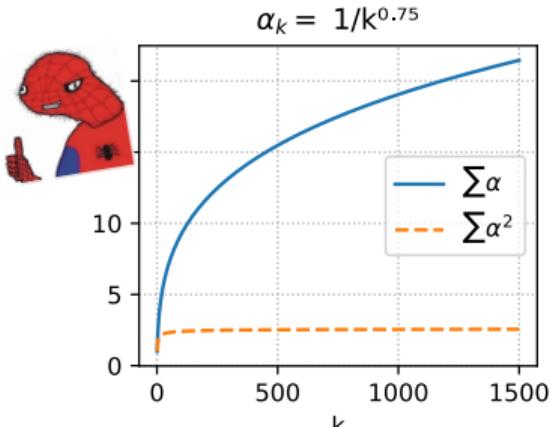
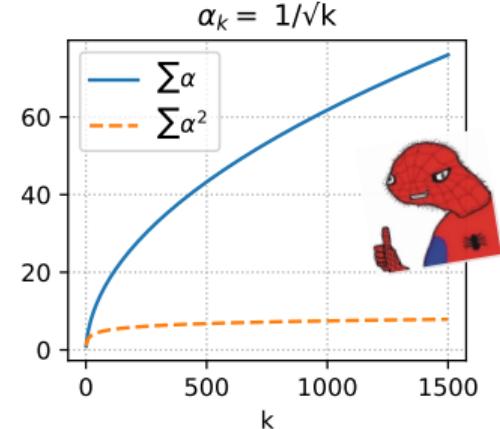
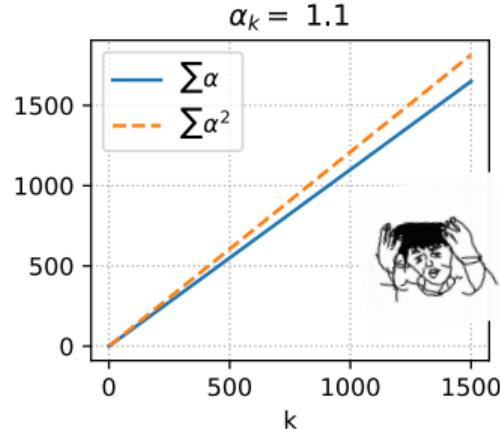
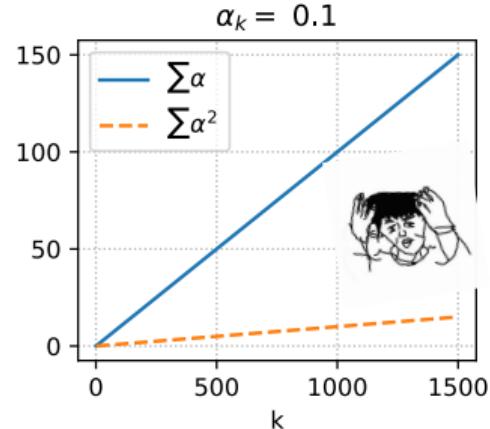
$$f_k^{\text{best}} - f(x^*) \leq \frac{R^2 + G^2 \sum_{k=0}^{T-1} \alpha_k^2}{2 \sum_{k=0}^{T-1} \alpha_k}$$

- From this point we can see, that if the stepsize strategy is such that

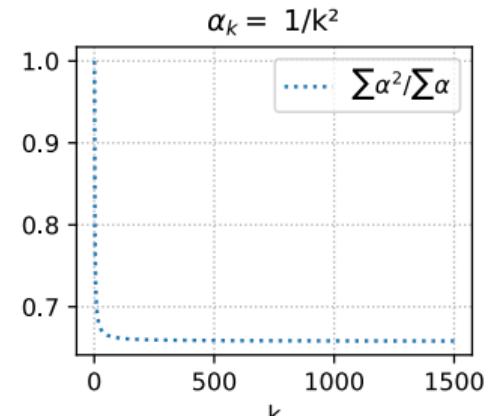
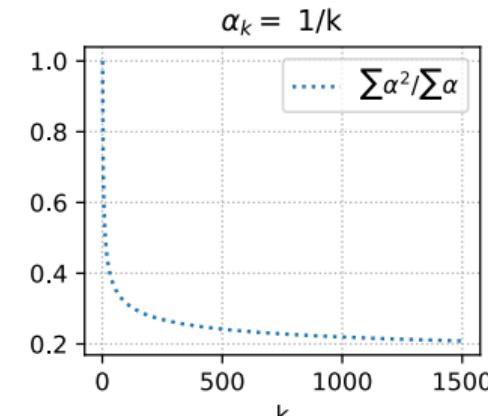
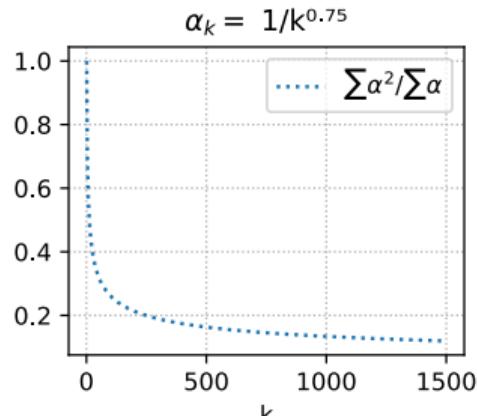
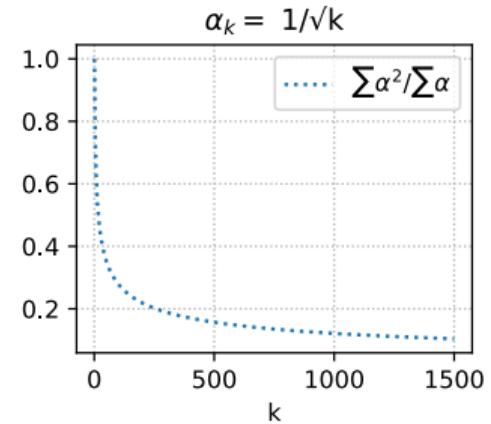
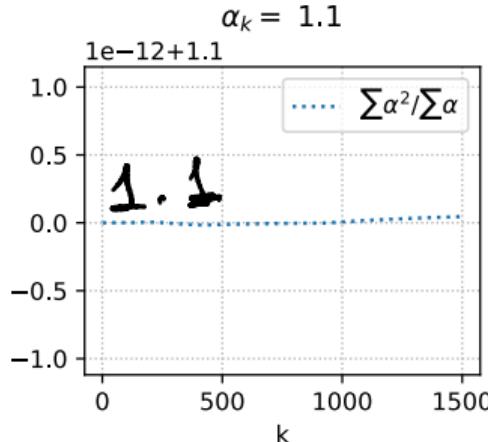
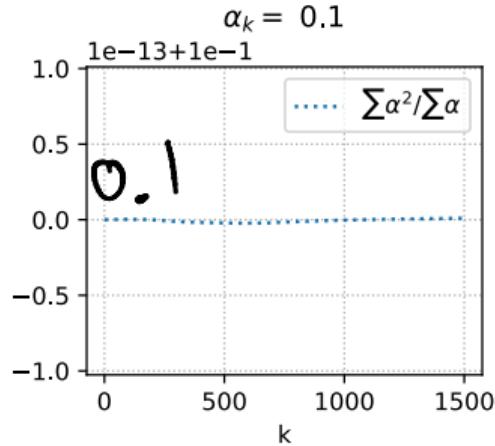
$$\sum_{k=0}^{T-1} \alpha_k^2 < \infty, \quad \sum_{k=0}^{T-1} \alpha_k = \infty,$$

then the subgradient method converges (step size should be decreasing, but not too fast).

Different step size strategies



Different step size strategies



Convergence bound. Non-smooth convex case. Constant step size

i Theorem

Let f be a convex G -Lipschitz function and $R = \|x_0 - x^*\|_2$. For a fixed step size α , subgradient method satisfies

$$f_k^{\text{best}} - f(x^*) \leq \frac{R^2}{2\alpha k} + \frac{\alpha}{2} G^2$$

- Note, that with any constant step size, the first term of the right-hand side is decreasing, but the second term stays constant.

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- Some versions of the subgradient method (e.g., diminishing nonsummable step lengths) work when the assumption on $\|g_k\|_2 \leq G$ doesn't hold; see ¹ or ².

¹B. Polyak. Introduction to Optimization. Optimization Software, Inc., 1987.

²N. Shor. Minimization Methods for Non-differentiable Functions. Springer Series in Computational Mathematics. Springer, 1985.

