

Exercise 1 (Monte Carlo for Gaussians)

1. Let's prove that $E[\phi(X)] = E[\phi(X + \theta) \exp(\frac{-1}{2}\theta^T \theta - \theta^T X)]$.

$$\begin{aligned} E[\phi(X + \theta) \exp(\frac{-1}{2}\theta^T \theta - \theta^T X)] &= \int_{\mathbb{R}^d} \phi(x + \theta) \exp(\frac{-1}{2}\theta^T \theta - \theta^T X) \pi(x) dx_1 \dots dx_d = \\ &= \int_{\mathbb{R}^d} \phi(x + \theta) \exp\left(\frac{-1}{2}\theta^T \theta - \theta^T X\right) \exp(-x^T x/2) \frac{1}{(\sqrt{2\pi})^d} dx_1 \dots dx_d = \\ &\quad \int_{\mathbb{R}^d} \phi(x + \theta) \exp\left(\frac{-1}{2}(x - \theta)^T (x - \theta)\right) \frac{1}{(\sqrt{2\pi})^d} dx_1 \dots dx_d \end{aligned}$$

Finally, making $x - \theta = y$,

$$\int_{\mathbb{R}^d} \phi(y) \exp\left(\frac{-1}{2}(y)^T (y)\right) \frac{1}{(\sqrt{2\pi})^d} dx_1 \dots dx_d = E[\phi(Y)]$$

□

2. Let's show that

$$\sigma^2(\theta) = E\left[\phi^2(X) \exp\left(\frac{-1}{2}X^T X + \frac{1}{2}(X - \theta)^T (X - \theta)\right)\right] - (E[\phi(X)])^2$$

Note that, using the result in the previous item we have:

$$\begin{aligned} \sigma^2(\theta) &= V\left[\phi(X + \theta) \exp\left(\frac{-1}{2}\theta^T \theta - \theta^T X\right)\right] = \\ &= E\left[\left(\phi(X + \theta) \exp\left(\frac{-1}{2}\theta^T \theta - \theta^T X\right)\right)^2\right] - E\left[\phi(X + \theta) \exp\left(\frac{-1}{2}\theta^T \theta - \theta^T X\right)\right]^2 = \\ &= E\left[\left(\phi(X + \theta) \exp\left(\frac{-1}{2}\theta^T \theta - \theta^T X\right)\right)^2\right] - E[\phi(X)]^2 \end{aligned}$$

Now, let's rearrange the first term in the variance.

$$\sigma^2(\theta) = \int_{\mathbb{R}^d} \phi(x + \theta)^2 \exp(-\theta^T \theta - 2\theta^T X) \exp(-x^T x/2) \frac{1}{(\sqrt{2\pi})^d} dx_1 \dots dx_d =$$

Make $X + \theta = Y$, then:

$$\begin{aligned}
& \int_{\mathbb{R}^d} \phi(y)^2 \exp(-\theta^T \theta - 2\theta^T(y - \theta)) \exp(-(y - \theta)^T(y - \theta)/2) \frac{1}{(\sqrt{2\pi})^d} dx_1 \dots dx_d = \\
& = \int_{\mathbb{R}^d} \phi(y)^2 \exp\left(\frac{1}{2}(y - \theta)^T(y - \theta) - \frac{y^T y}{2}\right) \exp\left(\frac{-y^T y}{2}\right) \frac{1}{(\sqrt{2\pi})^d} dx_1 \dots dx_d = \\
& = E\left[\phi^2(X) \exp\left(\frac{-1}{2}X^T X + \frac{1}{2}(X - \theta)^T(X - \theta)\right)\right]
\end{aligned}$$

Therefore,

$$\sigma^2(\theta) = E\left[\phi^2(X) \exp\left(\frac{-1}{2}X^T X + \frac{1}{2}(X - \theta)^T(X - \theta)\right)\right] - (E[\phi(X)])^2$$

□

3. Let's calculate $\nabla^2 \sigma^2(\theta) = H(\theta)$.

$$\begin{aligned}
\frac{\partial \sigma^2(\theta)}{\partial \theta_i} &= \frac{E[\phi(X)^2 \exp(\frac{-X^T X + (X - \theta)^T(X - \theta)}{2})]}{\partial \theta_i} = \\
&= \int_{\chi} \phi(x)^2 \exp(-x^T x) \frac{\partial}{\partial \theta_i} \exp\left(\frac{(x - \theta)^T(x - \theta)}{2}\right) \frac{1}{(\sqrt{2\pi})^d} dx = \\
&= \int_{\chi} \phi(x)^2 \exp(-x^T x) (\theta_i - x_i) \exp\left(\frac{(x - \theta)^T(x - \theta)}{2}\right) \frac{1}{(\sqrt{2\pi})^d} dx
\end{aligned}$$

