

Optimization Algorithms: HW1

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(1)

Given a twice differentiable function $\varphi : \mathbb{R}^d \rightarrow [-\infty, \infty]$, assume that it is logarithmically homogeneous, then by the definition, the following holds:

$$\varphi(\gamma x) = \varphi(x) - \log \gamma, \quad \forall x \in \mathbb{R}^d, \gamma > 0 \quad (1)$$

Claim: $\langle \nabla \varphi(x), x \rangle = -1$

To derive the first equation, we first define the following:

$$F(\gamma) = \varphi(\gamma x)$$

Then the original equation (1) would become:

$$F(\gamma) = \varphi(x) - \log \gamma$$

Taking the derivative w.r.t. γ on both sides, we get:

$$\frac{dF}{d\gamma} = \frac{d}{d\gamma} \varphi(\gamma x) = \nabla \varphi(\gamma x) \cdot x = \langle \nabla \varphi(\gamma x), x \rangle \quad (2)$$

$$\frac{dF}{d\gamma} = \frac{d}{d\gamma} (\varphi(x) - \log \gamma) = -\frac{1}{\gamma} \quad (3)$$

Thus by (2) and (3), we have:

$$\langle \nabla \varphi(\gamma x), x \rangle = -\frac{1}{\gamma}$$

Then by plugging in $\gamma = 1$, we have:

$$\langle \nabla \varphi(x), x \rangle = -1 \quad \square$$

Claim: $\nabla \varphi(x) = -\nabla^2 \varphi(x)x$

From the previous part, we have:

$$\nabla \varphi(x)^T x = -1$$

Compute the gradient of both sides, for the left hand side, we have:

$$\begin{aligned} \nabla(\nabla \varphi(x)^T x) &= \nabla(\nabla \varphi(x))^T x + \nabla \varphi(x)^T \nabla x \\ &= \nabla^2 \varphi(x)x + \nabla \varphi(x)^T \nabla x \end{aligned}$$

For the right hand side, we have:

$$\nabla(-1) = 0$$

Thus we have:

$$\begin{aligned} \nabla^2 \varphi(x)x + \nabla \varphi(x)^T \nabla x &= 0 \\ \Rightarrow \nabla \varphi(x)^T \nabla x &= -\nabla^2 \varphi(x)x \\ \Rightarrow \nabla \varphi(x)^T I_d &= -\nabla^2 \varphi(x)x \\ \Rightarrow \nabla \varphi(x) &= -\nabla^2 \varphi(x)x \quad \square \end{aligned}$$

Claim: $\langle x, \nabla^2 \varphi(x)x \rangle = 1$

From the previous part, we have:

$$\nabla \varphi(x) = -\nabla^2 \varphi(x)x$$

Multiply both sides by x^T , we have:

$$x^T \nabla \varphi(x) = -x^T \nabla^2 \varphi(x)x$$

Which is equivalent to the following by using $\langle \nabla \varphi(x), x \rangle = -1$:

$$\langle x, \nabla^2 \varphi(x)x \rangle = -\langle x, \nabla \varphi(x) \rangle = (-1) \times (-1) = 1 \quad \square$$

(2)

Suppose that $\varphi : \mathbb{R}^d \rightarrow [-\infty, \infty]$ is a twice differentiable function, and is strictly convex and logarithmically homogeneous, then the following holds by the definition:

$$\begin{aligned}\nabla^2 \varphi(x) &> 0 \quad \forall x \in \mathbb{R}^d \\ \varphi(\gamma x) &= \varphi(x) - \log \gamma, \quad \forall x \in \mathbb{R}^d, \gamma > 0.\end{aligned}$$

Also, we have the following properties from the previous subsection:

$$\langle \nabla \varphi(x), x \rangle = -1 \tag{1}$$

$$\nabla \varphi(x) = -\nabla^2 \varphi(x) x \tag{2}$$

$$\langle x, \nabla^2 \varphi(x) x \rangle = 1 \tag{3}$$

Claim: $\nabla^2 \varphi(x) \geq \nabla \varphi(x) (\nabla \varphi(x))^T$, $\forall x \in \text{dom } \varphi$

The claim is equivalent to proving that:

$$\nabla^2 \varphi(x) - \nabla \varphi(x) (\nabla \varphi(x))^T \succeq 0$$

where $\succeq 0$ denotes positive semidefinite.

Let z be any vector in \mathbb{R}^d , then we have:

$$\begin{aligned}z^T \left(\nabla^2 \varphi(x) - \nabla \varphi(x) (\nabla \varphi(x))^T \right) z &= z^T \nabla^2 \varphi(x) z - z^T \nabla \varphi(x) (\nabla \varphi(x))^T z \\ &= z^T \nabla^2 \varphi(x) z - (\nabla \varphi(x)^T z)^2\end{aligned} \tag{*}$$

Case 1: $x = z$

If $x = z$, then (*) becomes the following using (1) and (2):

$$\begin{aligned}z^T \left(\nabla^2 \varphi(x) - \nabla \varphi(x) (\nabla \varphi(x))^T \right) z &= z^T \nabla^2 \varphi(x) x - (\langle \nabla \varphi(x), x \rangle)^2 \\ &= x^T (-\nabla \varphi(x)) - (-1)^2 \\ &= x^T (-\nabla \varphi(x)) - 1 \\ &= -\langle \nabla \varphi(x), x \rangle - 1 \\ &= -(-1) - 1 \\ &= 0 \geq 0\end{aligned}$$

