

Optimization for Machine Learning HW 2

Shuyue Jia
BUID: U62343813

Due: 9/20/2023

All parts of each question are equally weighted. When solving one question/part, you may assume the results of all previous questions/parts. This HW provides an alternative analysis of SGD in the convex setting that provides a convergence bound for the *last iterate*: $\mathbb{E}[\mathcal{L}(\mathbf{w}_T) - \mathcal{L}(\mathbf{w}_*)] = \tilde{O}(1/\sqrt{T})$.

1. Prove the following technical identity: for any sequence of numbers a_1, \dots, a_T with $T > 1$,

$$T \cdot a_T = \sum_{t=1}^T a_t + \sum_{k=1}^{T-1} \frac{T}{(T-k)(T-k+1)} \sum_{t=k}^T (a_t - a_k)$$

(Hint: There are a number of different ways to show this. One way starts by showing that $\frac{T-k+1}{T-k} \sum_{t=k+1}^T a_t = \sum_{t=k}^T a_t + \frac{1}{T-k} \sum_{t=k}^T (a_t - a_k)$ and uses induction on k . Another is to rearrange the terms in the sums to directly show equality. For this, you might want to show the useful identity $\sum_{k=1}^{T-1} b_k \sum_{t=k}^T a_t = \sum_{t=1}^{T-1} a_t \sum_{k=1}^t b_k + a_T \sum_{k=1}^{T-1} b_k$, valid for all a and b . You might also want to observe that $\frac{T}{(T-k)(T-k+1)} = \frac{T}{T-k} - \frac{T}{T-k+1}$).

Proof. We will start with the second hint: “Another is to rearrange the terms in the sums to directly show equality. For this, you might want to show the useful identity $\sum_{k=1}^{T-1} b_k \sum_{t=k}^T a_t = \sum_{t=1}^{T-1} a_t \sum_{k=1}^t b_k + a_T \sum_{k=1}^{T-1} b_k$, valid for all a and b . You might also want to observe that $\frac{T}{(T-k)(T-k+1)} = \frac{T}{T-k} - \frac{T}{T-k+1}$.”

Firstly, we need to prove the hint identity, *i.e.*, $\sum_{k=1}^{T-1} b_k \sum_{t=k}^T a_t = \sum_{t=1}^{T-1} a_t \sum_{k=1}^t b_k + a_T \sum_{k=1}^{T-1} b_k$, because it will be useful to solve this problem. We first expand the summation of a_t from $t = k$ to T :

$$\begin{aligned} & \sum_{k=1}^{T-1} b_k \sum_{t=k}^T a_t \\ &= \sum_{k=1}^{T-1} b_k (a_k + a_{k+1} + \dots + a_T) \\ &= \sum_{k=1}^{T-1} (b_k a_k + b_k a_{k+1} + \dots + b_k a_T) \\ &= \sum_{k=1}^{T-1} b_k a_k + \sum_{k=1}^{T-1} b_k a_{k+1} + \dots + \sum_{k=1}^{T-1} b_k a_T \\ &= a_1 \sum_{k=1}^{T-1} b_k + a_2 \sum_{k=1}^{T-1} b_k + \dots + a_{T-1} \sum_{k=1}^{T-1} b_k + a_T \sum_{k=1}^{T-1} b_k \\ &= (a_1 + a_2 + \dots + a_{T-1} + a_T) \sum_{k=1}^{T-1} b_k \end{aligned} \tag{1}$$

Then, for the right-hand sum, we can expand the summation of a_t and b_k :

$$\begin{aligned}
& \sum_{t=1}^{T-1} a_t \sum_{k=1}^t b_k + a_T \sum_{k=1}^{T-1} b_k \\
&= (a_1 + a_2 + \dots + a_{T-1}) \sum_{k=1}^1 b_k + (a_1 + a_2 + \dots + a_{T-1}) \sum_{k=1}^2 b_k \\
&\quad + \dots + (a_1 + a_2 + \dots + a_{T-1}) \sum_{k=1}^{T-1} b_k + a_T \sum_{k=1}^{T-1} b_k \\
&= (a_1 + a_2 + \dots + a_{T-1}) \left(\sum_{k=1}^1 b_k + \sum_{k=1}^2 b_k + \dots + \sum_{k=1}^{T-1} b_k \right) + a_T \sum_{k=1}^{T-1} b_k \\
&= (a_1 + a_2 + \dots + a_{T-1}) \sum_{k=1}^{T-1} b_k + a_T \sum_{k=1}^{T-1} b_k \\
&= (a_1 + a_2 + \dots + a_T) \sum_{k=1}^{T-1} b_k
\end{aligned} \tag{2}$$

As a result, we can prove this identity $\sum_{k=1}^{T-1} b_k \sum_{t=k}^T a_t = \sum_{t=1}^{T-1} a_t \sum_{k=1}^t b_k + a_T \sum_{k=1}^{T-1} b_k$ holds true for all a and b .

