

## TTIC 31230 Fundamentals of Deep Learning

### SGD Problems.

**Problem 1. Variance of an exponential moving average.** For two independent random variables  $x$  and  $y$  and a weighted sum  $s = ax + by$  we have

$$\sigma_s^2 = a^2 \sigma_x^2 + b^2 \sigma_y^2$$

Now consider a running average for computing  $\hat{\mu}_1, \dots, \hat{\mu}_t$  from  $x_1, \dots, x_t$

$$\hat{\mu}_0 = 0$$

$$\hat{\mu}_t = \left(1 - \frac{1}{N}\right) \hat{\mu}_{t-1} + \frac{1}{N} x_t$$

(a) Assume that the values of  $x_t$  are independent and identically distributed with variance  $\sigma_x^2$ . We now have that  $\hat{\mu}_t$  is a random variable depending on the draws of  $x_t$ . The random variable  $\hat{\mu}_t$  has a variance  $\sigma_{\hat{\mu},t}^2$ . Assume that as  $t \rightarrow \infty$  we have that  $\sigma_{\hat{\mu},t}^2$  converges to a limit (it does). Solve for this limit  $\sigma_{\hat{\mu},\infty}^2$ . Your solution should yield that for  $N = 1$  we have  $\sigma_{\hat{\mu},\infty}^2 = \sigma_x^2$  (a sanity check).

**Solution:** The limit must satisfy

$$\sigma_{\hat{\mu},\infty}^2 = \left(1 - \frac{1}{N}\right)^2 \sigma_{\hat{\mu},\infty}^2 + \frac{1}{N^2} \sigma_x^2$$

We can then solve for  $\sigma_{\hat{\mu},\infty}^2$

$$\begin{aligned} \sigma_{\hat{\mu},\infty}^2 &= \left(1 - \frac{2}{N} + \frac{1}{N^2}\right) \sigma_{\hat{\mu},\infty}^2 + \frac{1}{N^2} \sigma_x^2 \\ 0 &= \left(\frac{-2}{N} + \frac{1}{N^2}\right) \sigma_{\hat{\mu},\infty}^2 + \frac{1}{N^2} \sigma_x^2 \\ &= \left((-2) + \frac{1}{N}\right) \sigma_{\hat{\mu},\infty}^2 + \frac{1}{N} \sigma_x^2 \\ \sigma_{\hat{\mu},\infty}^2 &= \frac{1}{\left(2 - \frac{1}{N}\right) N} \sigma_x^2 \end{aligned}$$

(b) Compare your answer to (a) with the variance of an average of  $N$  values of  $x_t$  defined by

$$\hat{\mu} = \frac{1}{N} \sum_{t=1}^N x_t$$

**Solution:** For an average of  $N$  we have  $\sigma_{\hat{\mu}}^2 = \sigma_x^2/N$ . For  $N$  large we have that the answer to part (a) is about half as large.

**Problem 2. Reformulating Momentum as a Exponential Moving Average.** Consider the following update equation.

$$\begin{aligned} y_0 &= 0 \\ y_t &= \left(1 - \frac{1}{N}\right) y_{t-1} + x_t \end{aligned}$$

(a) Assume that  $y_t$  converges to a limit, i.e., that  $\lim_{t \rightarrow \infty} y_t$  exists. If the input sequence is constant with  $x_t = c$  for all  $t \geq 1$ , what is  $\lim_{t \rightarrow \infty} y_t$ ? Give a derivation of your answer (Hint: you do not need to compute a closed form solution for  $y_t$ ).

**Solution:**

The limit  $y_\infty$  must satisfy

$$y_\infty = \left(1 - \frac{1}{N}\right) y_\infty + c$$

giving  $y_\infty = Nc$ .

(b)  $y_t$  is an exponential moving average of what quantity?

**Solution:** The update can be rewritten as

$$y_t = \left(1 - \frac{1}{N}\right) y_{t-1} + \frac{1}{N}(Nx_t)$$

so  $y_t$  is an exponential moving average of  $Nx_t$ .

(c) Express  $y_t$  as a function of  $\mu_t$  where  $\mu_t$  is defined by

$$\begin{aligned} \mu_0 &= 0 \\ \mu_t &= \left(1 - \frac{1}{N}\right) \mu_{t-1} + \frac{1}{N}x_t \end{aligned}$$

**Solution:**  $y_t$  is an exponential moving average of  $Nx_t$  which equals  $N$  times the moving average of  $x_t$  so we have

$$y_t = N\mu_t$$

**Problem 3. Bias Correction** Consider the following update equation for computing  $y_1, \dots, y_t$  from  $x_1, \dots, x_t$ .

$$y_t = \left(1 - \frac{1}{\min(t, N)}\right) y_{t-1} + \frac{1}{\min(t, N)} x_t$$

If  $x_t = c$  for all  $t \geq 1$  give a closed form solution for  $y_t$ .

**Solution:** For  $t = 1$  we get  $y_1 = x_1 = c$ . We then get that  $y_{t+1}$  is a convex combination of  $y_t$  and  $x_t$  which maintains the invariant that  $y_t = c$ .

**Problem 4. Batch Size Coupling to RMSProp and Adam.** Consider the following for-loop representation of a batch of matrix-vector products.

for  $b, i, j$   $y[b, j] += W[j, i]x[b, i]$

(a) Write the for-loop representation of back-propagation to  $W$ .grad following the convention that parameter gradients are averaged over the batch.