Convergence bound. Non-smooth convex case. Constant step size

$$x + \frac{1}{x} \rightarrow \min_{x \in \mathbb{R}^+}$$

Theorem

Let f be a convex G -Lipschitz function and $R = \|x_0 - x^*\|_2$. For a fixed step size α , subgradient method satisfies

$$f_k^{\text{best}} - f(x^*) \leq \boxed{\frac{R^2}{2\alpha k} + \frac{\alpha}{2} G^2} \rightarrow \min_{\alpha} \frac{R^2}{2k\alpha} = \frac{G^2}{2}$$

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- Some versions of the subgradient method (e.g., diminishing nonsummable step lengths) work when the assumption on $\|g_k\|_2 \leq G$ doesn't hold; see ¹ or ².
- Let's find the optimal step size α that minimizes the right-hand side of the inequality.

$$\alpha^2 = \frac{R^2}{G^2 K}$$

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Convergence bound. Non-smooth convex case. Constant step size

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Let f be a convex G -Lipschitz function and $R = \|x_0 - x^*\|_2$. For a fixed step size $\alpha = \frac{R}{G} \sqrt{\frac{1}{k}}$, subgradient method satisfies

$$f_k^{\text{best}} - f(x^*) \leq \frac{GR}{\sqrt{k}}$$

- This version requires knowledge of the number of iterations in advance, which is not usually practical.

Convergence bound. Non-smooth convex case. Constant step size

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- It is interesting to mention, that if you want to find the optimal stepsizes for the whole sequence $\alpha_0, \alpha_1, \dots, \alpha_{k-1}$, you will get the same result.
- Why? Because the right-hand side is convex and **symmetric** function of $\alpha_0, \alpha_1, \dots, \alpha_{k-1}$.

Convergence bound. Non-smooth convex case. Constant step length

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

i Theorem

Let f be a convex G -Lipschitz function and $R = \|x_0 - x^*\|_2$. For a fixed step length $\gamma = \alpha_k \|g_k\|_2$, i.e. $\alpha_k = \frac{\gamma}{\|g_k\|_2}$, subgradient method satisfies

$$f_k^{\text{best}} - f(x^*) \leq \frac{GR^2}{2\gamma k} + \frac{G\gamma}{2}$$

- Note, that for the subgradient method, we typically can not use the norm of the subgradient as a stopping criterion (imagine $f(x) = |x|$). There are some variants of more advanced stopping criteria, but the convergence is so slow, so typically we just set a maximum number of iterations.

Convergence bound. Non-smooth convex case. Practical strategy

i Theorem

Let f be a convex G -Lipschitz function and $R = \|x_0 - x^*\|_2$. For a diminishing step size strategy, subgradient method satisfies

$$f_k^{\text{best}} - f(x^*) \leq \frac{GR(2 + \ln k)}{4\sqrt{k+1}}$$

$$\alpha_k = \frac{R}{G\sqrt{k+1}},$$

1. Bounding sums:

Convergence bound. Non-smooth convex case. Practical strategy

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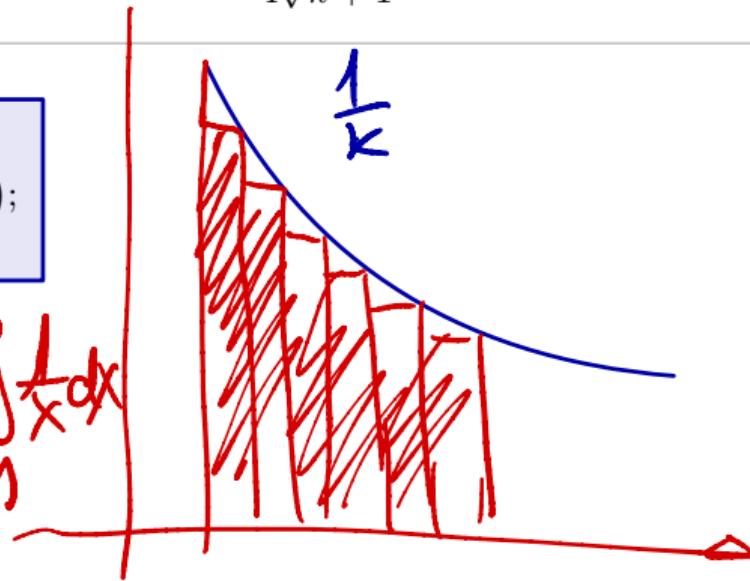
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$$\sum_{k=0}^{T-1} \alpha_k^2 = \frac{R^2}{G^2} \sum_{k=1}^T \frac{1}{k} \leq \frac{R^2}{G^2} (1 + \ln T);$$

~~||~~

$$\frac{1}{1} + \sum_{k=2}^T \frac{1}{k} \leq \int_1^T \frac{1}{x} dx$$



Convergence bound. Non-smooth convex case. Practical strategy

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Convergence bound. Non-smooth convex case. Practical strategy

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Convergence bound. Non-smooth convex case. Practical strategy

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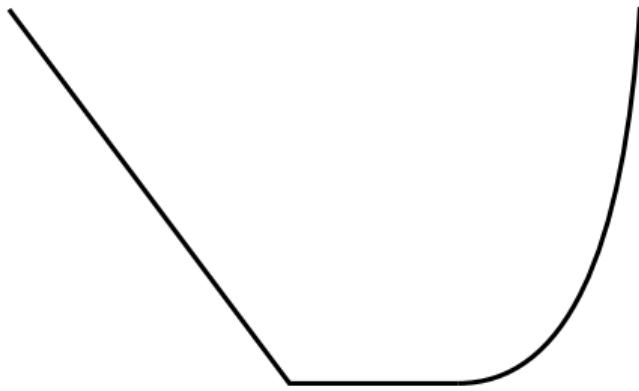
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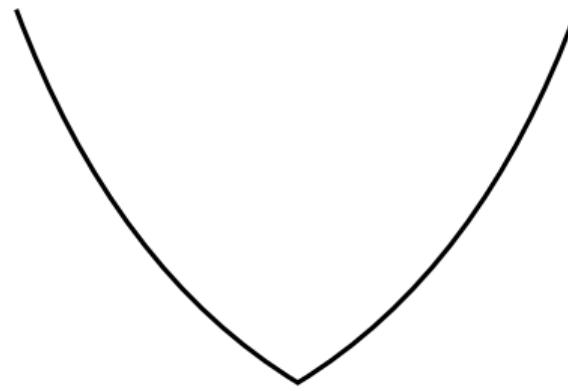
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Non-smooth strongly convex case

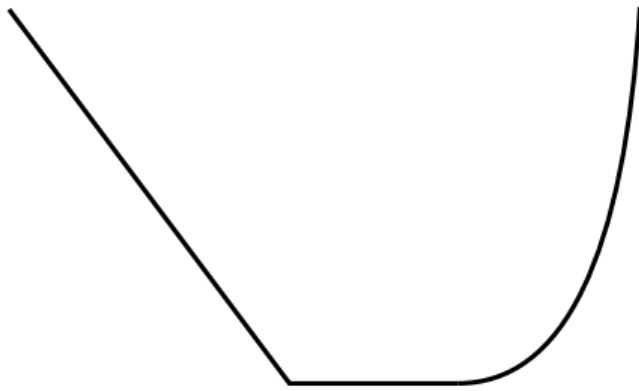


Non-smooth
Convex



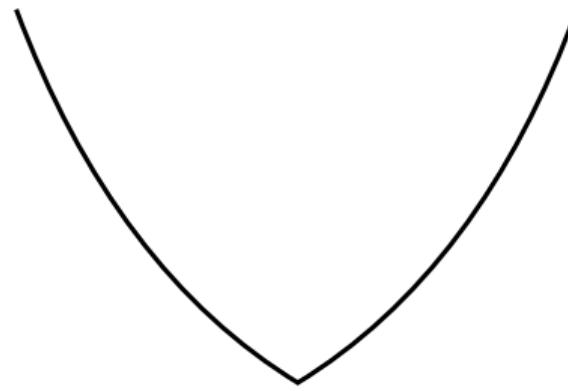
Non-smooth
 μ - strongly convex

Non-smooth strongly convex case



Non-smooth
Convex

$$\mathcal{O}\left(\frac{1}{\sqrt{k}}\right)$$



Non-smooth
 μ - strongly convex

$$\mathcal{O}\left(\frac{1}{k}\right)$$

Non-smooth strongly convex case

i Theorem

Let f be μ -strongly convex on a convex set and x, y be arbitrary points. Then for any $g \in \partial f(x)$,

$$\langle g, x - y \rangle \geq f(x) - f(y) + \frac{\mu}{2} \|x - y\|^2.$$

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4. Letting $\lambda \rightarrow 1^-$ gives $f(x) \leq f(y) + \langle g, x - y \rangle - \frac{\mu}{2}\|x - y\|^2 \rightarrow \langle g, x - y \rangle \geq f(x) - f(y) + \frac{\mu}{2}\|x - y\|^2$.

Convergence bound. Non-smooth strongly convex case.