Case 2: $x \neq z$

Using (2) to replace $\nabla\varphi(x)$ with $-\nabla^2\varphi(x)x$ in (*), and using the fact that $(\nabla^2\varphi(x))^T = \nabla^2\varphi(x)$ (the Hessian is symmetric):

$$\begin{aligned}
z^T \left(\nabla^2\varphi(x) - \nabla\varphi(x) (\nabla\varphi(x))^T \right) z &= z^T \nabla^2\varphi(x) z - (\nabla\varphi(x)^T z)^2 \\
&= z^T \nabla^2\varphi(x) z - ((-\nabla^2\varphi(x)x)^T z)^2 \\
&= z^T \nabla^2\varphi(x) z - \left(- \underbrace{x^T}_{A^T} \underbrace{(\nabla^2\varphi(x))^T z}_B \right)^2 \\
&= z^T \nabla^2\varphi(x) z - \underbrace{[(\nabla^2\varphi(x))^T z]^T x x^T [(\nabla^2\varphi(x))^T z]}_{B^T A A^T B} \\
&= z^T \nabla^2\varphi(x) z - [x^T (\nabla^2\varphi(x))^T z]^T [x^T (\nabla^2\varphi(x))^T z] \\
&= z^T \nabla^2\varphi(x) z - \|x^T (\nabla^2\varphi(x))^T z\|^2 \\
&= z^T \nabla^2\varphi(x) z - \|x^T (\nabla^2\varphi(x)) z\|^2
\end{aligned}$$

Let $H = \nabla^2\varphi(x)$, then the above expression is equivalent to:

$$z^T H z - (x^T H z)^2$$

Let's first check that we can define the function

$$h : \mathbb{R}^d \times \mathbb{R}^d \rightarrow \mathbb{R}, \quad h(u, v) = u^T H v$$

as the inner product on \mathbb{R}^d .¹

Using the fact that we assumed that $\nabla^2\varphi(x) > 0$, so H is positive definite, thus by theorem², there exists a one and only one positive definite matrix $H^{1/2}$ (also symmetric) such that $H = H^{1/2} H^{1/2}$.

- **Symmetry:** For any $u, v \in \mathbb{R}^d$, we have:

$$\begin{aligned}
h(u, v) &= u^T H v \\
&= u^T H^{1/2} H^{1/2} v \\
&= (H^{1/2} u)^T (H^{1/2} v) \\
&= (H^{1/2} v)^T (H^{1/2} u) \\
&= v^T H^{1/2} H^{1/2} u \\
&= v^T H u \\
&= h(v, u)
\end{aligned}$$

¹H. Amann and J. Escher, *Analysis I*, 1st ed., Birkhäuser Basel, 2005, p. 153.

²“Square root of a matrix”, Wikipedia, https://en.wikipedia.org/wiki/Square_root_of_a_matrix

- **Linearity:** For any $\lambda, \mu \in \mathbb{R}$ and $t, u, v \in \mathbb{R}^d$, we have:

$$\begin{aligned}
h(t, \lambda u + \mu v) &= t^T H(\lambda u + \mu v) \\
&= t^T H(\lambda u) + t^T H(\mu v) \\
&= \lambda t^T H u + \mu t^T H v \\
&= \lambda h(t, u) + \mu h(t, v)
\end{aligned}$$

- **Positive definiteness:** For any $u \in \mathbb{R}^d$, we have:

$$h(u, u) = u^T H u > 0 \quad \text{since } H \text{ is positive definite}$$

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Therefore, we have:

$$z^T H z - (x^T H z)^2 = \langle z, z \rangle_H - \langle x, z \rangle_H^2$$

Using the Cauchy-Schwarz inequality ⁴:

Cauchy-Schwarz inequality

Let $(E, (\cdot | \cdot))$ be an inner product space. Then

$$|(x | y)|^2 \leq (x | x)(y | y), \quad x, y \in E$$

We can derive the later equation using the fact that:

$$\langle x, x \rangle_H = x^T H x = x^T \nabla^2 \varphi(x) x = 1$$

(this is because property (3))

So we have:

$$\begin{aligned}
\langle x, z \rangle_H^2 &\leq \langle x, x \rangle_H \langle z, z \rangle_H \\
&= 1 \times \langle z, z \rangle_H \\
&= \langle z, z \rangle_H
\end{aligned}$$

Thus we have:

$$z^T H z - (x^T H z)^2 \geq 0 \quad \square$$

³I later found that we have "A function $\langle \cdot, \cdot \rangle : \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}$ is an inner product on \mathbb{R}^n if and only if there exists a symmetric positive-definite matrix \mathbf{M} such that $\langle x, y \rangle = x^T \mathbf{M} y$ for all $x, y \in \mathbb{R}^n$." on "Inner product space", Wikipedia, https://en.wikipedia.org/wiki/Inner_product_space

⁴H. Amann and J. Escher, *Analysis I*, 1st ed., Birkhäuser Basel, 2005, p. 154.

(3)

We need to prove the following equivalence:

$$\begin{aligned}
& (1) \quad e^{-\varphi(x)} \text{ is concave} \\
& \iff (2) \quad \varphi(y) \geq \varphi(x) - \log(1 - \langle \nabla \varphi(x), y - x \rangle), \quad \forall x, y \in \text{dom}(\varphi) \\
& \iff (3) \quad \nabla^2 \varphi(x) \succeq \nabla \varphi(x) \nabla \varphi(x)^\top, \quad \forall x \in \text{dom}(\varphi)
\end{aligned}$$

(1) \implies (2)

Let $f : \mathbb{R}^d \rightarrow \mathbb{R}$ be defined as $f(x) = e^{-\varphi(x)}$.

