

Homework 4 Solutions

1. Gradient Descent

(a) The gradient descent update rule has the form:

$$\theta_i^{(t+1)} = \theta_i^{(t)} - \alpha \frac{\partial \mathcal{C}(\theta)}{\partial \theta_i}$$

We derive the gradient $\frac{\partial \mathcal{C}(\theta)}{\partial \theta_i}$ as follows:

$$\begin{aligned} \frac{\partial \mathcal{C}(\theta)}{\partial \theta_i} &= \frac{\partial}{\partial \theta_i} \left[\frac{a_1}{2}(\theta_1 - r_1)^2 + \cdots + \frac{a_i}{2}(\theta_i - r_i)^2 + \cdots + \frac{\theta_N}{2}(\theta_N - r_N)^2 \right] \\ &= \frac{\partial}{\partial \theta_i} \left[\frac{a_i}{2}(\theta_i - r_i)^2 \right] \\ &= \frac{a_i}{2} \frac{\partial}{\partial \theta_i} (\theta_i - r_i)^2 \\ &= \frac{a_i}{2} \left[2(\theta_i - r_i) \frac{\partial}{\partial \theta_i} (\theta_i - r_i) \right] \\ &= a_i(\theta_i - r_i) \end{aligned}$$

Plugging this into the formula above, we obtain the final update rule:

$$\theta_i^{(t+1)} = \theta_i^{(t)} - \alpha a_i(\theta_i^{(t)} - r_i)$$

(b) From the definition of the error, we have:

$$e_i^{(t+1)} = \theta_i^{(t+1)} - r_i$$

Using the update rule derived in Part (a), we can write $\theta_i^{(t+1)}$ in terms of $\theta_i^{(t)}$:

$$e_i^{(t+1)} = \theta_i^{(t)} - \alpha a_i(\theta_i^{(t)} - r_i) - r_i$$

We can re-arrange the terms to find two groups that match the definition of $e_i^{(t)}$:

$$e_i^{(t+1)} = \underbrace{\theta_i^{(t)} - r_i}_{e_i^{(t)}} - \alpha a_i \underbrace{(\theta_i^{(t)} - r_i)}_{e_i^{(t)}}$$

Thus, we can express $e_i^{(t+1)}$ in terms of $e_i^{(t)}$ as follows:

$$\begin{aligned} e_i^{(t+1)} &= e_i^{(t)} - \alpha a_i e_i^{(t)} \\ &= (1 - \alpha a_i) e_i^{(t)} \end{aligned}$$

(c) We observe a pattern by expanding the first few elements of the recursion:

$t = 1$:

$$e_i^{(1)} = (1 - \alpha a_i) e_i^{(0)}$$

$t = 2$:

$$\begin{aligned} e_i^{(2)} &= (1 - \alpha a_i) e_i^{(1)} \\ &= (1 - \alpha a_i) \left[(1 - \alpha a_i) e_i^{(0)} \right] \\ &= (1 - \alpha a_i)^2 e_i^{(0)} \end{aligned}$$

\vdots

$t = N$:

$$e_i^{(N)} = (1 - \alpha a_i)^N e_i^{(0)}$$

We can prove this relationship by induction as follows:

Proof.

- **Base case:** When $N = 1$, by definition $e_i^{(1)} = (1 - \alpha a_i) e_i^{(0)} = (1 - \alpha a_i)^1 e_i^{(0)}$.
- **Inductive step:** We assume that for $N = k$, $e_i^{(k)} = (1 - \alpha a_i)^k e_i^{(0)}$. Based on this inductive assumption, we show that the relationship holds for $N = k + 1$:

$$\begin{aligned} e_i^{(k+1)} &= (1 - \alpha a_i) e_i^{(k)} \\ &= (1 - \alpha a_i) \left[(1 - \alpha a_i)^k e_i^{(0)} \right] \\ &= (1 - \alpha a_i)^{k+1} e_i^{(0)} \end{aligned}$$

□

Thus, we have solved the recurrence to obtain a closed formula for $e_i^{(t)}$ in terms of the initial error $e_i^{(0)}$:

$$e_i^{(t)} = (1 - \alpha a_i)^t e_i^{(0)}$$

Now we can reason about the effects of choosing certain values of α and a_i . First, note that both $\alpha > 0$ and $a_i > 0$. If $\alpha a_i \in (0, 1]$ then $1 - \alpha a_i \in [0, 1)$ and $\lim_{N \rightarrow \infty} (1 - \alpha a_i)^N = 0$, so the error *decays over time*.