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Let f be a μ -strongly convex function (possibly non-smooth) with minimizer x^* and bounded subgradients $\|g_k\| \leq G$. Using the step size $\alpha_k = \frac{2}{\mu(k+1)}$, the subgradient method guarantees for $k > 0$ that:

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$$\frac{2\mu(k+1)}{2\mu(k+1)} =$$

$$= \frac{\mu(k+1) - 2\mu}{2} =$$

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 \|x_{k+1} - x^*\|^2 &= \|x_k - x^* - \alpha_k g_k\|^2 = \\
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 2\alpha_k (f(x_k) - f(x^*)) &\leq (1 - \mu \alpha_k) \|x_k - x^*\|^2 - \|x_{k+1} - x^*\|^2 + \alpha_k^2 \|g_k\|^2 \\
 f(x_k) - f(x^*) &\leq \frac{1 - \mu \alpha_k}{2 \alpha_k} \|x_k - x^*\|^2 - \frac{1}{2 \alpha_k} \|x_{k+1} - x^*\|^2 + \frac{\alpha_k}{2} \|g_k\|^2
 \end{aligned}$$

Convergence bound. Non-smooth strongly convex case. Proof

2. Substitute the step size $\alpha_k = \frac{2}{\mu(k+1)}$ into the inequality:

$$2d_k(f_k - f^*) \leq r_k - r_{k+1} + d_k^2 G^2$$

$\sum 2d_k (f_k - f^*) \leq R^2 + \cancel{G^2} d_k^2$

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2. Substitute the step size $\alpha_k = \frac{2}{\mu(k+1)}$ into the inequality:

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r_k

r_{k+1}

$$\cancel{\frac{\mu k(k-1)}{4} r_k - \frac{\mu k(k+1)}{4} r_{k+1}}$$

$$+ \cancel{\frac{\mu (k+1)k}{4} r_{k+1} - \frac{\mu (k+1)(k+2)}{4} r_{k+2}}$$

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Convergence bound. Non-smooth strongly convex case. Proof

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$$f(x_k) - f(x^*) \leq \frac{\mu(k-1)}{4} \|x_k - x^*\|^2 - \frac{\mu(k+1)}{4} \|x_{k+1} - x^*\|^2 + \frac{1}{\mu(k+1)} \|g_k\|^2$$

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$$k(f(x_k) - f(x^*)) \leq \frac{\mu k(k-1)}{4} \|x_k - x^*\|^2 - \frac{\mu k(k+1)}{4} \|x_{k+1} - x^*\|^2 + \frac{1}{\mu} \|g_k\|^2$$

3. Summing up the inequalities for all $k = 0, 1, \dots, T-1$, we get:

$$\sum_{k=0}^{T-1} k(f(x_k) - f(x^*)) \leq 0 - \frac{\mu(T-1)T}{4} \|x_T - x^*\|^2 + \frac{1}{\mu} \sum_{k=0}^{T-1} \|g_k\|^2 \leq \frac{G^2 T}{\mu}$$

$$(f_{T-1}^{\text{best}} - f(x^*)) \sum_{k=0}^{T-1} k = \sum_{k=0}^{T-1} k (f_{T-1}^{\text{best}} - f(x^*)) \leq \sum_{k=0}^{T-1} k (f(x_k) - f(x^*)) \leq \frac{G^2 T}{\mu}$$

$$f_{T-1}^{\text{best}} - f(x^*) \leq \frac{G^2 T}{\mu \sum_{k=0}^{T-1} k} = \frac{2G^2 T}{\mu T(T-1)} \quad f_k^{\text{best}} - f(x^*) \leq \frac{2G^2}{\mu k}.$$

Summary. Subgradient method

Problem Type	Stepsize Rule	Convergence Rate	Iteration Complexity
Convex & Lipschitz problems	$\alpha \sim \frac{1}{\sqrt{k}}$	$\mathcal{O}\left(\frac{1}{\sqrt{k}}\right)$	$\mathcal{O}\left(\frac{1}{\varepsilon^2}\right)$
Strongly convex & Lipschitz problems	$\alpha \sim \frac{1}{k}$	$\mathcal{O}\left(\frac{1}{k}\right)$	$\mathcal{O}\left(\frac{1}{\varepsilon}\right)$

Numerical experiments

$$f(x) = \frac{1}{2m} \|Ax - b\|_2^2 + \lambda \|x\|_1 \rightarrow \min_{x \in \mathbb{R}^n}, \quad A \in \mathbb{R}^{m \times n}, \quad \lambda \left(\frac{1}{m} A^T A \right) \in [\mu; L].$$

Linear Least Squares with ℓ_1 Regularization (LASSO).
 $m=1000, n=100, \lambda=0, \mu=0, L=10$. Optimal sparsity: 0.0e+00

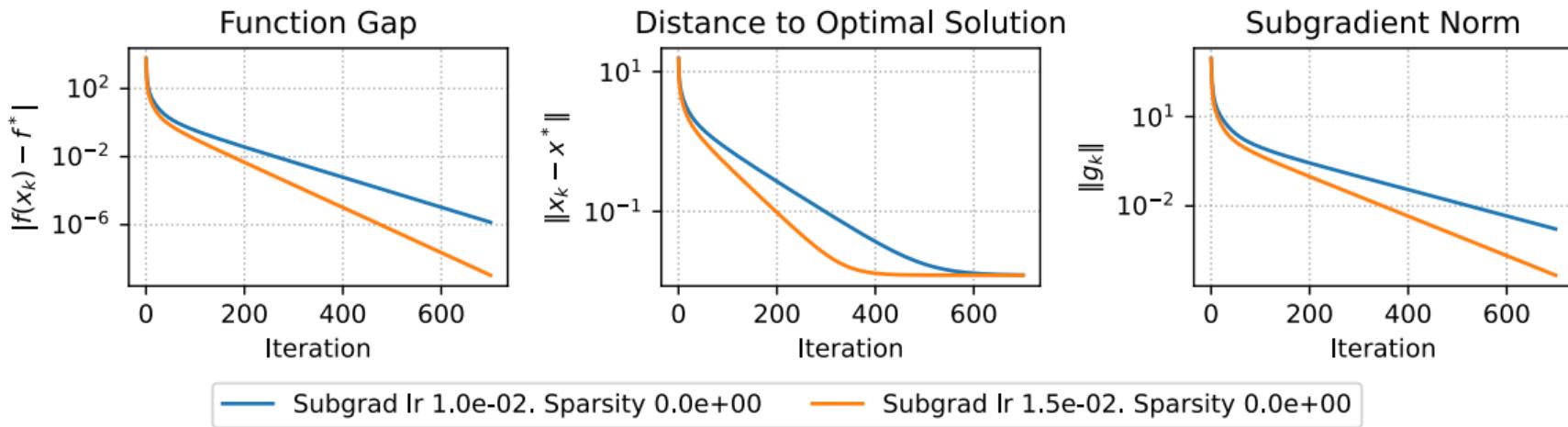


Figure 6: Smooth convex case. Sublinear convergence, no convergence in domain

Numerical experiments

$$f(x) = \frac{1}{2m} \|Ax - b\|_2^2 + \lambda \|x\|_1 \rightarrow \min_{x \in \mathbb{R}^n}, \quad A \in \mathbb{R}^{m \times n}, \quad \lambda \left(\frac{1}{m} A^T A \right) \in [\mu; L].$$

Linear Least Squares with ℓ_1 Regularization (LASSO).
 $m=1000, n=100, \lambda=0.1, \mu=0, L=10$. Optimal sparsity: 1.0e-02

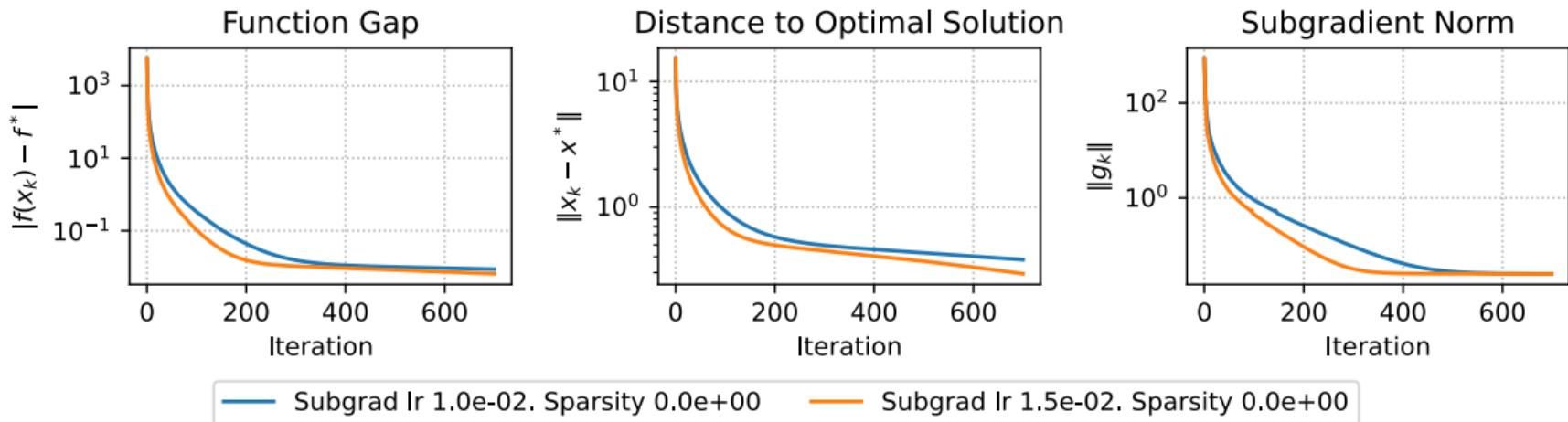


Figure 7: Non-smooth convex case. Small λ value imposes non-smoothness. No convergence with constant step size