Suppose that $f(x) = e^{-\varphi(x)}$ is concave, then by the definition of concavity ⁵:

Convex

A continuously differentiable function $f(x)$ is called convex on \mathbb{R}^n if for any $x, y \in \mathbb{R}^n$, we have:

$$f(y) \geq f(x) + \langle \nabla f(x), y - x \rangle$$

If $-f(x)$ is convex, then $f(x)$ is concave.

this means that our assumption is equivalent to saying that $-e^{-\varphi(x)}$ is convex. Let $g(x) = -f(x) = -e^{-\varphi(x)}$ a convex function, using the fact that:

$$\nabla g(x) = \frac{d}{dx}(-e^{-\varphi(x)}) = e^{-\varphi(x)} \nabla \varphi(x)$$

we have the following:

For any $x, y \in \mathbb{R}^d$:

$$\begin{aligned}
& g(y) \geq g(x) + \langle \nabla g(x), y - x \rangle \\
& \Rightarrow -e^{-\varphi(y)} \geq -e^{-\varphi(x)} + \langle e^{-\varphi(x)} \nabla \varphi(x), y - x \rangle \\
& \Rightarrow e^{-\varphi(y)} \leq e^{-\varphi(x)} - e^{-\varphi(x)} \langle \nabla \varphi(x), y - x \rangle \\
& \Rightarrow e^{-\varphi(y)} \leq e^{-\varphi(x)} (1 - \langle \nabla \varphi(x), y - x \rangle) \\
& \Rightarrow -\varphi(y) \leq -\varphi(x) + \log(1 - \langle \nabla \varphi(x), y - x \rangle) \\
& \Rightarrow \varphi(y) \geq \varphi(x) - \log(1 - \langle \nabla \varphi(x), y - x \rangle)
\end{aligned}$$

(2) \implies (3)

⁵Y. Nesterov, *Introductory Lectures on Convex Optimization: A Basic Course*, 1st ed., Springer, New York, NY, 2004, p. 52.

Suppose (2) holds, so we have:

$$\varphi(y) \geq \varphi(x) - \log(1 - \langle \nabla \varphi(x), y - x \rangle), \quad \forall x, y \in \text{dom}(\varphi)$$

By plugging in $y = x + h$ ($h = y - x$), with $\|h\| \rightarrow 0$, we have:

$$\varphi(x + h) \geq \varphi(x) - \log(1 - \langle \nabla \varphi(x), h \rangle) \quad (1)$$

Then by using the second-order approximation ⁶:

Second-order approximation

Let f be twice differentiable at \bar{x} . Then

$$f(y) = f(\bar{x}) + \langle \nabla f(\bar{x}), y - \bar{x} \rangle + \frac{1}{2} \langle \nabla^2 f(\bar{x})(y - \bar{x}), y - \bar{x} \rangle + o(\|y - \bar{x}\|^2)$$

Since φ is twice differentiable on its domain, we have:

$$\varphi(x + h) = \varphi(x) + \langle \nabla \varphi(x), h \rangle + \frac{1}{2} \langle \nabla^2 \varphi(x)h, h \rangle + o(\|h\|^2) \quad (2)$$

Combining (1) and (2), we have:

$$\begin{aligned} & \varphi(x) + \langle \nabla \varphi(x), h \rangle + \frac{1}{2} \langle \nabla^2 \varphi(x)h, h \rangle + o(\|h\|^2) \geq \varphi(x) - \log(1 - \langle \nabla \varphi(x), h \rangle) \\ \Rightarrow & \langle \nabla \varphi(x), h \rangle + \frac{1}{2} \langle \nabla^2 \varphi(x)h, h \rangle + o(\|h\|^2) \geq -\log(1 - \langle \nabla \varphi(x), h \rangle) \\ \Rightarrow & \langle \nabla \varphi(x), h \rangle + \frac{1}{2} \langle \nabla^2 \varphi(x)h, h \rangle + o(\|h\|^2) \geq -\left(-\sum_{n=1}^{\infty} \frac{\langle \nabla \varphi(x), h \rangle^n}{n}\right) \\ \Rightarrow & \langle \nabla \varphi(x), h \rangle + \frac{1}{2} \langle \nabla^2 \varphi(x)h, h \rangle + o(\|h\|^2) \geq \langle \nabla \varphi(x), h \rangle + \sum_{n=2}^{\infty} \frac{\langle \nabla \varphi(x), h \rangle^n}{n} \\ \Rightarrow & \frac{1}{2} \langle \nabla^2 \varphi(x)h, h \rangle + o(\|h\|^2) \geq \sum_{n=2}^{\infty} \frac{\langle \nabla \varphi(x), h \rangle^n}{n} \\ \Rightarrow & \frac{1}{2} \langle \nabla^2 \varphi(x)h, h \rangle + o(\|h\|^2) \geq \frac{\langle \nabla \varphi(x), h \rangle^2}{2} + \frac{\langle \nabla \varphi(x), h \rangle^3}{3} + \dots \quad (*) \end{aligned}$$

Examine the terms on the right hand side by Cauchy-Schwarz inequality:

⁶Y. Nesterov, *Introductory Lectures on Convex Optimization: A Basic Course*, 1st ed., Springer, New York, NY, 2004, p. 19.