(d) The cost function $\mathcal{C}(\theta^{(t)})$ is:

$$\mathcal{C}(\theta^{(t)}) = \frac{a_1}{2} (\theta_1^{(t)} - r_1)^2 + \cdots + \frac{a_N}{2} (\theta_N^{(t)} - r_N)^2$$

We observe that for each $i \in 1, \dots, N$, $\theta_i^{(t)} - r_i$ is the error $e_i^{(t)}$ that we worked with in Parts (b) and (c):

$$\mathcal{C}(\theta^{(t)}) = \frac{a_1}{2} \underbrace{(\theta_1^{(t)} - r_1)}_{e_1^{(t)}}^2 + \cdots + \frac{a_N}{2} \underbrace{(\theta_N^{(t)} - r_N)}_{e_N^{(t)}}^2$$

In Part (c), we found the following closed form for $e_i^{(t)}$:

$$e_i^{(t)} = (1 - \alpha a_i)^t (\theta_i^{(0)} - r_i)$$

Taking the square of this closed form, we have:

$$(e_i^{(t)})^2 = ((1 - \alpha a_i)^t (\theta_i^{(0)} - r_i))^2 = (1 - \alpha a_i)^{2t} (\theta_i^{(0)} - r_i)^2$$

Thus, we can write the formula for $\mathcal{C}(\theta^{(t)})$ as a function of the initial values $\theta^{(0)}$ as follows:

$$\begin{aligned} \mathcal{C}(\theta^{(t)}) &= \frac{a_1}{2} (1 - \alpha a_1)^{2t} (\theta_1^{(0)} - r_1)^2 + \dots + \frac{a_N}{2} (1 - \alpha a_N)^{2t} (\theta_N^{(0)} - r_N)^2 \\ &= \sum_{i=1}^N \frac{a_i}{2} (1 - \alpha a_i)^{2t} (\theta_i^{(0)} - r_i)^2 \end{aligned}$$

(e) The cost function has the form:

$$\mathcal{C}(\theta) = \frac{1}{2} (\theta - \mathbf{r})^T \mathbf{A} (\theta - \mathbf{r})$$

where $\theta \in \mathbb{R}^N$, $\mathbf{r} \in \mathbb{R}^N$, and $\mathbf{A} \in \mathbb{R}^{N \times N}$.

First, we want to derive a vectorized gradient descent update rule. Similarly to Part (a), this rule will have the form:

$$\theta^{(t+1)} = \theta^{(t)} - \alpha \frac{\partial \mathcal{C}(\theta)}{\partial \theta}$$

Thus, we need to find the gradient of $\mathcal{C}(\theta)$ with respect to θ .

We find:

$$\frac{\partial \mathcal{C}(\theta)}{\partial \theta} = \frac{1}{2} \cdot 2\mathbf{A}(\theta - \mathbf{r}) = \mathbf{A}(\theta - \mathbf{r})$$

The gradient update rule for the parameter vector θ is therefore:

$$\theta^{(t+1)} = \theta^{(t)} - \alpha \mathbf{A}(\theta^{(t)} - \mathbf{r})$$

Recurrence for the Error $\mathbf{e} = \theta - \mathbf{r}$.

$$\mathbf{e}^{(t+1)} = \theta^{(t+1)} - \mathbf{r}$$

As we found in the previous part,

$$\begin{aligned} \theta^{(t+1)} &= \theta^{(t)} - \alpha \mathbf{A}(\theta - \mathbf{r}) \\ &= \theta^{(t)} - \alpha \mathbf{A}\theta^{(t)} + \alpha \mathbf{A}\mathbf{r} \end{aligned}$$