Numerical experiments

$$f(x) = \frac{1}{2m} \|Ax - b\|_2^2 + \lambda \|x\|_1 \rightarrow \min_{x \in \mathbb{R}^n}, \quad A \in \mathbb{R}^{m \times n}, \quad \lambda \left(\frac{1}{m} A^T A \right) \in [\mu; L].$$

Linear Least Squares with ℓ_1 Regularization (LASSO).
 $m=1000, n=100, \lambda=1, \mu=0, L=10$. Optimal sparsity: 7.0e-02

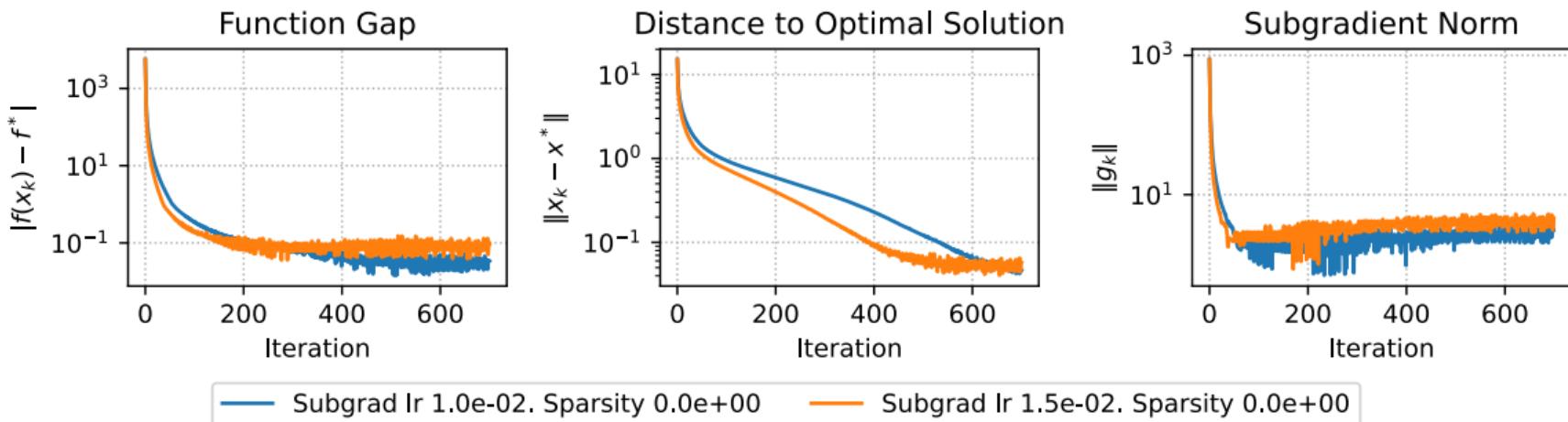


Figure 8: Non-smooth convex case. Larger λ value reveals non-monotonicity of $f(x_k)$. One can see that a smaller constant step size leads to a lower stationary level.

Numerical experiments

$$f(x) = \frac{1}{2m} \|Ax - b\|_2^2 + \lambda \|x\|_1 \rightarrow \min_{x \in \mathbb{R}^n}, \quad A \in \mathbb{R}^{m \times n}, \quad \lambda \left(\frac{1}{m} A^T A \right) \in [\mu; L].$$

Linear Least Squares with ℓ_1 Regularization (LASSO).
 $m=100, n=100, \lambda=1, \mu=0, L=10$. Optimal sparsity: 2.3e-01

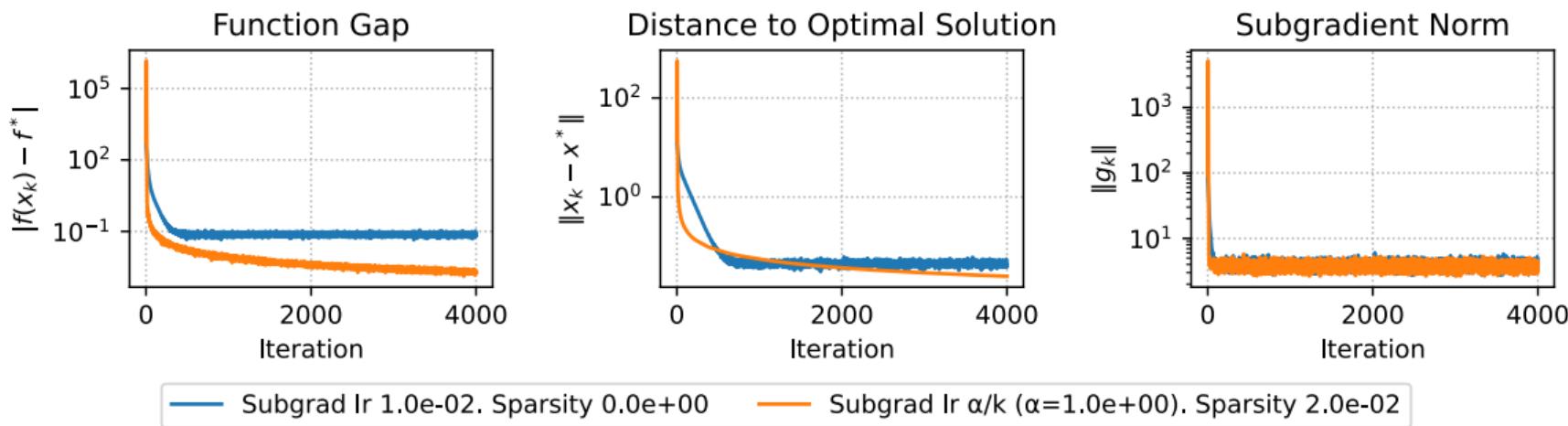


Figure 9: Non-smooth convex case. Diminishing step size leads to the convergence for the f_k^{best}

Numerical experiments

$$f(x) = \frac{1}{2m} \|Ax - b\|_2^2 + \lambda \|x\|_1 \rightarrow \min_{x \in \mathbb{R}^n}, \quad A \in \mathbb{R}^{m \times n}, \quad \lambda \left(\frac{1}{m} A^T A \right) \in [\mu; L].$$

Linear Least Squares with ℓ_1 Regularization (LASSO).
 $m=100, n=100, \lambda=1, \mu=0, L=10$. Optimal sparsity: 2.3e-01

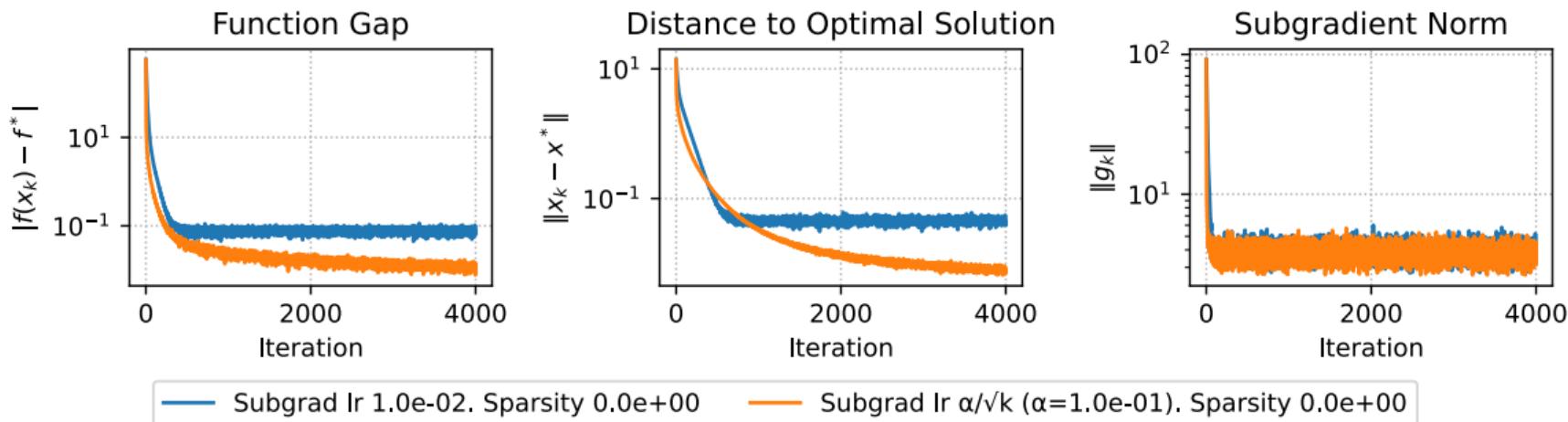


Figure 10: Non-smooth convex case. $\frac{\alpha_0}{\sqrt{k}}$ step size leads to the convergence for the f_k^{best}

Numerical experiments

$$f(x) = \frac{1}{2m} \|Ax - b\|_2^2 + \lambda \|x\|_1 \rightarrow \min_{x \in \mathbb{R}^n}, \quad A \in \mathbb{R}^{m \times n}, \quad \lambda \left(\frac{1}{m} A^T A \right) \in [\mu; L].$$

