

Bayesian Updates

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Chapter 1

Preliminaries

1.1 Circular Distributions

I'm anticipating that I might need to put more words into this later on, so am leaving space for them here.

1.1.1 Von Mises distribution

The Von-Mises distribution is given by:

$$f(x, \mu, \kappa) = \frac{1}{2\pi I_0 \kappa} \exp(\kappa \cos(x - \mu)), \quad -\pi \leq x \leq \pi,$$

where $I_0(\cdot)$ is the 0th modified Bessel function, where the n th modified Bessel function is given by

$$I_n(\kappa) = \frac{1}{\pi} \int_0^\pi \cos(n\theta) \exp(\kappa \cos \theta) d\theta.$$

The circular mean of the Von-Mises distribution is given by:

$$\mathbb{E}[\exp i\theta] = \frac{I_1(\kappa)}{I_0(\kappa)} e^{i\mu}.$$

In general, this can be seen via

$$\begin{aligned}
\mathbb{E}[e^{in\theta}] &= \frac{1}{2\pi I_0(\kappa)} \int_{-\pi}^{\pi} \exp(in\theta) \exp(\kappa \cos(\theta - \mu)) \, d\theta \\
&= \frac{1}{2\pi I_0(\kappa)} \int_{-\pi-\mu}^{\pi-\mu} \exp(in(\psi + \mu)) \exp(\kappa \cos(\psi)) \, d\psi \\
&= \frac{\exp(in\mu)}{2\pi I_0(\kappa)} \int_{-\pi}^{\pi} \exp(in\theta) \exp(\kappa \cos(\theta)) \, d\theta \\
&= \frac{\exp(in\mu)}{2\pi I_0(\kappa)} \int_{-\pi}^{\pi} \cos(n\theta) \exp(\kappa \cos(\theta)) \, d\theta \\
&= \frac{I_{|n|}(\kappa)}{I_0(\kappa)} e^{in\mu}
\end{aligned}$$

Chapter 2

Problem Statement

2.1 Setup

Goal: Given a single measurement of a Bernoulli random variable and a Von-Mises prior distribution, calculate the posterior distribution and approximate to a Von-Mises distribution.

- t - time step
- d_t - Grover depth of quantum circuit at time t
- Y_t - random variable representing a single shot measurement y_t of the quantum circuit at time t
- $\Pi(\theta|Y_1 = y_1, \dots, Y_t = y_t) = \Pi(\theta|\mathbf{Y}_t)$ - 'true' posterior at time t (though values for $t' < t$ have been used to approximate the earlier distributions)
- $\hat{\Pi}(\theta|Y_1 = y_1, \dots, Y_t = y_t) = \hat{\Pi}(\theta|\mathbf{Y}_t)$ - approximate posterior at time t .

According to Bayes rule:

$$\Pi(\theta|Y_t = y_t, \mathbf{Y}_{t-1}) = \frac{\Pi(Y_t = y_t|\theta)\Pi(\theta|\mathbf{Y}_{t-1})}{\Pi(Y_t = y_t)},$$

so we need to compute each of the quantities on the RHS.

At time t , we make a measurement y_t of $Y_t \sim \text{Ber}(p_t)$ at a Grover depth of d_t where

$$p_t = \frac{1}{2}(1 - \cos((4d_t + 2)\hat{\mu}_{t-1})).$$

Thus,

$$\Pi(Y_t = y_t|\theta) = \frac{1}{2}(1 + (-1)^{y_t} \cos((4d_t + 2)\hat{\mu}_{t-1})).$$

For convenience, let $\lambda_t = 4d_t + 2$.

To simplify some of the computations, we're going to assert that the posterior follows a Von-Mises distribution after every update, so we calculate the new values $\hat{\mu}_t, \hat{\kappa}_t$ and generate our approximate posterior

$$\hat{\Pi}(\theta|\mathbf{Y}_t) \sim VM(\hat{\mu}_t, \hat{\kappa}_t).$$

Now, via Bayes rule, we're computing

$$\Pi(\theta|Y_t = y_t, \mathbf{Y}_{t-1}) = \frac{\Pi(Y_t = y_t|\theta)\hat{\Pi}(\theta|\mathbf{Y}_{t-1})}{\Pi(Y_t = y_t)},$$

2.2 Single shot updates

For simplicity, we're going to consider the first step of the update, which makes things a lot nicer. In this case, we want to know what the circular mean of the posterior distribution is after updating.

- $\Pi(\theta) \sim VM(\mu, \kappa)$ - prior
- $\Pi(Y|\theta) \sim \text{Ber}(\frac{1}{2}(1 - \cos(\lambda\theta)))$

This gives us:

$$\begin{aligned} \Pi(Y = y) &= \int_{-\pi}^{\pi} \Pi(Y = y|\theta)\Pi(\theta) d\theta \\ &= \frac{1}{2\pi I_0(\kappa)} \int_{-\pi}^{\pi} \frac{1}{2}(1 + (-1)^y \cos(\lambda\theta)) \exp(\kappa \cos(\theta - \mu)) d\theta \\ &= \frac{1}{2\pi I_0(\kappa)} \left(\int_{-\pi}^{\pi} \frac{1}{2} \exp(\kappa \cos(\theta - \mu)) d\theta \right. \\ &\quad \left. + (-1)^y \int_{-\pi}^{\pi} \frac{1}{2} \cos(\lambda\theta) \exp(\kappa \cos(\theta - \mu)) d\theta \right) \\ &= \frac{1}{4\pi I_0(\kappa)} \left(2\pi I_0(\kappa) + (-1)^y \int_{-\pi}^{\pi} \frac{e^{i\lambda\theta} + e^{-i\lambda\theta}}{2} \exp(\kappa \cos(\theta - \mu)) d\theta \right) \\ &= \frac{1}{2} \left(1 + (-1)^y \cos(\lambda\mu) \frac{I_\lambda(\kappa)}{I_0(\kappa)} \right) \end{aligned}$$

where in the penultimate line, we use the expression for the n th circular moment. Putting this all together, and letting

$$C(y, \lambda, \mu, \kappa) = \frac{\frac{1}{2} \frac{1}{2\pi I_0(\kappa)}}{\frac{1}{2}(1 + (-1)^y \cos(\lambda\mu) \frac{I_\lambda(\kappa)}{I_0(\kappa)})} = \frac{1}{2\pi(I_0(\kappa) + (-1)^y \cos(\lambda\mu) I_\lambda(\kappa))}$$

gives

$$\begin{aligned}
\mathbb{E}[e^{i\theta}|Y=y] &= C(y, \lambda, \mu, \kappa) \int_{-\pi}^{\pi} e^{i\theta} (1 + (-1)^y \cos(\lambda\theta)) \exp(\kappa \cos(\theta - \mu)) d\theta \\
&= C(y, \lambda, \mu, \kappa) \left(\int_{-\pi}^{\pi} e^{i\theta} \exp(\kappa \cos(\theta - \mu)) d\theta \right. \\
&\quad \left. + (-1)^y \int_{-\pi}^{\pi} e^{i\theta} \cos(\lambda\theta) \exp(\kappa \cos(\theta - \mu)) d\theta \right) \\
&= C(y, \lambda, \mu, \kappa) \left(2\pi I_1(\kappa) e^{i\mu} \right. \\
&\quad \left. + (-1)^y \int_{-\pi}^{\pi} e^{i\theta} \left(\frac{e^{i\lambda\theta} + e^{-i\lambda\theta}}{2} \right) \exp(\kappa \cos(\theta - \mu)) d\theta \right) \\
&= 2\pi C(y, \lambda, \mu, \kappa) \left(I_1(\kappa) e^{i\mu} + \frac{(-1)^y}{2} \left(I_{\lambda+1}(\kappa) e^{i(\lambda+1)\mu} + I_{\lambda-1}(\kappa) e^{-i(\lambda-1)\mu} \right) \right)
\end{aligned}$$

where in the penultimate line, we use the fact that

$$\int_{-\pi}^{\pi} e^{in\theta} \exp(\kappa \cos(\theta - \mu)) d\theta = 2\pi I_0(\kappa) \mathbb{E}[e^{in\theta}] = I_{|n|}(\kappa) e^{in\mu}.$$

This gives us that

$$\mathbb{E}[e^{i\theta}|Y=y] = \frac{I_1(\kappa) e^{i\mu} + \frac{(-1)^y}{2} (I_{\lambda+1}(\kappa) e^{i(\lambda+1)\mu} + I_{\lambda-1}(\kappa) e^{-i(\lambda-1)\mu})}{I_0(\kappa) + (-1)^y \cos(\lambda\mu) I_{\lambda}(\kappa)}.$$

If we then take expectations over Y (i.e. multiply by $\Pi(Y=y)$ and sum) this gives us

$$\mathbb{E}[e^{i\theta}] = \frac{I_1(\kappa)}{I_0(\kappa)} e^{i\mu}.$$

This is problematic. We're not expecting μ to move anywhere on average, but we're hoping that κ is going to increase ($1/\kappa$ is analogous to σ^2 for a normal distribution).