$$\frac{(\langle \nabla \varphi(x), h \rangle)^3}{3} \leq \frac{(\|\nabla \varphi(x)\| \cdot \|h\|)^3}{3}$$

Since $\|h\| \rightarrow 0$ by our assumption, we can write:

$$\frac{\langle \nabla \varphi(x), h \rangle^2}{2} + \frac{\langle \nabla \varphi(x), h \rangle^3}{3} + \dots = o(\|h\|^2)$$

Substituting this bound back into (*), we have:

$$\begin{aligned} & \frac{1}{2} \langle \nabla^2 \varphi(x) h, h \rangle + o(\|h\|^2) \geq \frac{\langle \nabla \varphi(x), h \rangle^2}{2} + o(\|h\|^2) \\ \Rightarrow & \frac{1}{2} \langle \nabla^2 \varphi(x) h, h \rangle \geq \frac{\langle \nabla \varphi(x), h \rangle^2}{2} \\ \Rightarrow & \langle \nabla^2 \varphi(x) h, h \rangle \geq \langle \nabla \varphi(x), h \rangle^2 \\ \Rightarrow & (\nabla^2 \varphi(x) h)^T h \geq (\nabla \varphi(x)^T h)^T (\nabla \varphi(x)^T h) \\ \Rightarrow & h^T (\nabla^2 \varphi(x))^T h \geq h^T \nabla \varphi(x) (\nabla \varphi(x))^T h \\ \Rightarrow & h^T ((\nabla^2 \varphi(x))^T - \nabla \varphi(x) (\nabla \varphi(x))^T) h \geq 0 \\ \Rightarrow & \nabla^2 \varphi(x) - \nabla \varphi(x) (\nabla \varphi(x))^T \succeq 0 \quad (\text{since the Hessian is symmetric}) \end{aligned}$$

Thus, we have proved that:

$$\nabla^2 \varphi(x) \geq \nabla \varphi(x) (\nabla \varphi(x))^T, \quad \forall x, y \in \text{dom } \varphi$$

(3) \implies (1)

Suppose (3) holds, so we have:

$$\nabla^2 \varphi(x) \geq \nabla \varphi(x) (\nabla \varphi(x))^T, \quad \forall x, y \in \text{dom } \varphi$$

Since we need to show that $e^{-\varphi(x)}$ is concave, similar to the previous proof, we can define $g(x) = -f(x) = -e^{-\varphi(x)}$ (where $f(x) = e^{-\varphi(x)}$), and show that $g(x)$ is convex.

By theorem ⁷, we have:

⁷Y. Nesterov, *Introductory Lectures on Convex Optimization: A Basic Course*, 1st ed., Springer, New York, NY, 2004, p. 55.

Theorem 2.1.4

Two times continuously differentiable function $f \in \mathcal{F}^2(\mathbb{R}^n)$ iff for any $x \in \mathbb{R}^n$, we have:

$$f''(x) \succeq 0$$

Therefore, we need to show that $\nabla^2 g(x) \succeq 0$. We derive the following using the Scalar-by-vector identity ⁸:

If $u = u(x)$ and $v = v(x)$ are vector functions of x , then:

$$\nabla(u \cdot v) = (\nabla u)v^T + u^T(\nabla v)$$

Hence, we have:

$$\begin{aligned} \nabla^2 g(x) &= \nabla(e^{-\varphi(x)} \nabla \varphi(x)) \\ &= \left[\frac{d}{dx}(e^{-\varphi(x)}) \right] (\nabla \varphi(x))^T + e^{-\varphi(x)} \nabla^2 \varphi(x) \\ &= -e^{-\varphi(x)} (\nabla \varphi(x))(\nabla \varphi(x))^T + e^{-\varphi(x)} \nabla^2 \varphi(x) \\ &= e^{-\varphi(x)} [\nabla^2 \varphi(x) - (\nabla \varphi(x))(\nabla \varphi(x))^T] \end{aligned}$$

By our assumption, we knew that $\nabla^2 \varphi(x) - \nabla \varphi(x)(\nabla \varphi(x))^T \succeq 0$, and multiplying by $e^{-\varphi(x)} > 0$ would not change the sign, therefore we have:

$$\nabla^2 g(x) \succeq 0$$

And the equivalence of the three statements is proved. \square

(3)

We're given:

The ratio of the d stocks on the t -th day:

$$x_t \in \Delta = \left\{ x = (x[1], \dots, x[d]) \in \mathbb{R}_+^d : \sum_{i=1}^d x[i] = 1 \right\},$$

The price relative on the t -th day:

$$a_t = (a_t[1], \dots, a_t[d]) = \left(\frac{p_t^c[1]}{p_t^o[1]}, \dots, \frac{p_t^c[d]}{p_t^o[d]} \right) \in \mathbb{R}_+^d$$

⁸"Matrix calculus", Wikipedia, https://en.wikipedia.org/wiki/Matrix_calculus

where:

$p_t^c[i]$: the closing price of the i -th stock on the t -th day
 $p_t^o[i]$: the opening price of the i -th stock on the t -th day

Suppose a_1, \dots, a_T are i.i.d. random vectors, following known common probability distribution P .

Strategy:

$$x_t \in \operatorname{argmin}_{x \in \Delta} f(x); \quad f(x) := \mathbb{E}[-\log \langle a_t, x \rangle], \quad \forall t \in \mathbb{N}$$

Assume f strictly convex.