Pugging this into the equation for $\mathbf{e}^{(t+1)}$ yields:

$$\begin{aligned} \mathbf{e}^{(t+1)} &= \theta^{(t)} - \alpha \mathbf{A}\theta^{(t)} + \alpha \mathbf{A}\mathbf{r} - \mathbf{r} \\ &= \underbrace{\theta^{(t)} - \mathbf{r}}_{\mathbf{e}^{(t)}} - \alpha \mathbf{A} \underbrace{(\theta^{(t)} - \mathbf{r})}_{\mathbf{e}^{(t)}} \\ &= \mathbf{e}^{(t)} - \alpha \mathbf{A}\mathbf{e}^{(t)} \\ &= (\mathbf{I} - \alpha \mathbf{A})\mathbf{e}^{(t)} \end{aligned}$$

The last line expresses a recurrence of the form $\mathbf{e}^{(t+1)} = \mathbf{B}\mathbf{e}^{(t)}$, where $\mathbf{B} = \mathbf{I} - \alpha\mathbf{A}$. Note that \mathbf{B} is symmetric because: 1) if we multiply a symmetric matrix by a scalar, the result is a symmetric matrix, so $-\alpha\mathbf{A}$ is symmetric; 2) the sum of two symmetric matrices is symmetric, and both \mathbf{I} and $\mathbf{I} - \alpha\mathbf{A}$ are symmetric, so $\mathbf{I} - \alpha\mathbf{A}$ is symmetric. Now we wish to find an explicit form for $\mathbf{e}^{(t)}$ in terms of $\theta^{(0)}$. Note that:

$$\begin{aligned}\mathbf{e}^{(1)} &= \mathbf{B}\mathbf{e}^{(0)} \\ \mathbf{e}^{(2)} &= \mathbf{B}\mathbf{e}^{(1)} = \mathbf{B}(\mathbf{B}\mathbf{e}^{(0)}) = (\mathbf{B}\mathbf{B})\mathbf{e}^{(0)} = \mathbf{B}^2\mathbf{e}^{(0)} \\ &\vdots \\ \mathbf{e}^{(t)} &= \mathbf{B}^t\mathbf{e}^{(0)}\end{aligned}$$

We can exploit the structure of the matrix \mathbf{B} in order to be able to find powers \mathbf{B}^t easily, rather than actually performing t matrix multiplications. Since \mathbf{A} is a symmetric positive definite matrix, we can express it using its *eigendecomposition*, as $\mathbf{A} = \mathbf{Q}\mathbf{\Lambda}\mathbf{Q}^{-1} = \mathbf{Q}\mathbf{\Lambda}\mathbf{Q}^T$, where \mathbf{Q} is a matrix whose columns are the *eigenvectors* of \mathbf{A} , and $\mathbf{\Lambda}$ is a *diagonal* matrix containing the *eigenvalues* of \mathbf{A} (that is, $\mathbf{\Lambda} = \text{diag}(\lambda)$, where λ is the vector of eigenvalues of \mathbf{A}).

Now, if \mathbf{x} is an eigenvector of \mathbf{A} with corresponding eigenvalue λ , then:

$$\begin{aligned}\mathbf{B}\mathbf{x} &= (\mathbf{I} - \alpha\mathbf{A})\mathbf{x} \\ &= \mathbf{I}\mathbf{x} - \alpha\mathbf{A}\mathbf{x} \\ &= \mathbf{x} - \alpha(\mathbf{A}\mathbf{x}) \\ &= \mathbf{x} - \alpha\lambda\mathbf{x} \\ &= (1 - \alpha\lambda)\mathbf{x}\end{aligned}$$

So \mathbf{x} is also an eigenvector of \mathbf{B} with eigenvalue $1 - \alpha\lambda$. We see that the eigenvectors of \mathbf{B} are the same as those of \mathbf{A} , and for each eigenvalue λ of \mathbf{A} , we have a corresponding eigenvalue $1 - \alpha\lambda$ of \mathbf{B} . Thus, the eigendecomposition of $\mathbf{B} = \mathbf{Q}(\mathbf{I} - \alpha\mathbf{\Lambda})\mathbf{Q}^T$.