Linear Least Squares with ℓ_1 Regularization (LASSO).
 $m=100, n=100, \lambda=1, \mu=0, L=10$. Optimal sparsity: 2.3e-01

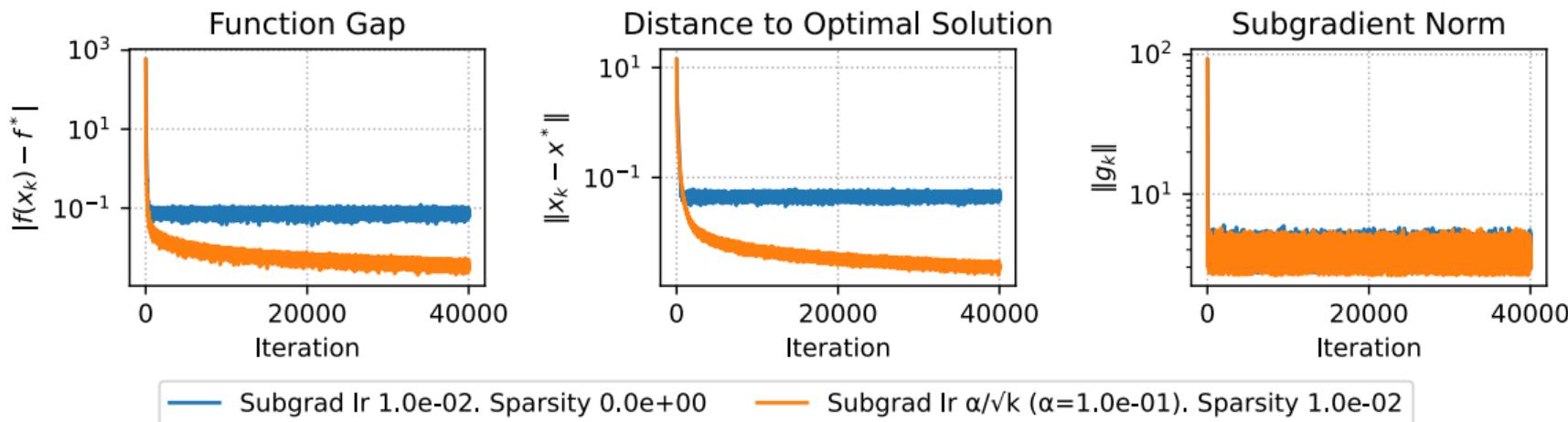


Figure 11: Non-smooth convex case. $\frac{\alpha_0}{\sqrt{k}}$ step size leads to the convergence for the f_k^{best}

Numerical experiments

$$f(x) = \frac{1}{2m} \|Ax - b\|_2^2 + \lambda \|x\|_1 \rightarrow \min_{x \in \mathbb{R}^n}, \quad A \in \mathbb{R}^{m \times n}, \quad \lambda \left(\frac{1}{m} A^T A \right) \in [\mu; L].$$

Linear Least Squares with ℓ_1 Regularization (LASSO).
 $m=100, n=100, \lambda=1, \mu=1, L=10$. Optimal sparsity: 2.0e-01

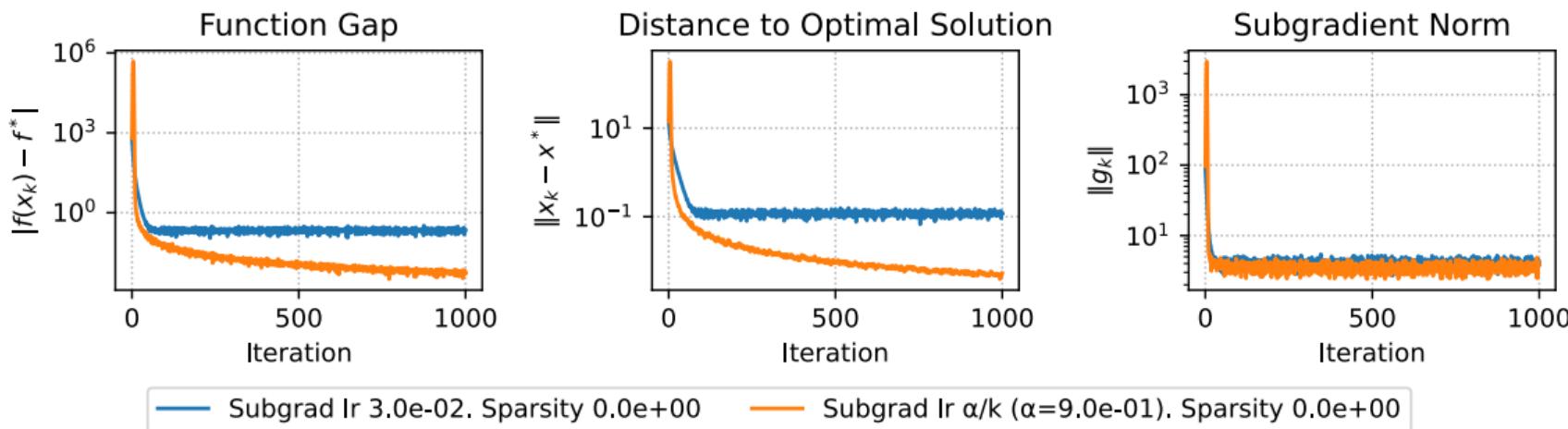


Figure 12: Non-smooth strongly convex case. $\frac{\alpha_0}{k}$ step size leads to the convergence for the f_k^{best}

Numerical experiments

$$f(x) = \frac{1}{2m} \|Ax - b\|_2^2 + \lambda \|x\|_1 \rightarrow \min_{x \in \mathbb{R}^n}, \quad A \in \mathbb{R}^{m \times n}, \quad \lambda \left(\frac{1}{m} A^T A \right) \in [\mu; L].$$

Linear Least Squares with ℓ_1 Regularization (LASSO).
 $m=100, n=100, \lambda=1, \mu=1, L=10$. Optimal sparsity: 2.0e-01

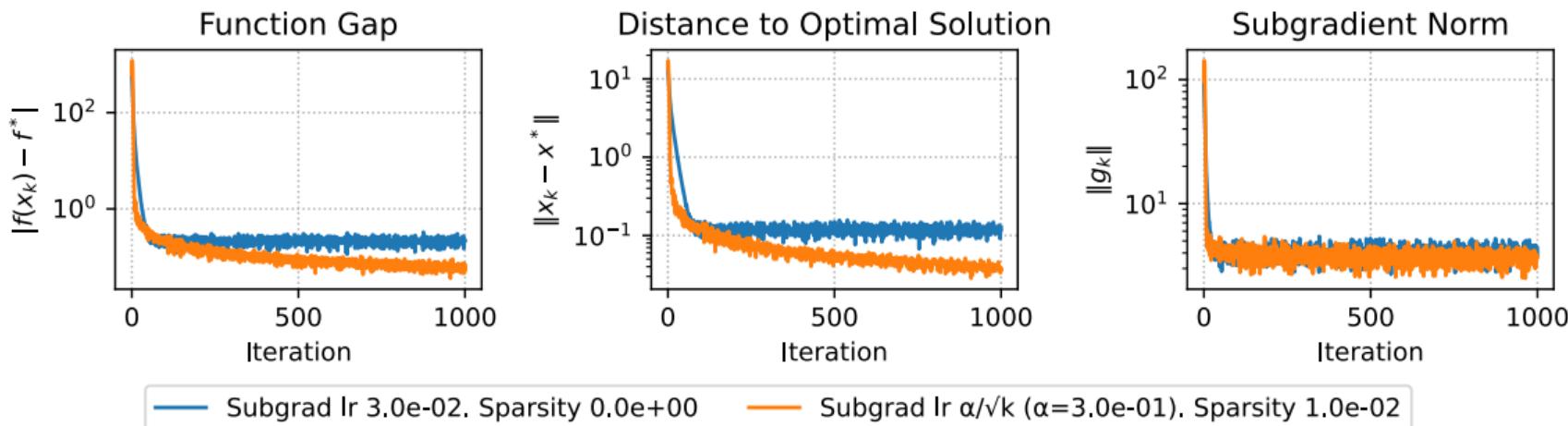


Figure 13: Non-smooth strongly convex case. $\frac{\alpha_0}{\sqrt{k}}$ step size works worse

Numerical experiments

$$f(x) = \frac{1}{m} \sum_{i=1}^m \log(1 + \exp(-b_i(A_i x))) + \lambda \|x\|_1 \rightarrow \min_{x \in \mathbb{R}^n}, \quad A_i \in \mathbb{R}^n, \quad b_i \in \{-1, 1\}$$

Binary Logistic Regression with ℓ_1 Regularization.
 $m=300$, $n=50$, $\lambda=0.1$. Optimal sparsity: 8.6e-01

