Optimization Theory, MATH 273A
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Homework 1
Due on Friday, October 10, 2025.

Problem 1: *Least-squares derivatives.* Let $X_1, \dots, X_N \in \mathbb{R}^p$ and $Y_1, \dots, Y_N \in \mathbb{R}$. Define

$$X = \begin{bmatrix} X_1^\intercal \\ \vdots \\ X_N^\intercal \end{bmatrix} \in \mathbb{R}^{N \times p}, \qquad Y = \begin{bmatrix} Y_1 \\ \vdots \\ Y_N \end{bmatrix} \in \mathbb{R}^N.$$

Let

$$\mathcal{L}(\theta) = \frac{1}{2}\|X\theta - Y\|^2.$$

Show that $\nabla_\theta \mathcal{L}(\theta) = X^\intercal(X\theta - Y)$.

Hint. Use the fact that

$$Mv = \sum_{i=1}^N M_{:,i} v_i \in \mathbb{R}^p$$

for any $M \in \mathbb{R}^{p \times N}$, $v \in \mathbb{R}^N$, where $M_{:,i}$ is the ith column of M for $i = 1, \dots, N$.

Problem 2: *Diverging univariate GD.* Consider the univariate function $f(x) = x^2/2$. Show that

$$x_{k+1} = x_k - \alpha f'(x_k)$$

with $x_0 \neq 0$ diverges if $\alpha > 2$.

Problem 3: *Diverging multivariate GD.* Let $X \in \mathbb{R}^{N \times p}$ and $Y \in \mathbb{R}^N$, and consider the optimization problem

$$\underset{\theta \in \mathbb{R}^p}{\text{minimize}} \quad f(\theta)$$

with

$$f(\theta) = \frac{1}{2}\|X\theta - Y\|^2.$$

Show

$$\theta_{k+1} = \theta_k - \alpha \nabla f(\theta_k)$$

with $\alpha > 2/\rho(X^\intercal X)$ diverges for most starting points $\theta_0 \in \mathbb{R}^m$. Here, ρ denotes the spectral radius, i.e., $\rho(X^\intercal X)$ is the largest eigenvalue of the symmetric matrix $X^\intercal X$. For simplicity, you may assume $X^\intercal X$ is invertible.

Hint. Let $\theta_\star = (X^\intercal X)^{-1} X^\intercal Y$ and show that

$$\theta_{k+1} - \theta_\star = \text{Some function of } (\theta_k - \theta_\star).$$

Remark. "Most starting points" can be formalized as "almost everywhere with respect to the Lebesgue measure". If you are unfamiliar with measure theory, you can understand the statement as holding for all starting points except for a lower dimensional set.

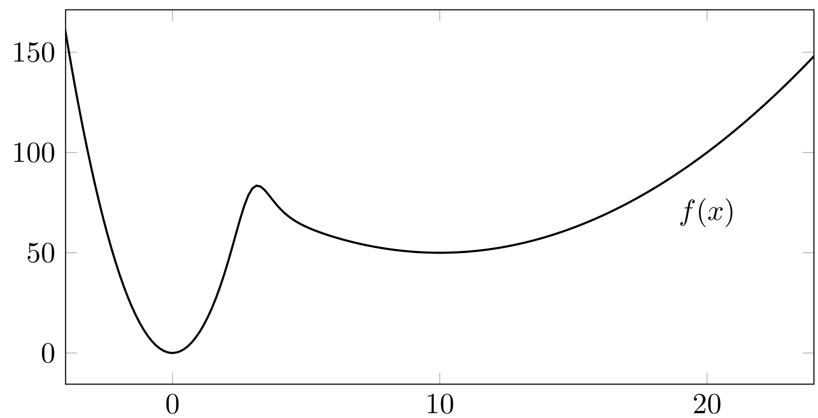
Problem 4: *GD converging to wide local minima.* Consider the optimization problem

$$\underset{x\in\mathbb{R}}{\text{minimize}} \quad f(x)$$

with

$$f(x) = \frac{10x^2 + e^{3(x-3)}((x-10)^2/2 + 50)}{1 + e^{3(x-3)}}.$$

Code for evaluating f and f' is implemented in the starter code `wideMinima.py`. We call the global minimum near $x = 0$ the *sharp* minimum and the local minimum near $x = 10$ the *wide* minimum.