(1)

Since Alice has one unit of wealth before the first day, let $W_0 = 1$. And let W_{t-1} be the wealth of Alice before the t -th day.

So after the end of the t -th day, Alice would have her wealth W_t :

$$\begin{aligned} W_t &= W_{t-1} \cdot x_t[1] \cdot a_t[1] + W_{t-1} \cdot x_t[2] \cdot a_t[2] + \dots + W_{t-1} \cdot x_t[d] \cdot a_t[d] \\ &= W_{t-1} \cdot \langle a_t, x_t \rangle \end{aligned}$$

For example, if $a_t[1] = 2$, then the price of the first stock on day t is twice as high as the price on day $t-1$, we can then calculate how much Alice invests in the first stock on day t , which is $W_{t-1} \cdot x_t[1]$, and multiply this price relative to get the wealth on day t .

Using this formula, we knew that:

$$\begin{aligned} W_1 &= W_0 \cdot \langle a_1, x_1 \rangle \\ W_2 &= W_1 \cdot \langle a_2, x_2 \rangle = W_0 \cdot \langle a_1, x_1 \rangle \cdot \langle a_2, x_2 \rangle \\ W_3 &= W_2 \cdot \langle a_3, x_3 \rangle = W_0 \cdot \langle a_1, x_1 \rangle \cdot \langle a_2, x_2 \rangle \cdot \langle a_3, x_3 \rangle \\ &\vdots \\ W_T &= W_0 \cdot \langle a_1, x_1 \rangle \cdot \langle a_2, x_2 \rangle \cdot \dots \cdot \langle a_T, x_T \rangle \end{aligned}$$

Which is the same as required since $W_0 = 1$, and we have:

$$W_T = \langle a_1, x_1 \rangle \cdot \langle a_2, x_2 \rangle \cdot \dots \cdot \langle a_T, x_T \rangle \quad \square$$

(2)

Our aim is to show that:

$$\lim_{T \rightarrow \infty} \mathbb{E} \left[\frac{W_T(x)}{W_T^*} \right] \leq 1, \quad \forall x \in \Delta \quad (*)$$

where $W_T(x)$ (given by the problem statement) and W_T^* (by the previous sub-problem) are defined as:

$$W_T(x) := \langle a_1, x \rangle \cdots \langle a_T, x \rangle = \prod_{t=1}^T \langle a_t, x \rangle$$

$$W_T^* := \langle a_1, x_1 \rangle \cdots \langle a_T, x_T \rangle = \prod_{t=1}^T \langle a_t, x_t \rangle$$

From Alice's strategy, we have:

$$x_t \in \operatorname{argmin}_{x \in \Delta} f(x); \quad f(x) := \mathbb{E}[-\log \langle a_t, x \rangle], \quad \forall t \in \mathbb{N}$$

This means that Alice decides the ratio of the t -th day by finding the x that minimizes the function f , which is the expected loss of using x as the ratio.

By the fact that f is strictly convex and $x_t \in \operatorname{argmin}_{x \in \Delta} f(x)$, we have:

$$f(x_t) < f(x) \quad \forall x \in \Delta \setminus \{x_t\}$$

Replace by the definition of f , and using the fact that expectation is linear:

$$\begin{aligned} & \mathbb{E}[-\log \langle a_t, x_t \rangle] < \mathbb{E}[-\log \langle a_t, x \rangle] \quad \forall x \in \Delta \setminus \{x_t\} \\ \Rightarrow & -\mathbb{E}[\log \langle a_t, x_t \rangle] < -\mathbb{E}[\log \langle a_t, x \rangle] \quad \forall x \in \Delta \setminus \{x_t\} \\ \Rightarrow & \mathbb{E}[\log \langle a_t, x \rangle] - \mathbb{E}[\log \langle a_t, x_t \rangle] < 0 \quad \forall x \in \Delta \setminus \{x_t\} \\ \Rightarrow & \mathbb{E}[\log \langle a_t, x \rangle - \log \langle a_t, x_t \rangle] < 0 \quad \forall x \in \Delta \setminus \{x_t\} \\ \Rightarrow & \lim_{T \rightarrow \infty} \frac{1}{T} \sum_{t=1}^T \mathbb{E}[\log \langle a_t, x \rangle - \log \langle a_t, x_t \rangle] < 0 \quad \forall x \in \Delta \setminus \{x_t\} \\ \Rightarrow & \lim_{T \rightarrow \infty} \frac{1}{T} \mathbb{E} \left[\sum_{t=1}^T (\log \langle a_t, x \rangle - \log \langle a_t, x_t \rangle) \right] < 0, \quad \forall x \in \Delta \setminus \{x_t\} \end{aligned}$$

The above inequality would be equality only when $x_t = x$, so if we modify the set to not exclude x_t , we would have the following:

$$\lim_{T \rightarrow \infty} \frac{1}{T} \mathbb{E} \left[\sum_{t=1}^T (\log \langle a_t, x \rangle - \log \langle a_t, x_t \rangle) \right] \leq 0, \quad \forall x \in \Delta$$