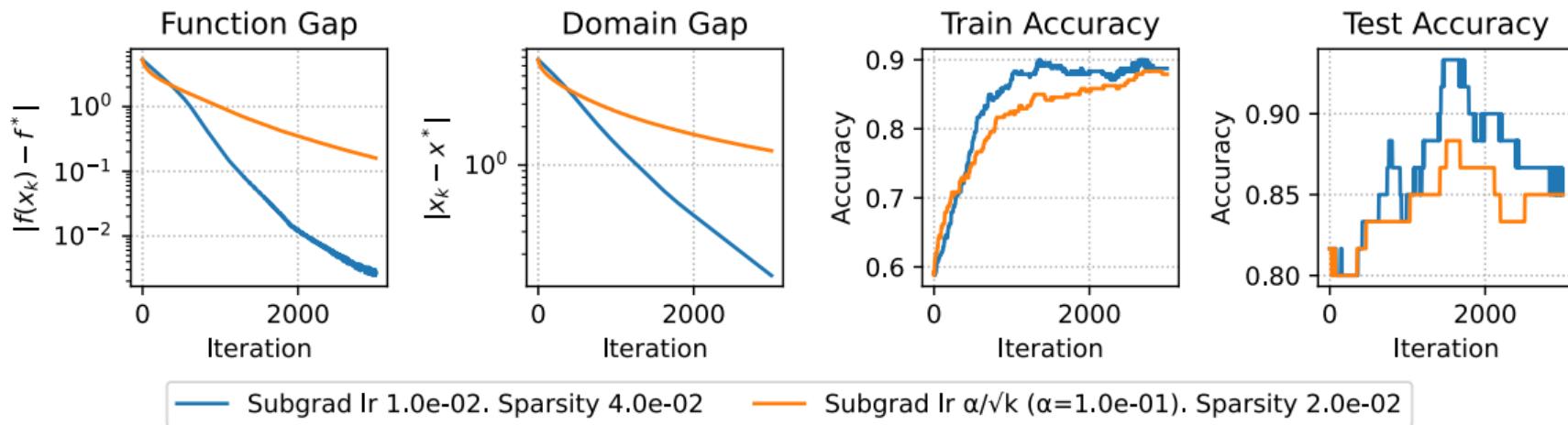


Figure 14: Logistic regression with ℓ_1 regularization

Numerical experiments

$$f(x) = \frac{1}{m} \sum_{i=1}^m \log(1 + \exp(-b_i(A_i x))) + \lambda \|x\|_1 \rightarrow \min_{x \in \mathbb{R}^n}, \quad A_i \in \mathbb{R}^n, \quad b_i \in \{-1, 1\}$$

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 $m=300$, $n=50$, $\lambda=0.1$. Optimal sparsity: 8.6e-01

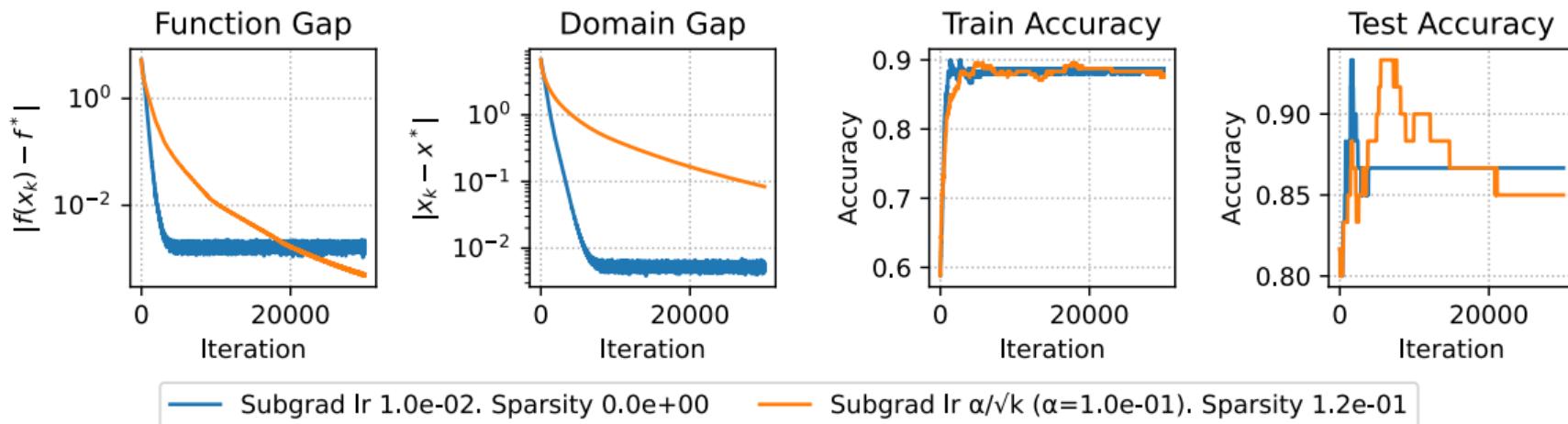


Figure 15: Logistic regression with ℓ_1 regularization

Numerical experiments

$$f(x) = \frac{1}{m} \sum_{i=1}^m \log(1 + \exp(-b_i(A_i x))) + \lambda \|x\|_1 \rightarrow \min_{x \in \mathbb{R}^n}, \quad A_i \in \mathbb{R}^n, \quad b_i \in \{-1, 1\}$$

Binary Logistic Regression with ℓ_1 Regularization.
 $m=300$, $n=50$, $\lambda=0.25$. Optimal sparsity: 9.6e-01

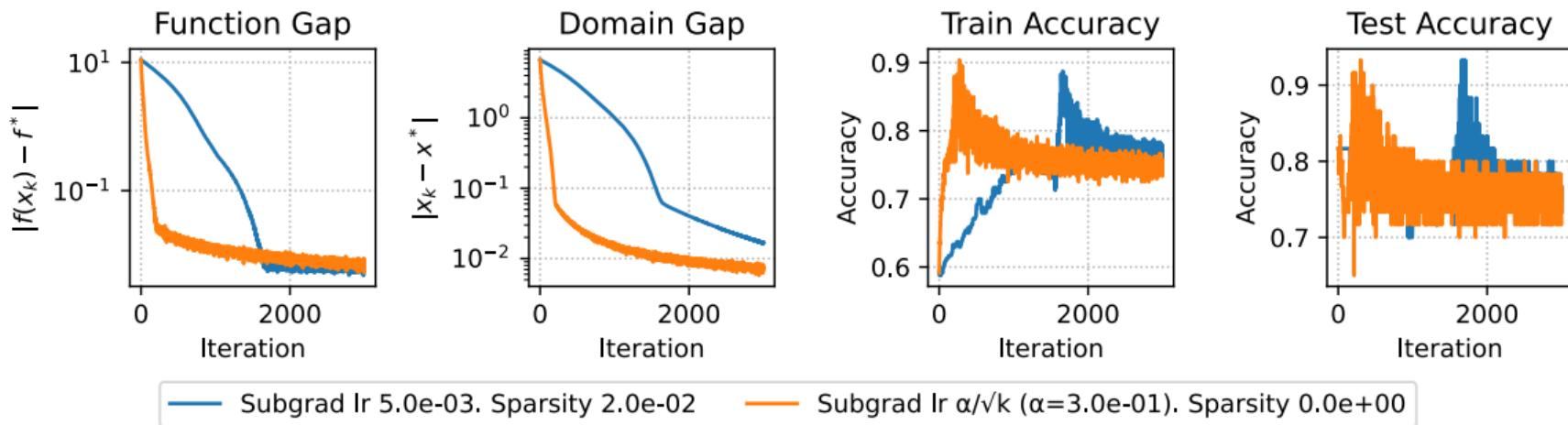


Figure 16: Logistic regression with ℓ_1 regularization

Numerical experiments

$$f(x) = \frac{1}{m} \sum_{i=1}^m \log(1 + \exp(-b_i(A_i x))) + \lambda \|x\|_1 \rightarrow \min_{x \in \mathbb{R}^n}, \quad A_i \in \mathbb{R}^n, \quad b_i \in \{-1, 1\}$$

Binary Logistic Regression with ℓ_1 Regularization.
 $m=300$, $n=50$, $\lambda=0.25$. Optimal sparsity: 9.6e-01