Secondly, let $b_k = \frac{T}{(T-k)(T-k+1)}$ to simplify computation. Then, we obtain:

$$\begin{aligned}
& \sum_{t=1}^T a_t + \sum_{k=1}^{T-1} b_k \sum_{t=k}^T (a_t - a_k) \\
&= \sum_{t=1}^T a_t + \sum_{k=1}^{T-1} b_k \sum_{t=k}^T a_t - \sum_{k=1}^{T-1} b_k \sum_{t=k}^T a_k
\end{aligned} \tag{3}$$

Finally, from Eqn. (1) and Eqn. (2), we know that $\sum_{k=1}^{T-1} b_k \sum_{t=k}^T a_t = \sum_{t=1}^{T-1} a_t \sum_{k=1}^t b_k + a_T \sum_{k=1}^{T-1} b_k$. Then, we will have

$$\begin{aligned}
& \sum_{t=1}^T a_t + \sum_{k=1}^{T-1} b_k \sum_{t=k}^T (a_t - a_k) \\
&= \sum_{t=1}^T a_t + \sum_{t=1}^{T-1} a_t \sum_{k=1}^t b_k + a_T \sum_{k=1}^{T-1} b_k - \sum_{k=1}^{T-1} b_k \sum_{t=k}^T a_k \\
&= \sum_{t=1}^T a_t + \sum_{t=1}^{T-1} T \left(\frac{1}{T-t} - \frac{1}{T} \right) a_t + T \left(1 - \frac{1}{T} \right) a_T - \sum_{k=1}^{T-1} b_k (T - K + 1) a_k \\
&= \sum_{t=1}^T a_t + \sum_{t=1}^{T-1} \frac{t}{T-t} a_t + \left(1 - \frac{1}{T} \right) a_T - \sum_{k=1}^{T-1} \frac{T}{T-k} a_k \\
&= \sum_{t=1}^T a_t + \sum_{t=1}^{T-1} \left(\frac{t}{T-t} - \frac{T}{T-t} \right) + T a_T - a_T \\
&= a_T + \sum_{t=1}^{T-1} a_t - \sum_{t=1}^{T-1} a_t + T a_T - a_T \\
&= T a_T
\end{aligned} \tag{4}$$

□

2. Consider stochastic gradient descent with a constant learning rate η : $\mathbf{w}_{t+1} = \mathbf{w}_t - \eta \nabla \ell(\mathbf{w}_t, z_t)$. Suppose that ℓ is convex and G -Lipschitz. Show that for all k :

$$\sum_{t=k}^T \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_k)] \leq \frac{\eta(T-k+1)G^2}{2}$$

Proof. The proof is actually very similar to the proof for the **Theorem 3.2** of Stochastic Gradient Descent. All expectations presented here are not over the randomness of the algorithm, *i.e.*, over the choices z_1, \dots, z_T . Besides, we denote $\mathbf{g}_t = \nabla \ell(\mathbf{w}_t, z_t)$ for simplicity.

$$\begin{aligned} & \mathbb{E}[\|\mathbf{w}_{t+1} - \mathbf{w}_k\|^2] \\ &= \mathbb{E}[\|\mathbf{w}_t - \eta \mathbf{g}_t - \mathbf{w}_k\|^2] \\ &= \mathbb{E}[\|(\mathbf{w}_t - \mathbf{w}_k) - \eta \mathbf{g}_t\|^2] \\ &= \mathbb{E}[\|\mathbf{w}_t - \mathbf{w}_k\|^2 - 2\eta \langle \mathbf{g}_t, \mathbf{w}_t - \mathbf{w}_k \rangle + \eta^2 \|\mathbf{g}_t\|^2] \end{aligned} \tag{1}$$

By rearranging the above equation, we have:

$$\begin{aligned} & \mathbb{E}[\langle \mathbf{g}_t, \mathbf{w}_t - \mathbf{w}_k \rangle] \\ &= \frac{\mathbb{E}[\|\mathbf{w}_{t+1} - \mathbf{w}_k\|^2 - \|\mathbf{w}_t - \mathbf{w}_k\|^2]}{2\eta} + \frac{\eta \mathbb{E}[\|\mathbf{g}_t\|^2]}{2} \end{aligned} \tag{2}$$