We can find $\mathbf{e}^{(t)}$ more easily by expressing it in terms of the eigendecomposition of \mathbf{B} :

$$\begin{aligned}\mathbf{e}^{(t)} &= \mathbf{B}^t\mathbf{e}^{(0)} \\ &= \mathbf{Q}(\mathbf{I} - \alpha\mathbf{\Lambda})^t\mathbf{Q}^T\mathbf{e}^{(0)}\end{aligned}$$

Putting this all together in the context of the cost function, we have:

$$\begin{aligned}
\mathcal{C}(\theta^{(t)}) &= \frac{1}{2}(\theta^{(t)} - \mathbf{r})^T \mathbf{A}(\theta^{(t)} - \mathbf{r}) \\
&= \frac{1}{2}(\mathbf{e}^{(t)})^T \mathbf{A}(\mathbf{e}^{(t)}) \\
&= \frac{1}{2} \left[\mathbf{Q}(\mathbf{I} - \alpha\mathbf{\Lambda})^t \mathbf{Q}^T \mathbf{e}^{(0)} \right]^T \mathbf{A} \left[\mathbf{Q}(\mathbf{I} - \alpha\mathbf{\Lambda})^t \mathbf{Q}^T \mathbf{e}^{(0)} \right] \\
&= \frac{1}{2} \left[(\mathbf{e}^{(0)})^T \mathbf{Q}(\mathbf{I} - \alpha\mathbf{\Lambda})^t \mathbf{Q}^T \right] \mathbf{A} \left[\mathbf{Q}(\mathbf{I} - \alpha\mathbf{\Lambda})^t \mathbf{Q}^T \mathbf{e}^{(0)} \right] \\
&= \frac{1}{2} (\mathbf{e}^{(0)})^T \mathbf{Q}(\mathbf{I} - \alpha\mathbf{\Lambda})^t \mathbf{Q}^T [\mathbf{Q}\mathbf{\Lambda}\mathbf{Q}^T] \mathbf{Q}(\mathbf{I} - \alpha\mathbf{\Lambda})^t \mathbf{Q}^T \mathbf{e}^{(0)} \\
&= \frac{1}{2} (\mathbf{e}^{(0)})^T \mathbf{Q}(\mathbf{I} - \alpha\mathbf{\Lambda})^t (\mathbf{Q}^T \mathbf{Q}) \mathbf{\Lambda} (\mathbf{Q}^T \mathbf{Q}) (\mathbf{I} - \alpha\mathbf{\Lambda})^t \mathbf{Q}^T \mathbf{e}^{(0)} \\
&= \frac{1}{2} (\mathbf{e}^{(0)})^T \mathbf{Q}(\mathbf{I} - \alpha\mathbf{\Lambda})^t \mathbf{\Lambda} (\mathbf{I} - \alpha\mathbf{\Lambda})^t \mathbf{Q}^T \mathbf{e}^{(0)}
\end{aligned}$$

Since $(\mathbf{I} - \alpha\mathbf{\Lambda})^t$ and $\mathbf{\Lambda}$ are both diagonal matrices, we can commute their order, and combine the two instances of $(\mathbf{I} - \alpha\mathbf{\Lambda})^t$ to yield $(\mathbf{I} - \alpha\mathbf{\Lambda})^{2t}$:

$$\mathcal{C}(\theta^{(t)}) = \frac{1}{2} (\mathbf{e}^{(0)})^T \mathbf{Q}(\mathbf{I} - \alpha\mathbf{\Lambda})^{2t} \mathbf{\Lambda} \mathbf{Q}^T \mathbf{e}^{(0)}$$

Replacing $\mathbf{e}^{(0)}$ with $\theta^{(0)} - \mathbf{r}$, we obtain:

$$\mathcal{C}(\theta^{(t)}) = \frac{1}{2} (\theta^{(0)} - \mathbf{r})^T \mathbf{Q}(\mathbf{I} - \alpha\mathbf{\Lambda})^{2t} \mathbf{\Lambda} \mathbf{Q}^T (\theta^{(0)} - \mathbf{r})$$