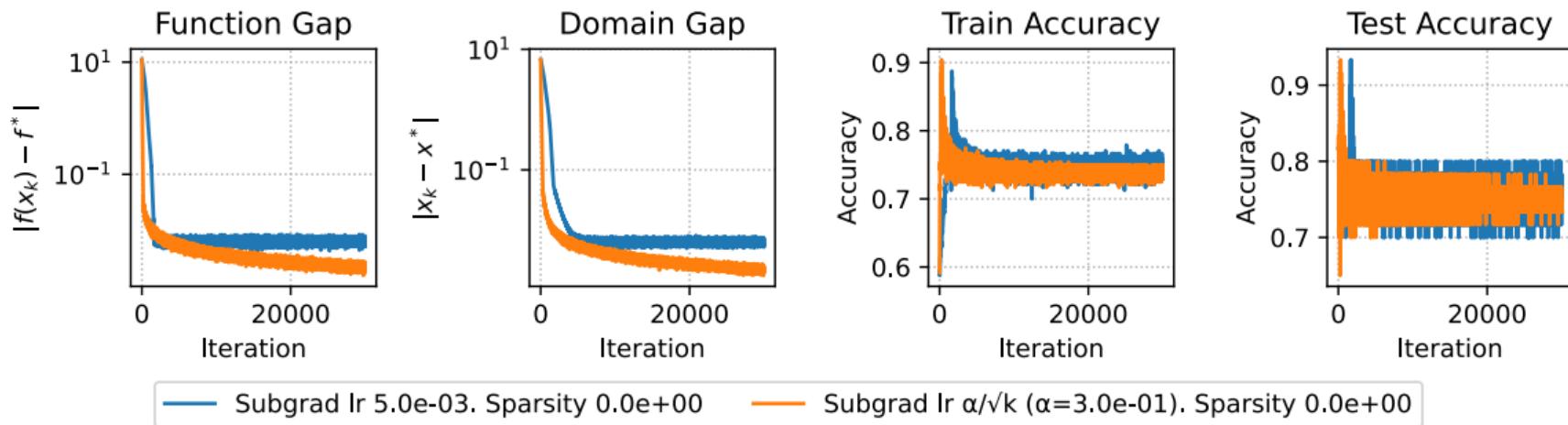


Figure 17: Logistic regression with ℓ_1 regularization

Numerical experiments

$$f(x) = \frac{1}{m} \sum_{i=1}^m \log(1 + \exp(-b_i(A_i x))) + \lambda \|x\|_1 \rightarrow \min_{x \in \mathbb{R}^n}, \quad A_i \in \mathbb{R}^n, \quad b_i \in \{-1, 1\}$$

Binary Logistic Regression with ℓ_1 Regularization.
 $m=300$, $n=50$, $\lambda=0.27$. Optimal sparsity: $1.0e+00$

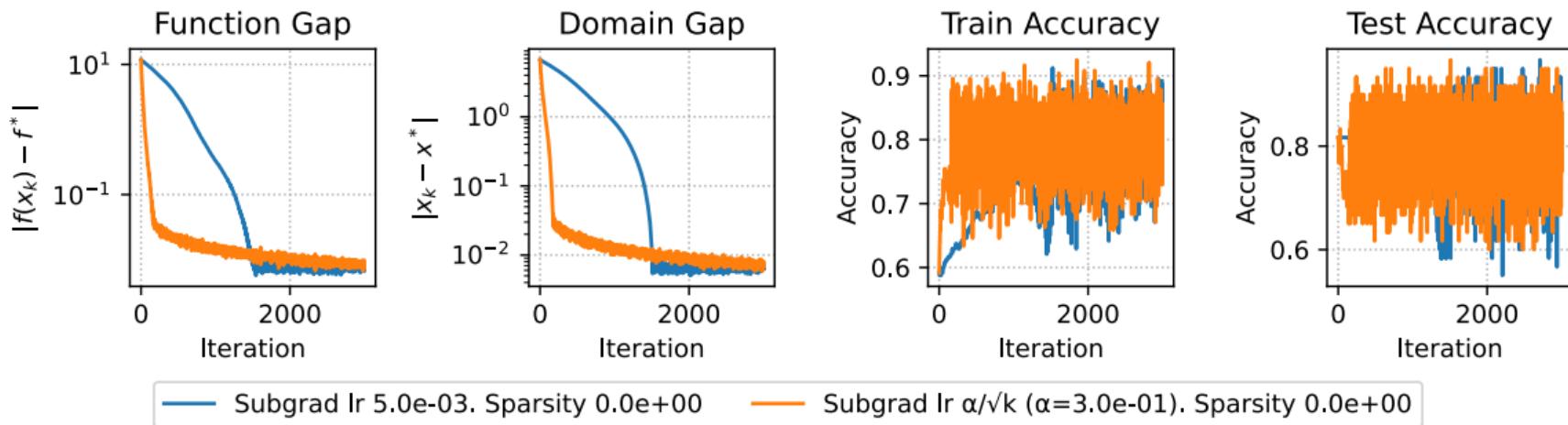


Figure 18: Logistic regression with ℓ_1 regularization

Numerical experiments

$$f(x) = \frac{1}{m} \sum_{i=1}^m \log(1 + \exp(-b_i(A_i x))) + \lambda \|x\|_1 \rightarrow \min_{x \in \mathbb{R}^n}, \quad A_i \in \mathbb{R}^n, \quad b_i \in \{-1, 1\}$$

Binary Logistic Regression with ℓ_1 Regularization.
 $m=300$, $n=50$, $\lambda=0.27$. Optimal sparsity: $1.0e+00$

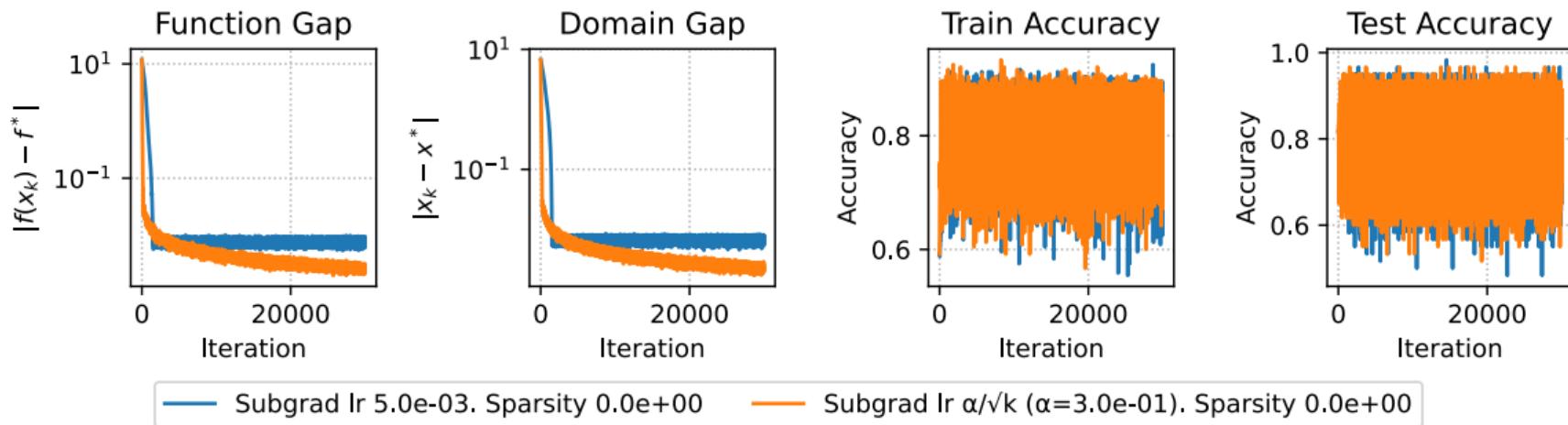


Figure 19: Logistic regression with ℓ_1 regularization

Lower bounds

Lower bounds

convex (non-smooth) ³	smooth (non-convex) ⁴	smooth & convex ⁵	smooth & strongly convex (or PL) ¹
$\mathcal{O}\left(\frac{1}{\sqrt{k}}\right)$	$\mathcal{O}\left(\frac{1}{k^2}\right)$	$\mathcal{O}\left(\frac{1}{k^2}\right)$	$\mathcal{O}\left(\left(\frac{\sqrt{\kappa}-1}{\sqrt{\kappa}+1}\right)^k\right)$
$k_\varepsilon \sim \mathcal{O}\left(\frac{1}{\varepsilon^2}\right)$	$k_\varepsilon \sim \mathcal{O}\left(\frac{1}{\sqrt{\varepsilon}}\right)$	$k_\varepsilon \sim \mathcal{O}\left(\frac{1}{\sqrt{\varepsilon}}\right)$	$k_\varepsilon \sim \mathcal{O}\left(\sqrt{\kappa} \log \frac{1}{\varepsilon}\right)$

³Nesterov, Lectures on Convex Optimization

⁴Carmon, Duchi, Hinder, Sidford, 2017

⁵Nemirovski, Yudin, 1979

Black box iteration

The iteration of gradient descent:

$$\begin{aligned}x^{k+1} &= x^k - \alpha^k \nabla f(x^k) \\&= x^{k-1} - \alpha^{k-1} \nabla f(x^{k-1}) - \alpha^k \nabla f(x^k) \\&\quad \vdots \\&= x^0 - \sum_{i=0}^k \alpha^{k-i} \nabla f(x^{k-i})\end{aligned}$$

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Consider a family of first-order methods, where

$$\begin{aligned}x^{k+1} &\in x^0 + \text{span} \{ \nabla f(x^0), \nabla f(x^1), \dots, \nabla f(x^k) \} && f - \text{smooth} \\x^{k+1} &\in x^0 + \text{span} \{ g_0, g_1, \dots, g_k \}, \text{ where } g_i \in \partial f(x^i) && f - \text{non-smooth}\end{aligned}\tag{1}$$

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To construct a lower bound, we need to find a function f from the corresponding class such that any method from the family 1 will work at least as slowly as the lower bound.