Then, we start from the perspective of unbiasedness and convexity, and we can also observe that \mathbf{w}_t is a deterministic function of z_1, \dots, z_{t-1} , and that \mathbf{g}_t is independent of z_1, \dots, z_{t-1} given \mathbf{w}_t ,

$$\begin{aligned} & \mathbb{E}[\langle \mathbf{g}_t, \mathbf{w}_t - \mathbf{w}_k \rangle] \\ &= \mathbb{E}_{z_1, \dots, z_{t-1}}[\mathbb{E}[\langle \mathbf{g}_t, \mathbf{w}_t - \mathbf{w}_k \rangle | z_1, \dots, z_{t-1}]] \\ &= \mathbb{E}_{z_1, \dots, z_{t-1}}[\langle \nabla \mathcal{L}(\mathbf{w}_t), \mathbf{w}_t - \mathbf{w}_k \rangle] \\ &= \mathbb{E}[\langle \nabla \mathcal{L}(\mathbf{w}_t), \mathbf{w}_t - \mathbf{w}_k \rangle] \\ &\geq \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_k)] \end{aligned} \tag{3}$$

Thus, according to Eqn. (2) and Eqn. (3), we have:

$$\mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_k)] \leq \frac{\mathbb{E}[\|\mathbf{w}_{t+1} - \mathbf{w}_k\|^2 - \|\mathbf{w}_t - \mathbf{w}_k\|^2]}{2\eta} + \frac{\eta \mathbb{E}[\|\mathbf{g}_t\|^2]}{2} \tag{4}$$

Next, we sum $\mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_k)]$ from $t = k$ to T ,

$$\begin{aligned} & \mathbb{E}\left[\sum_{t=k}^T \mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_k)\right] \\ &\leq \sum_{t=k}^T \frac{\eta \mathbb{E}[\|\mathbf{g}_t\|^2]}{2} - \frac{\mathbb{E}[\|\mathbf{w}_{T+1} - \mathbf{w}_k\|^2]}{2\eta} \\ &\leq \eta \frac{\sum_{t=k}^T \mathbb{E}[\|\mathbf{g}_t\|^2]}{2} \end{aligned} \tag{5}$$

Finally, since ℓ is convex and G -Lipschitz, we have $\mathbf{g}_t = \nabla \ell(\mathbf{w}_t, z_t) \leq G$. As a result, we get:

$$\begin{aligned} \mathbb{E}\left[\sum_{t=k}^T \mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_k)\right] &\leq \frac{\eta \sum_{t=k}^T G^2}{2} \\ &\leq \frac{\eta(T-k+1)G^2}{2} \end{aligned} \tag{6}$$

□

3. Show that for G -Lipschitz convex losses, SGD with constant learning rate $\eta = \frac{\|\mathbf{w}_1 - \mathbf{w}_*\|}{G\sqrt{T}}$ guarantees:

$$\mathbb{E}[\mathcal{L}(\mathbf{w}_T) - \mathcal{L}(\mathbf{w}_*)] \leq O\left(\frac{\|\mathbf{w}_* - \mathbf{w}_1\| G \log(T)}{\sqrt{T}}\right)$$

(Hint: you will need to show $\sum_{t=1}^T \frac{1}{t} \leq 1 + \log(T)$. As an intermediate step, try showing $\sum_{t=2}^T \frac{1}{t} \leq \int_1^T \frac{dt}{t}$ - note the sum starts at 2. Drawing a picture might help).

By having a learning rate that changes appropriately over time (called a “schedule”) it is possible to eliminate the logarithmic factor, but it is quite difficult to do so - finding such a schedule was open until as recently as 2019! See <https://arxiv.org/abs/1904.12443> for the first such result via a very complicated schedule and analysis. Just this summer, <https://arxiv.org/abs/2307.11134> provided a much tighter analysis with a simpler learning rate.