And this implies:

$$\begin{aligned} & \lim_{T \rightarrow \infty} \frac{1}{T} \mathbb{E} \left[\sum_{t=1}^T (\log \langle a_t, x \rangle - \log \langle a_t, x_t \rangle) \right] \leq 0, \quad \forall x \in \Delta \\ \Rightarrow & \lim_{T \rightarrow \infty} \frac{1}{T} \mathbb{E} \left[\sum_{t=1}^T \log \langle a_t, x \rangle - \sum_{t=1}^T \log \langle a_t, x_t \rangle \right] \leq 0, \quad \forall x \in \Delta \\ \Rightarrow & \lim_{T \rightarrow \infty} \frac{1}{T} \mathbb{E} \left[\log \prod_{t=1}^T \langle a_t, x \rangle - \log \prod_{t=1}^T \langle a_t, x_t \rangle \right] \leq 0, \quad \forall x \in \Delta \\ \Rightarrow & \lim_{T \rightarrow \infty} \frac{1}{T} \mathbb{E} \left[\log \left(\frac{\prod_{t=1}^T \langle a_t, x \rangle}{\prod_{t=1}^T \langle a_t, x_t \rangle} \right) \right] \leq 0, \quad \forall x \in \Delta \\ \Rightarrow & \lim_{T \rightarrow \infty} \frac{1}{T} \mathbb{E} \left[\log \left(\frac{W_T(x)}{W_T^*} \right) \right] \leq 0, \quad \forall x \in \Delta \\ \Rightarrow & \mathbb{E} \left[\log \left(\frac{W_T(x)}{W_T^*} \right) \right] \leq 0, \quad \forall x \in \Delta \end{aligned}$$

(3)

(4)

We're given:

$$\begin{aligned} f : \mathbb{R}^d &\rightarrow \mathbb{R} && \text{differentiable, may be non-convex} \\ \nabla f : &L\text{-Lipschitz, } L > 0 && \text{i.e.} \\ \|\nabla f(y) - \nabla f(x)\|_* &\leq L\|y - x\|, && \forall x, y \in \mathbb{R}^d \\ \text{where } \|u\|_* &:= \max_{x \in \mathbb{R}^d, \|x\| \leq 1} \langle u, x \rangle \end{aligned}$$

And the definition of a point x being ϵ -stationary for some $\epsilon > 0$ if:

$$\|\nabla f(x)\|_* \leq \epsilon$$

(1)

Need to show:

$$f(y) \leq f(x) + \langle \nabla f(x), y - x \rangle + \frac{L}{2} \|y - x\|^2, \quad \forall x, y \in \mathbb{R}^d$$

The thought is to use the proof process of Lemma 1.2.3⁹:

Lemma 1.2.3

Let $f \in C_L^{1,1}(\mathbb{R}^n)$. Then for any $x, y \in \mathbb{R}^n$, we have:

$$|f(y) - f(x) - \langle \nabla f(x), y - x \rangle| \leq \frac{L}{2} \|y - x\|^2$$

Let $g(\tau) = x + \tau(y - x)$, where $\tau \in [0, 1]$, which means that $g(0) = x$ and $g(1) = y$. Then we have:

$$\begin{aligned} \frac{d}{d\tau} g(\tau) &= y - x \\ \nabla f(g(\tau)) &= \nabla f(x + \tau(y - x)) \end{aligned}$$

Then, for all $x, y \in \mathbb{R}^d$, we have:

$$\begin{aligned} f(y) - f(x) &= \int_x^y \nabla f(g(\tau)) \cdot dg(\tau) \\ &= \int_0^1 \nabla f(x + \tau(y - x)) \cdot (y - x) d\tau \\ &= \int_0^1 \langle \nabla f(x + \tau(y - x)), y - x \rangle d\tau \end{aligned}$$

Which is the same as the following, using the fact that the integral is linear, and $f(x), y - x$ are not functions of τ :

$$\begin{aligned} f(y) &= f(x) + \int_0^1 \langle \nabla f(x + \tau(y - x)), y - x \rangle d\tau \\ \Rightarrow f(y) &= f(x) + \int_0^1 \langle \nabla f(x + \tau(y - x)) + \nabla f(x) - \nabla f(x), y - x \rangle d\tau \\ \Rightarrow f(y) &= f(x) + \int_0^1 \langle \nabla f(x), y - x \rangle d\tau + \int_0^1 \langle \nabla f(x + \tau(y - x)) - \nabla f(x), y - x \rangle d\tau \\ \Rightarrow f(y) &= f(x) + \langle \nabla f(x), y - x \rangle + \int_0^1 \langle \nabla f(x + \tau(y - x)) - \nabla f(x), y - x \rangle d\tau \end{aligned} \tag{*}$$

⁹Y. Nesterov, *Introductory Lectures on Convex Optimization: A Basic Course*, 1st ed., Springer, New York, NY, 2004, p. 22-23.

And we're given for any $x, y \in \mathbb{R}^d$:

$$\begin{aligned} & \underbrace{\|\nabla f(y) - \nabla f(x)\|_*}_{\mathbf{u}} \leq L\|y - x\| \\ \Rightarrow & \max_{z \in \mathbb{R}^d, \|z\| \leq 1} \langle \nabla f(y) - \nabla f(x), z \rangle \leq L\|y - x\| \end{aligned}$$

Let $y = x + \tau(y - x)$, then we have:

$$\begin{aligned} & \|\nabla f(y) - \nabla f(x)\|_* = \|\nabla f(x + \tau(y - x)) - \nabla f(x)\|_* \leq L\|x + \tau(y - x) - x\| = L\tau\|y - x\| \\ \Rightarrow & \|\nabla f(x + \tau(y - x)) - \nabla f(x)\|_* \leq L\tau\|y - x\| \end{aligned} \quad (1)$$