We calculated the gradient, let's now calculate the second derivative. First the diagonal.

$$\begin{aligned}
& \frac{\partial}{\partial \theta_i} \int_{\chi} \phi(x)^2 \exp(-x^T x) (\theta_i - x_i) \exp\left(\frac{(x - \theta)^T(x - \theta)}{2}\right) \frac{1}{(\sqrt{2\pi})^d} dx = \\
& = E[\phi(X)^2] + \int_{\chi} \phi(x)^2 \exp(-x^T x) \exp\left(\frac{(x - \theta)^T(x - \theta)}{2}\right) (x_i - \theta_i)(x_i - \theta_i) \frac{1}{(\sqrt{2\pi})^d} dx
\end{aligned}$$

Now the rest:

$$\begin{aligned}
& \frac{\partial}{\partial \theta_j} \int_{\chi} \phi(x)^2 \exp(-x^T x) (\theta_i - x_i) \exp\left(\frac{(x - \theta)^T(x - \theta)}{2}\right) \frac{1}{(\sqrt{2\pi})^d} dx = \\
& = \int_{\chi} \phi(x)^2 \exp(-x^T x) \exp\left(\frac{(x - \theta)^T(x - \theta)}{2}\right) (x_i - \theta_i)(x_j - \theta_j) \frac{1}{(\sqrt{2\pi})^d} dx
\end{aligned}$$

□

4. We already know that the Hessian is positive definite. Hence, we only need to show that the derivative is equal to zero at θ^* .

$$\begin{aligned}
 \nabla \sigma^2(\theta) &= \int_{\mathcal{X}} \phi(x)^2 \exp(-x^T x) (\theta - x) \exp\left(\frac{-(x - \theta)^T (x - \theta)}{2}\right) \frac{1}{(\sqrt{2\pi})^d} dx = \\
 &= \int_{\mathcal{X}} \phi(x)^2 \exp(-x^T x) (\theta - x) \exp\left(\frac{-(x - \theta)^T (x - \theta)}{2}\right) \frac{1}{(\sqrt{2\pi})^d} dx = \\
 &= \int_{\mathcal{X}} \phi(x)^2 (\theta - x) \exp\left(\frac{-x^T x}{2} - \theta^T x + \frac{-\theta^T \theta}{2}\right) \frac{1}{(\sqrt{2\pi})^d} dx = \\
 &= \int_{\mathcal{X}} \phi(x)^2 (\theta - x) \exp(-\theta^T x) \exp(-x^T x/2) \frac{\exp(\theta^T \theta/2)}{(\sqrt{2\pi})^d} dx = 0
 \end{aligned}$$

Finally, since the last term doesn't depend on X , we can eliminate it, obtaining:

$$E[\phi(X)^2 (\theta - X) \exp(-\theta^T X)] = 0$$

□

5. Couldn't solve.

Exercise 2 (Metropolis-Hastings)

1. First, generate $Y \sim q(X_t, \cdot)$. With probability equal to $\alpha(x, y)$, make $X_{t+1} = Y$, and with probability $1 - \sum_{z \in \mathbb{Z}} \alpha(x, z)q(x, z)$ make $X_{t+1} = X_t$. Then, repeat the process.
2. We want to show that $\pi(x)T(x, y) = \pi(y)T(y, x)$. For $y = x$, this is trivial. Now, assume $y \neq x$. Therefore:

$$\begin{aligned}\pi(x)T(x, y) &= \pi(x)\alpha(x, y)q(x, y) = \pi(x)\frac{\gamma(x, y)}{\pi(x)q(x, y)} = \gamma(y, x) = \\ &= \pi(y)\frac{\gamma(y, x)q(y, x)}{\pi(y)q(y, x)} = \pi(y)T(y, x)\end{aligned}$$

□

3. Using Metropolis-Hastings, one has:

$$\alpha = \min \left\{ 1, \frac{\pi(x^*)q(x_{t-1} | x^*)}{\pi(x_{t-1})q(x^* | x_{t-1})} \right\}$$

So, $\alpha(x, y) = \frac{\gamma(x, y)}{\pi(x)q(x, y)}$, for $x = x_{t-1}, x^* = y, q(x, y) = q(x^* | x_{t-1})$.