Proof. In **Problem 1**, we obtain

$$Ta_T = \sum_{t=1}^T a_t + \sum_{k=1}^{T-1} \frac{T}{(T-k)(T-k+1)} \sum_{t=k}^T (a_t - a_k) \quad (1)$$

Here, let $a_t = \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_*)]$ and $a_t - a_k = \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_k)]$. Then, we will have:

$$T \cdot \mathbb{E}[\mathcal{L}(\mathbf{w}_T) - \mathcal{L}(\mathbf{w}_*)] = \sum_{t=1}^T \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_*)] + \sum_{k=1}^{T-1} \frac{T}{(T-k)(T-k+1)} \sum_{t=k}^T \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_k)] \quad (2)$$

Then, from the results of **Theorem 3.2** in the Lecture Notes, we have:

$$\begin{aligned} \mathbb{E}\left[\sum_{t=1}^T \mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_*)\right] &\leq \sum_{t=1}^T \frac{\mathbb{E}[\|\mathbf{w}_t - \mathbf{w}_*\|^2 - \|\mathbf{w}_{t+1} - \mathbf{w}_*\|^2]}{2\eta} + \frac{\eta \mathbb{E}[\mathbf{g}_t]^2}{2} \\ &\leq \frac{\mathbb{E}[\|\mathbf{w}_1 - \mathbf{w}_*\|^2]}{2\eta} + \frac{\eta TG^2}{2} \end{aligned} \quad (3)$$

By applying Eqn. (3) to Eqn. (2), we get:

$$\begin{aligned} T \cdot \mathbb{E}[\mathcal{L}(\mathbf{w}_T) - \mathcal{L}(\mathbf{w}_*)] &= \sum_{t=1}^T \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_*)] + \sum_{k=1}^{T-1} \frac{T}{(T-k)(T-k+1)} \sum_{t=k}^T \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_k)] \\ &\leq \frac{\mathbb{E}[\|\mathbf{w}_1 - \mathbf{w}_*\|^2]}{2\eta} + \frac{\eta TG^2}{2} + \sum_{k=1}^{T-1} \frac{T}{(T-k)(T-k+1)} \sum_{t=k}^T \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_k)] \end{aligned} \quad (4)$$

Next, in **Problem 2**, we have:

$$\mathbb{E}\left[\sum_{t=k}^T \mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_k)\right] \leq \frac{\eta(T-k+1)G^2}{2} \quad (5)$$

By applying Eqn. (5) to Eqn. (4), we get:

$$\begin{aligned}
T \cdot \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_*)] &\leq \frac{\mathbb{E}[\|\mathbf{w}_1 - \mathbf{w}_*\|^2]}{2\eta} + \frac{\eta TG^2}{2} + \sum_{k=1}^{T-1} \frac{T}{(T-k)(T-k+1)} \sum_{t=k}^T \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_k)] \\
&\leq \frac{\mathbb{E}[\|\mathbf{w}_1 - \mathbf{w}_*\|^2]}{2\eta} + \frac{\eta TG^2}{2} + \sum_{k=1}^{T-1} \frac{T}{(T-k)(T-k+1)} \frac{\eta(T-k+1)G^2}{2} \\
&\leq \frac{\mathbb{E}[\|\mathbf{w}_1 - \mathbf{w}_*\|^2]}{2\eta} + \frac{\eta TG^2}{2} + \frac{\eta TG^2}{2} \sum_{k=1}^{T-1} \frac{1}{(T-k)}
\end{aligned} \tag{6}$$

Here, since $\sum_{k=1}^{T-1} \frac{1}{(T-k)} = \sum_{k=1}^{T-1} \frac{1}{k} = 1 + \frac{1}{1} + \dots + \frac{1}{T-1}$, the above inequality can be written as follows,

$$\begin{aligned}
T \cdot \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_*)] &\leq \frac{\mathbb{E}[\|\mathbf{w}_1 - \mathbf{w}_*\|^2]}{2\eta} + \frac{\eta TG^2}{2} + \frac{\eta TG^2}{2} \sum_{k=1}^{T-1} \frac{1}{(T-k)} \\
&\leq \frac{\mathbb{E}[\|\mathbf{w}_1 - \mathbf{w}_*\|^2]}{2\eta} + \frac{\eta TG^2}{2} + \frac{\eta TG^2}{2} \sum_{k=1}^{T-1} \frac{1}{k}
\end{aligned} \tag{7}$$

Further, we know that the learning rate η is constant, *i.e.*, $\eta = \frac{\|\mathbf{w}_1 - \mathbf{w}_*\|}{G\sqrt{T}}$. We use this η in the above inequality.