Going back to the definition $\|u\|_* := \max_{x \in \mathbb{R}^d, \|x\| \leq 1} \langle u, x \rangle$, this means that for any $z \in \mathbb{R}^d, \|z\| \leq 1$:

$$\langle u, z \rangle \leq \|u\|_*$$

If we want to expand the definition to arbitrary $v \in \mathbb{R}^d$ (not necessarily $\|v\| \leq 1$), we can let $z = \frac{v}{\|v\|}$, then we have:

$$\begin{aligned} \langle u, z \rangle &= \langle u, \frac{v}{\|v\|} \rangle = \frac{\langle u, v \rangle}{\|v\|} \leq \|u\|_* \\ \Rightarrow \langle u, v \rangle &\leq \|u\|_* \|v\| \quad \forall u, v \in \mathbb{R}^d \end{aligned}$$

Let $u = \nabla f(x + \tau(y - x)) - \nabla f(x)$, $v = y - x$, then we have:

$$\langle \nabla f(x + \tau(y - x)) - \nabla f(x), y - x \rangle \leq \|\nabla f(x + \tau(y - x)) - \nabla f(x)\|_* \|y - x\| \quad (2)$$

Multiply the result of (1) by $\|y - x\|$, we have:

$$\begin{aligned} & \|\nabla f(x + \tau(y - x)) - \nabla f(x)\|_* \leq L\tau\|y - x\| \\ \Rightarrow & \|\nabla f(x + \tau(y - x)) - \nabla f(x)\|_* \|y - x\| \leq L\tau\|y - x\|^2 \end{aligned} \quad (3)$$

Combining (2) and (3), we have:

$$\langle \nabla f(x + \tau(y - x)) - \nabla f(x), y - x \rangle \leq L\tau\|y - x\|^2$$

Substituting this back into (*), we have:

$$\begin{aligned}
f(y) &\leq f(x) + \langle \nabla f(x), y - x \rangle + \int_0^1 L\tau \|y - x\|^2 d\tau \\
\Rightarrow f(y) &\leq f(x) + \langle \nabla f(x), y - x \rangle + L\|y - x\|^2 \int_0^1 \tau d\tau \\
\Rightarrow f(y) &\leq f(x) + \langle \nabla f(x), y - x \rangle + \frac{L}{2}\|y - x\|^2 \quad \square
\end{aligned}$$

(2)

We're given the algorithm (generalization of gradient descent):

$$\begin{aligned}
&x_1 \in \mathbb{R}^d \\
&\text{for every } t \in \mathbb{N} \\
&\quad x_{t+1} \in \operatorname{argmin}_{x \in \mathbb{R}^d} \langle \nabla f(x_t), x - x_t \rangle + \frac{L}{2}\|x - x_t\|^2
\end{aligned}$$

Need to show:

$$f(x_{t+1}) - f(x_t) \leq -\frac{1}{2L}\|\nabla f(x_t)\|_*^2, \quad \forall t \in \mathbb{N}$$

Let the function to minimize in the update rule be g :

$$\begin{aligned}
&g : \mathbb{R}^d \rightarrow \mathbb{R} \\
&g(x) = \langle \nabla f(x_t), x - x_t \rangle + \frac{L}{2}\|x - x_t\|^2
\end{aligned}$$

Let $z = x - x_t$, then we have:

$$g(x) = \langle \nabla f(x_t), z \rangle + \frac{L}{2}\|z\|^2$$

So:

$$\operatorname{argmin}_x g(x) = x_t + \operatorname{argmin}_z \{ \langle \nabla f(x_t), z \rangle + \frac{L}{2}\|z\|^2 \}$$

Let $h(z) = \langle \nabla f(x_t), z \rangle + \frac{L}{2}\|z\|^2$, we can rearrange the equation as:

$$h(z) - \frac{L}{2}\|z\|^2 = \langle \nabla f(x_t), z \rangle$$

Using the following proposition ¹⁰:

Proposition: Equivalent conditions of strong convexity

A differentiable function f is strongly convex with constant $\mu > 0$

$$\Leftrightarrow g(x) = f(x) - \frac{\mu}{2}\|x\|^2 \text{ is convex, } \forall x$$

Since $\langle \nabla f(x_t), z \rangle$ is affine, $h(z) - \frac{L}{2}\|z\|^2$ is convex, so $h(z)$ is strongly convex with convexity parameter L .

Then, taking the gradient of $h(z)$ with respect to z , we have:

$$\begin{aligned} \partial h(z) &= \frac{d}{dz} \left(\langle \nabla f(x_t), z \rangle + \frac{L}{2}\|z\|^2 \right) \\ &= \nabla f(x_t) + \partial \left(\frac{L}{2}\|z\|^2 \right) \end{aligned}$$

Here we can be sure that the derivative of $\langle \nabla f(x_t), z \rangle$ is $\nabla f(x_t)$, since this term is linear in z , and a linear map is differentiable, however, we need to take the subdifferential for $\frac{L}{2}\|z\|^2$, since the norm is uncertain. ¹¹

Using the following theorem ¹²:

Theorem 3.1.15

We have $f(x^*) = \min_{x \in \text{dom } f} f(x)$ iff.

$$0 \in \partial f(x^*)$$

Since we knew that $h(z)$ is strongly convex, this means that the above equation is equivalent to saying there exists a unique minimizer z^* for $h(z)$ such that:

$$0 \in \partial h(z^*)$$

so there exists $u \in \partial(\frac{1}{2}\|z\|^2)$ such that:

$$\begin{aligned} \nabla f(x_t) + Lu &= 0 \\ \Rightarrow u &= -\frac{1}{L}\nabla f(x_t) \end{aligned}$$

¹⁰*Strong Convexity*, available at: <https://xingyuzhou.org/blog/notes/strong-convexity>, accessed: Apr. 21, 2025.