Implement gradient descent and run it with random starting points within the range $[-5, 20]$. Experimentally demonstrate that gradient descent with step size $\alpha = 0.01$ converges to either of the two minima, with $\alpha = 0.3$ converges to the wide minimum, and with $\alpha = 4$ does not converge for most starting points.

Remark. The moral of this problem is that the step size of GD (and SGD) determines the sharpness of the minima the algorithm converges to. This has implications on the generalization performance in machine learning.[1]

[1] Y. Jiang, B. Neyshabur, H. Mobahi, D. Krishnan, S. Bengio, Fantastic Generalization Measures and Where to Find Them, *ICLR*, 2020.
P. Foret, A. Kleiner, H. Mobahi, B. Neyshabur, Sharpness-aware Minimization for Efficiently Improving Generalization, *ICLR*, 2020.

Problem 5: *L-smoothness lemma.* Let $f\colon \mathbb{R}^n \to \mathbb{R}$ be L-smooth. Show that

$$f(x) + \langle \nabla f(x), \delta \rangle - \frac{L}{2}\|\delta\|^2 \le f(x+\delta), \qquad \forall\, x, \delta \in \mathbb{R}^n.$$

Problem 6: *L-smoothness and Hessian.* Let $f\colon \mathbb{R}^n \to \mathbb{R}$ be twice continuously differentiable. Show that f is L-smooth if and only if

$$-L \le \lambda_{\min}(\nabla^2 f(x)) \le \lambda_{\max}(\nabla^2 f(x)) \le +L \qquad \text{for all } x \in \mathbb{R}^n.$$

Hint. For ($\Rightarrow$), recall the directional derivative formula

$$\nabla^2 f(x) h = \lim_{h \to 0} \frac{\nabla f(x + h\delta) - \nabla f(x)}{h}, \qquad \text{for all } x, v \in \mathbb{R}^n.$$

For ($\Leftarrow$), let $g(t) = \nabla f(x + t(y-x))$, and note $g(1) - g(0) = \int_0^1 g'(t)\, dt$. Then, consider the spectral norm (operator norm) of $\nabla^2 f(x)$.

Problem 7: *If iterates of GD converge, the limit is a stationary point.* Let $L > 0$, and let $f\colon \mathbb{R}^n \to \mathbb{R}$ be L-smooth. Consider gradient descent with constant stepsize with $\alpha \in (0, 2/L)$:

$$x_{k+1} = x_k - \alpha \nabla f(x_k)$$

for $k = 0, 1, \dots$. Show that if $x_k \to x_\infty \in \mathbb{R}^n$, then x_∞ is a stationary point.

Clarification. Recall, x_∞ is a stationary point if $\nabla f(x_\infty) = 0$.
Hint. L-smoothness implies ∇f is continuous.

Problem 8: *If iterates of GD with linesearch converge, the limit is a stationary point.* Let $f\colon \mathbb{R}^n \to \mathbb{R}$ be continuously differentiable. Consider gradient descent with exact line search:

$$\begin{aligned} g_k &= \nabla f(x_k) \\ \alpha_k &\in \operatorname*{argmin}_{\alpha \in \mathbb{R}} f(x_k - \alpha g_k) \\ x_{k+1} &= x_k - \alpha_k \nabla f(x_k) \end{aligned}$$

for $k = 0, 1, \dots$, where we assume a minimizer α_k exist for all $k = 0, 1, \dots$.

(a) Show that $\langle \nabla f(x_{k+1}), \nabla f(x_k) \rangle = 0$ for $k = 0, 1, \dots$.

(b) Show that if $x_k \to x_\infty \in \mathbb{R}^n$, then x_∞ is a stationary point.

Clarification. Recall, x_∞ is a stationary point if $\nabla f(x_\infty) = 0$.