Non-smooth convex case

i Theorem

There exists a function f that is G -Lipschitz and convex such that any method 1 satisfies

$$\min_{i \in [1, k]} f(x^i) - \min_{x \in \mathbb{B}(R)} f(x) \geq \frac{GR}{2(1 + \sqrt{k})}$$

for $R > 0$ and $k \leq n$, where n is the dimension of the problem.

$$f(x) = f_{\text{наг}}(x) + r(x)$$

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||
 $\lambda \|x\|_1$

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for $R > 0$ and $k \leq n$, where n is the dimension of the problem.

Proof idea: build such a function f that, for any method 1, we have

$$\text{span}\{g_0, g_1, \dots, g_k\} \subset \text{span}\{e_1, e_2, \dots, e_i\}$$

where e_i is the i -th standard basis vector. At iteration $k \leq n$, there are at least $n - k$ coordinate of x are 0. This helps us to derive a bound on the error.

Non-smooth case (proof)

Consider the function:

$$f(x) = \beta \max_{i \in [1, k]} x[i] + \frac{\alpha}{2} \|x\|_2^2,$$

where $\alpha, \beta \in \mathbb{R}$ are parameters, and $x[1 : k]$ denotes the first k components of x .

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- The function $f(x)$ is α -strongly convex due to the quadratic term $\frac{\alpha}{2} \|x\|_2^2$.

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- The function is non-smooth because the first term introduces a non-differentiable point at the maximum coordinate of x .

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- The function $f(x)$ is α -strongly convex due to the quadratic term $\frac{\alpha}{2} \|x\|_2^2$.
- The function is non-smooth because the first term introduces a non-differentiable point at the maximum coordinate of x .

Consider the subdifferential of $f(x)$ at x :

$$\begin{aligned}\partial f(x) &= \partial \left(\beta \max_{i \in [1, k]} x[i] \right) + \partial \left(\frac{\alpha}{2} \|x\|_2^2 \right) \\ &= \beta \partial \left(\max_{i \in [1, k]} x[i] \right) + \alpha x \\ &= \beta \text{conv} \left\{ e_i \mid i : x[i] = \max_j x[j] \right\} + \alpha x\end{aligned}$$

Non-smooth case (proof)

Consider the function:

$$f(x) = \beta \max_{i \in [1, k]} x[i] + \frac{\alpha}{2} \|x\|_2^2,$$

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It is easy to see, that if $g \in \partial f(x)$ and $\|x\| \leq R$, then
 $\|g\| \leq \alpha R + \beta$

Thus, f is $\alpha R + \beta$ -Lipschitz on $B(R)$.

Non-smooth case (proof)

Next, we describe the first-order oracle for this function. When queried for a subgradient at a point x , the oracle returns

$$\alpha x + \gamma e_i,$$

where i is the *first* coordinate for which $x[i] = \max_{1 \leq j \leq k} x[j]$.

- We ensure that $\|x^0\| \leq R$ by starting from $x^0 = 0$.

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- We ensure that $\|x^0\| \leq R$ by starting from $x^0 = 0$.
- When the oracle is queried at $x^0 = 0$, it returns e_1 . Consequently, x^1 must lie on the line generated by e_1 .
- By an induction argument, one shows that for all i , the iterate x^i lies in the linear span of $\{e_1, \dots, e_i\}$. In particular, for $i \leq k$, the $k+1$ -th coordinate of x_i is zero and due to the structure of $f(x)$:

$$f(x^i) \geq 0.$$

Non-smooth case (proof)

- It remains to compute the minimal value of f . Define the point $y \in \mathbb{R}^n$ as

$$y[i] = -\frac{\beta}{\alpha k} \quad \text{for } 1 \leq i \leq k, \quad y[i] = 0 \quad \text{for } k+1 \leq i \leq n.$$

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- Note, that $0 \in \partial f(y)$:

$$\begin{aligned}\partial f(y) &= \alpha y + \beta \operatorname{conv} \left\{ e_i \mid i : y[i] = \max_j y[j] \right\} \\ &= \alpha y + \beta \operatorname{conv} \{e_i \mid i : y[i] = 0\} \\ 0 &\in \partial f(y).\end{aligned}$$

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- It follows that the minimum value of $f = f(y) = f(x^*)$ is

$$f(y) = -\frac{\beta^2}{\alpha k} + \frac{\alpha}{2} \cdot \frac{\beta^2}{\alpha^2 k} = -\frac{\beta^2}{2\alpha k}.$$

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$$f(y) = -\frac{\beta^2}{\alpha k} + \frac{\alpha}{2} \cdot \frac{\beta^2}{\alpha^2 k} = -\frac{\beta^2}{2\alpha k}.$$

- Now we have:

$$f(x^i) - f(x^*) \geq 0 - \left(-\frac{\beta^2}{2\alpha k} \right) \geq \frac{\beta^2}{2\alpha k}.$$

Non-smooth case (proof)

We have: $f(x^i) - f(x^*) \geq \frac{\beta^2}{2\alpha k}$, while we need to prove that $\min_{i \in [1, k]} f(x^i) - f(x^*) \geq \frac{GR}{2(1+\sqrt{k})}$.

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Convex case

$$\alpha = \frac{G}{R} \frac{1}{1 + \sqrt{k}} \quad \beta = \frac{\sqrt{k}}{1 + \sqrt{k}}$$

$$\frac{\beta^2}{2\alpha} = \frac{GRk}{2(1 + \sqrt{k})}$$

Note, in particular, that $\|y\|_2^2 = \frac{\beta^2}{\alpha^2 k} = R^2$ with these parameters

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Strongly convex case

$$\alpha = \frac{G}{2R} \quad \beta = \frac{G}{2}$$

Note, in particular, that $\|y\|_2^2 = \frac{\beta^2}{\alpha^2 k} = \frac{G^2}{4\alpha^2 k} = R^2$ with these parameters

$$\min_{i \in [1, k]} f(x^i) - f(x^*) \geq \frac{G^2}{8\alpha k}$$

Applications

Linear Least Squares with l_1 -regularization

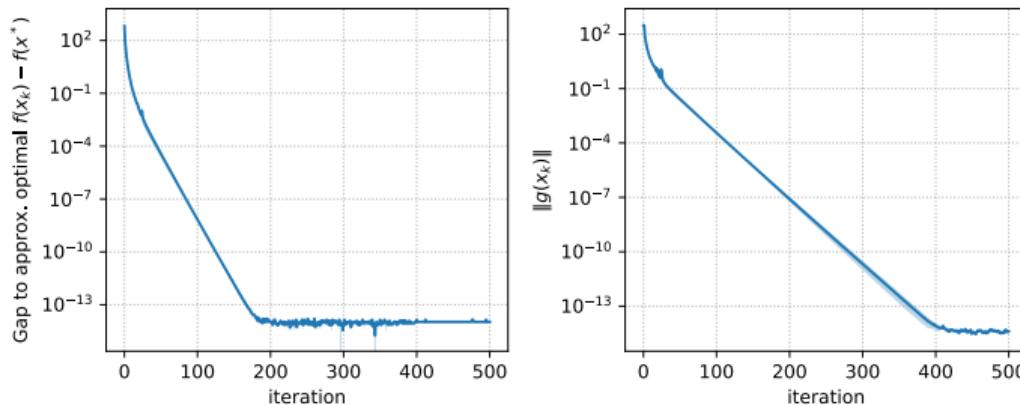
$$\min_{x \in \mathbb{R}^n} \frac{1}{2} \|Ax - b\|_2^2 + \lambda \|x\|_1$$

The algorithm will be written as:

$$x_{k+1} = x_k - \alpha_k \left(A^\top (Ax_k - b) + \lambda \text{sign}(x_k) \right),$$

where the signum function is taken element-wise.

LLS with l_1 regularization. 2 runs. $\lambda = 1$



Regularized logistic regression

Given $(x_i, y_i) \in \mathbb{R}^p \times \{0, 1\}$ for $i = 1, \dots, n$, the logistic regression function is defined as:

$$f(\theta) = \sum_{i=1}^n (-y_i x_i^T \theta + \log(1 + \exp(x_i^T \theta)))$$

This is a smooth and convex function with its gradient given by:

$$\nabla f(\theta) = \sum_{i=1}^n (y_i - s_i(\theta)) x_i$$

where $s_i(\theta) = \frac{\exp(x_i^T \theta)}{1 + \exp(x_i^T \theta)}$, for $i = 1, \dots, n$. Consider the regularized problem:

$$f(\theta) + \lambda r(\theta) \rightarrow \min_{\theta}$$

where $r(\theta) = \|\theta\|_2^2$ for the ridge penalty, or $r(\theta) = \|\theta\|_1$ for the lasso penalty.

Support Vector Machines

Let $D = \{(x_i, y_i) \mid x_i \in \mathbb{R}^n, y_i \in \{\pm 1\}\}$

We need to find $\theta \in \mathbb{R}^n$ and $b \in \mathbb{R}$ such that

$$\min_{\theta \in \mathbb{R}^n, b \in \mathbb{R}} \frac{1}{2} \|\theta\|_2^2 + C \sum_{i=1}^m \max[0, 1 - y_i(\theta^\top x_i + b)]$$

References

- Subgradient Methods Stephen Boyd (with help from Jaehyun Park)