Make:

$$\begin{aligned}\gamma(x, y) &= \max \{ \pi(y)q(y, x), \pi(x)q(x, y) \} \\ &\quad \therefore \\ \alpha(x, y) &= \frac{\max \{ \pi(y)q(y, x), \pi(x)q(x, y) \}}{\pi(x)q(x, y)} = \\ &= \min \left\{ 1, \frac{\pi(y)q(y, x)}{\pi(x)q(x, y)} \right\}\end{aligned}$$

□

4. First, let's rewrite the estimate as a function of Y . Note that $Y^{(k)} = X^{(\tau_k)}$, hence:

$$\frac{1}{\tau_k - 1} \sum_{t=1}^{\tau_k-1} \phi(X^{(t)}) = \frac{1}{k - 1} \sum_{t=1}^{k-1} \phi(Y^{(t)})$$

Now, let's prove it has the transition desired transition kernel.

$$K(x, y) = P(Y^{(k)} = y | Y^{(k-1)} = x) = P(X^{(\tau_k)} = y | X^{(\tau_k-1)} = x)$$

The event $X^{(\tau_k)} = y | X^{(\tau_k-1)} = x$ is equivalent to selecting y starting from x and then accepting y , hence $q(x, y) \cdot \alpha(x, y) = P(X^{(\tau_k)} = y | X^{(\tau_k-1)} = x)$.

$$\text{Therefore, } P(Y^{(k)} = y | Y^{(k-1)} = x) = \frac{q(x, y)\alpha(x, y)}{\sum_{z \in \mathbb{Z}} \alpha(x, z)q(x, z)}.$$

□

5. Let's show that $\tilde{\pi}(x)K(x, y) = \tilde{\pi}(y)K(y, x)$.

$$\frac{\pi(x)m(x)}{\sum_{z \in \mathbb{Z}} \pi(z)m(z)} \cdot \frac{q(x, y)\alpha(x, y)}{\sum_{z \in \mathbb{Z}} \alpha(x, z)q(x, z)} = \frac{\pi(x)q(x, y)\alpha(x, y)}{\sum_{z \in \mathbb{Z}} \pi(z)m(z)}$$

Note that $\alpha(x, y) = \frac{\gamma(x, y)}{\pi(x)q(x, y)} = \frac{\gamma(y, x)}{\pi(x)q(x, y)}$. Therefore:

$$\frac{\pi(x)q(x, y)\gamma(x, y)}{\alpha(x, z)q(x, z) \sum_{z \in \mathbb{Z}} \pi(z)m(z)} = \frac{\gamma(y, x)}{\sum_{z \in \mathbb{Z}} \pi(z)m(z)} = \frac{\alpha(y, x)\pi(y)q(y, x)}{\sum_{z \in \mathbb{Z}} \pi(z)m(z)} = \tilde{\pi}(y)K(y, x)$$

□

6. Couldn't solve.

Exercise 3 (Metropolis-Hastings)

1. Let's show that $\int_{\mathcal{X}} \pi(x)(\alpha(x)q(y)(1 - \alpha(x)))\delta_x(y)dx = \pi(y)$. Note that, $\pi(x) = \frac{q(x)}{\alpha(x)Z_\pi}$, hence:

$$\begin{aligned}\int_{\mathcal{X}} \pi(x)(\alpha(x)q(y)(1 - \alpha(x)))\delta_x(y)dx &= \int_{\mathcal{X}} \frac{q(x)}{\alpha(x)Z_\pi}(\alpha(x)q(y)(1 - \alpha(x)))\delta_x(y)dx = \\ &= \int_{\mathcal{X}} \frac{q(x)}{\alpha(x)Z_\pi}\alpha(x)q(y)dx + \pi(y)(1 - \alpha(y)) = \frac{q(y)}{Z_\pi} \int_{\mathcal{X}} q(x)dx + \pi(y)(1 - \alpha(y)) = \\ &= \pi(y)\alpha(y) + \pi(y)(1 - \alpha(y)) = \pi(y)\end{aligned}$$

□

2. Couldn't solve.

Exercise 4 (Gibbs Sampler)

1.

$$\pi(x | y) = \frac{\pi(x, y)}{\pi(y)} \propto \frac{\exp((x-1)^2(y-2)^2)/2}{(y-2)^{-1}} \sim N(1, (y-2)^{-2})$$

Now, follow the same procedure to for $\pi(y | x)$, hence:

$$\pi(y | x) \sim N(2, (x-1)^{-2})$$

□

2. The sampler doesn't make sense, because:

$$\begin{aligned} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \pi(x, y) dx dy &\propto \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \exp((x-1)^2(y-2)^2)/2 dx dy = \\ &= \int_{-\infty}^{\infty} \sqrt{2\pi}((y-2)^{-2})^{\frac{1}{2}} dy = \infty \end{aligned}$$

□