¹¹The definition of subdifferential is from Nesterov, Y. N., *Introductory Lectures on Convex Optimization: A Basic Course*, 1st ed., Springer, New York, NY, 2004, p. 126.

¹²Nesterov, Y. N., *Introductory Lectures on Convex Optimization: A Basic Course*, 1st ed., Springer, New York, NY, 2004, p. 129.

Define:

$$\begin{aligned}\phi : \mathbb{R}^d &\rightarrow \mathbb{R} \\ \phi(z) &= \frac{L}{2} \|z\|^2\end{aligned}$$

Then the conjugate ¹³ of ϕ is defined as:

$$\begin{aligned}\phi^*(v) &= \sup_{z \in \mathbb{R}^d} (\langle v, z \rangle - \phi(z)) \\ &= \sup_{z \in \mathbb{R}^d} \left(\langle v, z \rangle - \frac{L}{2} \|z\|^2 \right)\end{aligned}$$

Let $z = \alpha z'$, where $\|z'\| = 1$, then:

$$\begin{aligned}\phi^*(v) &= \sup_{z \in \mathbb{R}^d} \left(\alpha \langle v, z' \rangle - \frac{L}{2} \langle \alpha z', \alpha z' \rangle \right) \\ &= \sup_{\alpha \in \mathbb{R}} \left(\alpha \langle v, z' \rangle - \frac{L\alpha^2}{2} \right)\end{aligned}$$

And by the definition of dual norm, we can derive the inequality (generalization of Cauchy-Schwarz inequality) ¹⁴ :

$$\alpha \langle v, z' \rangle \leq \alpha \|v\|_* \|z'\| = \alpha \|v\|_*$$

And the original conjugate can be rewritten as:

$$\phi^*(v) = \sup_{\alpha \in \mathbb{R}} \left(\alpha \|v\|_* - \frac{L}{2} \alpha^2 \right)$$

Taking the derivative:

$$\frac{d}{d\alpha} \left(\alpha \|v\|_* - \frac{L}{2} \alpha^2 \right) = \|v\|_* - L\alpha \implies \alpha = \frac{\|v\|_*}{L}$$

Plugging back in:

¹³S. Boyd and L. Vandenberghe, *Convex Optimization*, Cambridge University Press, 2004, p. 91. Available online at https://web.stanford.edu/~boyd/cvxbook/bv_cvxbook.pdf.

¹⁴S. Boyd and L. Vandenberghe, *Convex Optimization*, Cambridge University Press, 2004, p. 637.

$$\begin{aligned}
\phi^*(v) &= \frac{\|v\|_*}{L} \cdot \|v\|_* - \frac{L}{2} \cdot \frac{\|v\|_*^2}{L^2} \\
&= \frac{\|v\|_*^2}{L} - \frac{\|v\|_*^2}{2L} \\
&= \frac{\|v\|_*^2}{2L}
\end{aligned}$$

By Fenchel's inequality ¹⁵, which is stated as follows:

Fenchel's inequality
<p>For all x, y:</p> $f(x) + f^*(y) \geq \langle x, y \rangle$

Therefore, we have for all $z, v \in \mathbb{R}^d$:

$$\begin{aligned}
\phi(z) + \phi^*(v) &\geq \langle z, v \rangle \\
\Rightarrow \frac{L}{2} \|z\|^2 + \frac{\|v\|_*^2}{2L} &\geq \langle z, v \rangle
\end{aligned}$$

Let $v = \nabla f(x_t)$, and since $z = x - x_t$, which means that choosing the optimal z is equivalent to choosing the optimal x , which is x_{t+1} , so $z = x_{t+1} - x_t$, and we have:

$$\frac{L}{2} \|x_{t+1} - x_t\|^2 + \frac{1}{2L} \|\nabla f(x_t)\|_*^2 \geq \langle x_{t+1} - x_t, \nabla f(x_t) \rangle$$

By the result of subproblem (1), and plugging in $y = x_{t+1}$ and $x = x_t$, we have:

$$\begin{aligned}
f(x_{t+1}) &\leq f(x_t) + \langle \nabla f(x_t), x_{t+1} - x_t \rangle + \frac{L}{2} \|x_{t+1} - x_t\|^2 \\
\Rightarrow f(x_{t+1}) - f(x_t) &\leq \langle \nabla f(x_t), x_{t+1} - x_t \rangle + \frac{L}{2} \|x_{t+1} - x_t\|^2 \\
\Rightarrow f(x_{t+1}) - f(x_t) &\leq \frac{1}{2L} \|\nabla f(x_t)\|_*^2 + \frac{L}{2} \|x_{t+1} - x_t\|^2 + \frac{L}{2} \|x_{t+1} - x_t\|^2
\end{aligned}$$

Claim:

¹⁵S. Boyd and L. Vandenberghe, *Convex Optimization*, Cambridge University Press, 2004, p. 94.

$$\min_{1 \leq \tau \leq t} \|\nabla f(x_\tau)\|_*^2 \leq \frac{2L [f(x_1) - f(x_{t+1})]}{t}, \quad \forall t \in \mathbb{N}$$

(3)