**Solution:**

for  $b, i, j$   $w.\text{grad}[j, i] += \frac{1}{B} y.\text{grad}[b, j]x[b, i]$

(b) Write a for-loop representation for computing  $W.\text{grad}[b, i, j]$  where this is the derivative of loss with respect to  $W[i, j]$  for batch element  $b$ .

**Solution:**

for  $b, i, j$   $w.\text{grad}[b, j, i] += y.\text{grad}[b, j]x[b, i]$

(c) Consider

$$W.\text{grad2}[j, i] = \frac{1}{B} \sum_b W.\text{grad}[b, j, i]^2$$

Is it possible to compute  $W.\text{grad2}[j, i]$  from  $W.\text{grad}[j, i]$ ? Explain your answer.

**Solution:** No.  $W.\text{grad2}[j, i]$  is the average over the batch of the square of the gradient. The average value does not determine the average square value — the average value does not determine the variance.

(d) Explain how your answer to (c) is related to batch size scaling of RMSProp and Adam.

**Solution:** Adam and RMSProp both compute a moving average of  $\hat{g}[i]^2$  defined by

$$s_{t+1}[i] = \left(1 - \frac{1}{N_s}\right) s_t + \frac{1}{N_s} \hat{g}[i]^2$$

At batch sized greater than 1 this fails to take into account the variance of the gradients within the batch. This implies that  $s_t[i]$  will be reduced as the batch size increases and in the limit of large batches  $s_t[i]$  will converge to the mean squared rather than the second moment.

**Problem 5. The stationary distribution with minibatching.** This problem is on batch size scaling and stationary distributions (temperature). We consider batched SGD as defined by

$$\Phi \leftarrow \eta \hat{g}^B$$

where  $\hat{g}^B$  is the average of  $B$  sampled gradients. Let  $g$  be the average gradient  $g = E \hat{g}$ .

The covariance matrix at batch size  $B$  is

$$\Sigma^B[i, j] = E (\hat{g}^B[i] - g[i])(\hat{g}^B[j] - g[j]).$$

The stochastic differential equation model of SGD is

$$\Phi(t + \Delta t) = \Phi(t) - g\Delta t + \epsilon\sqrt{\Delta t} \quad \epsilon \sim \mathcal{N}(0, \eta\Sigma^B)$$

Show that for  $\eta = B\eta_0$  the stationary distribution is determined by  $\eta_0$  independent of  $B$ .

**Solution:**

$$\begin{aligned} \Sigma^B[i, j] &= E (\hat{g}^B[i] - g[i])(\hat{g}^B[j] - g[j]) \\ &= \frac{1}{B^2} E \left( \sum_b \hat{g}_b[i] - g[i] \right) \left( \sum_b \hat{g}_b[j] - g[j] \right) \\ &= \frac{1}{B^2} E \sum_{b, b'} (\hat{g}_b[i] - g[i]) (\hat{g}_{b'}[j] - g[j]) \\ &= \frac{1}{B^2} \sum_b E (\hat{g}_b[i] - g[i]) (\hat{g}_b[j] - g[j]) + \sum_{b, b' \neq b} E (\hat{g}_b[i] - g[i]) (\hat{g}_{b'}[j] - g[j]) \\ &= \frac{1}{B^2} \sum_b E (\hat{g}_b[i] - g[i]) (\hat{g}_b[j] - g[j]) + \sum_{b, b' \neq b} (E \hat{g}_b[i] - g[i]) (E \hat{g}_{b'}[j] - g[j]) \\ &= \frac{1}{B^2} \sum_b E (\hat{g}_b[i] - g[i]) (\hat{g}_b[j] - g[j]) \\ &= \frac{1}{B} \Sigma^1[i, j] \end{aligned}$$

So for  $\eta = B\eta_0$  we have  $\eta\Sigma^B = \eta_0\Sigma^1$  which yields the equivalence.

**Problem 6. The stationary distribution of weighted average updates.**

In this problem we consider the more general principle that the stationary distribution (the temperature) is determined by the effect of each individual training point on the parameter vector. This principle was used in the claim that in the presence of momentum setting the learning rate by  $\eta = (1 - \mu)B\eta_0$  yields a temperature determined by  $\eta_0$  independent of  $\mu$  and  $B$ . In this problem we justify the general principle of examining the influence of each individual training point.

Let  $\hat{g}_1, \dots, \hat{g}_N$  be the loss gradients of  $N$  individual training points (Batch size 1). Consider a weighted sum (such as that used in momentum).

$$\Delta\Phi = \sum_i \alpha_i \hat{g}_i$$

Assume the updates are small so that for any given training point  $i$  we have that  $\hat{g}_i$  is unaffected by the drift in the parameter vector. In that case, even if parameter updates are being made between gradient measurements, the random variables  $g_i$  are essentially independent and identically distributed (over the random draw of a training point). Let  $\Sigma_g$  be the covariance matrix of the distribution of the random variable  $\hat{g}_i$ . Let  $\Sigma_{\Delta\Phi}$  be the covariance matrix of the random variable  $\Delta\Phi$ . Show

$$\Sigma_{\Delta\Phi} = \left( \sum_i \alpha_i^2 \right) \Sigma_g$$