$$\begin{aligned}
T \cdot \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_*)] &\leq \frac{\mathbb{E}[\|\mathbf{w}_1 - \mathbf{w}_*\|^2]}{2\eta} + \frac{\eta G^2 T}{2} + \frac{\eta G^2 T}{2} \sum_{k=1}^{T-1} \frac{1}{k} \\
&\leq \frac{\mathbb{E}[\|\mathbf{w}_1 - \mathbf{w}_*\|^2] G\sqrt{T}}{2\|\mathbf{w}_1 - \mathbf{w}_*\|} + \frac{\|\mathbf{w}_1 - \mathbf{w}_*\| G^2 T}{2G\sqrt{T}} + \frac{\|\mathbf{w}_* - \mathbf{w}_1\| GT}{2\sqrt{T}} \sum_{k=1}^{T-1} \frac{1}{k} \\
&\leq \frac{\|\mathbf{w}_1 - \mathbf{w}_*\|^2 G\sqrt{T}}{2\|\mathbf{w}_1 - \mathbf{w}_*\|} + \frac{\|\mathbf{w}_1 - \mathbf{w}_*\| G^2 T}{2G\sqrt{T}} + \frac{\|\mathbf{w}_* - \mathbf{w}_1\| GT}{2\sqrt{T}} \sum_{k=1}^{T-1} \frac{1}{k} \\
&\leq \frac{\|\mathbf{w}_1 - \mathbf{w}_*\| G\sqrt{T}}{2} + \frac{\|\mathbf{w}_1 - \mathbf{w}_*\| GT}{2\sqrt{T}} + \frac{\|\mathbf{w}_* - \mathbf{w}_1\| GT}{2\sqrt{T}} \sum_{k=1}^{T-1} \frac{1}{k} \\
&\leq \frac{\|\mathbf{w}_* - \mathbf{w}_1\| GT}{\sqrt{T}} + \frac{\|\mathbf{w}_* - \mathbf{w}_1\| GT}{2\sqrt{T}} \sum_{k=1}^{T-1} \frac{1}{k}
\end{aligned} \tag{8}$$

Here, we learn that $\sum_{t=1}^T \frac{1}{t} \leq 1 + \log(T)$ from the hint. The proof is as follows,

$$\begin{aligned}
\sum_{t=1}^T \frac{1}{t} &= 1 + \sum_{t=2}^T \frac{1}{t} \\
&= 1 + \int_{t=2}^T \frac{1}{t} dt \\
&\leq 1 + \int_{t=1}^T \frac{1}{t} dt \\
&\leq 1 + (\log(T) - \log(1)) \\
&\leq 1 + \log(T)
\end{aligned} \tag{9}$$

Hereby, we get:

$$\begin{aligned}
T \cdot \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_*)] &\leq \frac{\|\mathbf{w}_* - \mathbf{w}_1\|GT}{\sqrt{T}} + \frac{\|\mathbf{w}_* - \mathbf{w}_1\|GT}{2\sqrt{T}} \sum_{k=1}^{T-1} \frac{1}{k} \\
&\leq \frac{\|\mathbf{w}_* - \mathbf{w}_1\|GT}{\sqrt{T}} + \frac{\|\mathbf{w}_* - \mathbf{w}_1\|GT}{2\sqrt{T}} (1 + \log(T-1)) \\
&\leq \frac{\|\mathbf{w}_* - \mathbf{w}_1\|GT(3 + \log(T-1))}{2\sqrt{T}}
\end{aligned} \tag{10}$$

Finally,

$$\begin{aligned}
\mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_*)] &\leq \frac{\|\mathbf{w}_* - \mathbf{w}_1\|G(3 + \log(T-1))}{2\sqrt{T}} \\
&\leq O\left(\frac{\|\mathbf{w}_* - \mathbf{w}_1\|G \log(T)}{\sqrt{T}}\right)
\end{aligned} \tag{11}$$

□

BONUS: Consider SGD with a *varying* learning rate $\eta_t = \frac{\|\mathbf{w}_1 - \mathbf{w}_*\|}{G\sqrt{t}}$. Show that for all T :

$$\mathbb{E}[\mathcal{L}(\mathbf{w}_T) - \mathcal{L}(\mathbf{w}_*)] \leq O\left(\frac{\|\mathbf{w}_* - \mathbf{w}_1\|G \log(T)}{\sqrt{T}}\right)$$

Proof. From **Problem 3**, we have

$$T \cdot \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_*)] = \sum_{t=1}^T \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_*)] + \sum_{k=1}^{T-1} \frac{T}{(T-k)(T-k+1)} \sum_{t=k}^T \mathbb{E}[\mathcal{L}(\mathbf{w}_t) - \mathcal{L}(\mathbf{w}_k)] \tag{1}$$

Since the learning rate η is varying, we will have: