

# Homework 1

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## Exercise 1

Let  $X = (x_1, x_2, \dots, x_n)$

$$x_i \sim \text{Pois}(\lambda) \quad \lambda \sim \Gamma(\alpha, \beta)$$

We have that:

$$\begin{aligned} P(\lambda \mid X) &= \frac{P(X \mid \lambda)P(\lambda)}{P(X)} \\ &\propto P(X \mid \lambda)P(\lambda) \\ &\propto \lambda^{n\bar{x}} e^{-n\lambda} \lambda^{\alpha-1} e^{-\beta\lambda} \\ &= \lambda^{n\bar{x}+\alpha-1} e^{-(n+\beta)\lambda} \end{aligned}$$

Therefore,  $P(\lambda \mid X) \sim \Gamma(n\bar{x} + \alpha, \beta + n)$  and the Gamma distribution is conjugate to the Poisson distribution.

## Exercise 2

Let  $s = (s_1, s_2, \dots, s_n)$ ,  $s' = (s'_1, s'_2, \dots, s'_n)$  and  $s_{-i} = (s_1, \dots, s_{i-1}, s_{i+1}, \dots, s_n)$

We will show that Gibbs sampling satisfies the detailed balance equation:  $\pi(s)P(s, s') = \pi(s')P(s', s)$

w.l.g consider an update for  $s_1$

*Case 1:*  $s_{-1} \neq s'_{-1}$

$$\pi(s)P(s, s') = \pi(s')P(s', s) = 0$$

*Case 2:*  $s_{-1} = s'_{-1}$

$$\begin{aligned}\pi(s)P(s, s') &= \pi(s)P(s'_1 \mid s'_{-1}) \\ &= \pi(s) \frac{\pi(s')}{\sum_z \pi(z, s'_{-1})} \\ &= \pi(s') \frac{\pi(s)}{\sum_z \pi(z, s_{-1})} \\ &= \pi(s')P(s_1 \mid s_{-1}) \\ &= \pi(s')P(s', s)\end{aligned}$$

Consider the move from  $s$  to  $s'$ . The acceptance probability for MH will be

$$\frac{\pi(s')P(s', s)}{\pi(s)P(s, s')} = 1$$

## Exercise 3

a)

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##1. enumeration and conditioning:

## condition and marginalize:
## compute joint:
p = np.zeros((2, 2, 2, 2)) # c,s,r,w
for c in range(2):
    for s in range(2):
        for r in range(2):
            for w in range(2):
                p[c, s, r, w] = p_C(c) * p_S_given_C(s, c) * p_R_given_C(r, c) * p_W_given_S_R(w, s, r)

p_C_given_W = np.zeros(2)
for c in range(2):
    for s in range(2):
        for r in range(2):
            p_C_given_W[c] += p[c, s, r, 1]

p_C_given_W /= np.sum(p_C_given_W)

print('There is a {:.2f}% chance it is cloudy given the grass is wet'.format(p_C_given_W[1] * 100))
```

b)

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##2. ancestral sampling and rejection:
# https://www.cs.ubc.ca/~fwood/CS532W-539W/lectures/mcmc.pdf

num_samples = 10000
samples = np.zeros(num_samples)
rejections = 0
i = 0
while i < num_samples:
    c = np.argmax(np.random.multinomial(1, [p_C(0), p_C(1)]))
    s = np.argmax(np.random.multinomial(1, [p_S_given_C(0, c), p_S_given_C(1, c)]))
    r = np.argmax(np.random.multinomial(1, [p_R_given_C(0, c), p_R_given_C(1, c)]))
    w = np.argmax(np.random.multinomial(1, [p_W_given_S_R(0, s, r), p_W_given_S_R(1, s, r)]))
    if w != 1:
        rejections += 1
        continue
    else:
        samples[i] = c
        i += 1

print('The chance of it being cloudy given the grass is wet is {:.2f}%'.format(samples.mean() * 100))
print(' {:.2f}% of the total samples were rejected'.format(100 * rejections / (samples.shape[0] + rejections)))
```

c)

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##gibbs sampling
num_samples = 10000
samples = np.zeros(num_samples)
state = np.zeros(4, dtype='int')
# c,s,r,w, set w = True

c, s, r, w = 0, 1, 2, 3
i = 0
state[w] = 1
while i < num_samples:
    state[c] = np.argmax(np.random.multinomial(1, p_C_given_S_R[:, state[s], state[r]]))
    state[s] = np.argmax(np.random.multinomial(1, p_S_given_C_R_W[state[c], :, state[r], state[w]]))
    state[r] = np.argmax(np.random.multinomial(1, p_R_given_C_S_W[state[c], state[s], :, state[w]]))

    samples[i] = state[c]
    i += 1

print('The chance of it being cloudy given the grass is wet is {:.2f}%'.format(samples.mean() * 100))

```

Results:

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There is a 57.58% chance it is cloudy given the grass is wet
The chance of it being cloudy given the grass is wet is 58.05%
34.73% of the total samples were rejected
The chance of it being cloudy given the grass is wet is 58.91%

Process finished with exit code 0

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## Exercise 4

MH within Gibbs on blocks  $\mathbf{w}$  and  $\hat{\mathbf{t}}$ :

$\mathbf{w}$  block

Let  $q(\mathbf{w}, \mathbf{w}')$  be the proposal distribution. We also have that,

$$\begin{aligned}\pi(\mathbf{w}) &\propto p(\mathbf{t}, \mathbf{x}, \sigma^2, \mathbf{w}, \alpha) \\ &= \prod_{n=1}^N \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{t_n - \mathbf{w}^T \mathbf{x}_n}{\sigma})^2} \prod_{d=1}^D \frac{1}{\sqrt{2\pi\alpha}} e^{-\frac{1}{2}(\frac{\mathbf{w}_d}{\sqrt{\alpha}})^2}\end{aligned}$$

So the update probability is,

$$\begin{aligned}r &= \frac{\pi(\mathbf{w}')q(\mathbf{w}, \mathbf{w}')}{\pi(\mathbf{w})q(\mathbf{w}', \mathbf{w})} \\ &= \frac{\prod_{n=1}^N \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{t_n - \mathbf{w}'^T \mathbf{x}_n}{\sigma})^2} \prod_{d=1}^D \frac{1}{\sqrt{2\pi\alpha}} e^{-\frac{1}{2}(\frac{\mathbf{w}'_d}{\sqrt{\alpha}})^2} q(\mathbf{w}', \mathbf{w})}{\prod_{n=1}^N \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{t_n - \mathbf{w}^T \mathbf{x}_n}{\sigma})^2} \prod_{d=1}^D \frac{1}{\sqrt{2\pi\alpha}} e^{-\frac{1}{2}(\frac{\mathbf{w}_d}{\sqrt{\alpha}})^2} q(\mathbf{w}, \mathbf{w}')} \\ &\propto e^{-\frac{1}{2} \sum_{n=1}^N (\frac{t_n - \mathbf{w}'^T \mathbf{x}_n}{\sigma})^2 - (\frac{t_n - \mathbf{w}^T \mathbf{x}_n}{\sigma})^2} e^{-\frac{1}{2} \sum_{d=1}^D (\frac{\mathbf{w}'_d}{\sqrt{\alpha}})^2 - (\frac{\mathbf{w}_d}{\sqrt{\alpha}})^2} \frac{q(\mathbf{w}', \mathbf{w})}{q(\mathbf{w}, \mathbf{w}')} \\ &= \frac{q(\mathbf{w}', \mathbf{w})}{q(\mathbf{w}, \mathbf{w}')} e^{-\frac{1}{2} \sum_{n=1}^N (\frac{t_n - \mathbf{w}'^T \mathbf{x}_n}{\sigma})^2 - (\frac{t_n - \mathbf{w}^T \mathbf{x}_n}{\sigma})^2} e^{-\frac{1}{2} \sum_{d=1}^D (\frac{\mathbf{w}'_d}{\sqrt{\alpha}})^2 - (\frac{\mathbf{w}_d}{\sqrt{\alpha}})^2}\end{aligned}$$

$\hat{\mathbf{t}}$  block

Let  $q(\mathbf{w}, \mathbf{w}')$  be the proposal distribution.

$$\pi(\hat{\mathbf{t}}) \propto N(\mathbf{w}^T \hat{\mathbf{x}}, \sigma^2)$$

The update probability is,

$$\begin{aligned}r &= \frac{\pi(\hat{\mathbf{t}}')q(\hat{\mathbf{t}}, \hat{\mathbf{t}}')}{\pi(\hat{\mathbf{t}})q(\hat{\mathbf{t}}', \hat{\mathbf{t}})} \\ &\propto \frac{\frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{\hat{\mathbf{t}}' - \mathbf{w}^T \hat{\mathbf{x}}}{\sigma})^2} q(\hat{\mathbf{t}}', \hat{\mathbf{t}})}{\frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{\hat{\mathbf{t}} - \mathbf{w}^T \hat{\mathbf{x}}}{\sigma})^2} q(\hat{\mathbf{t}}, \hat{\mathbf{t}}')} \\ &= e^{-\frac{1}{2}(\frac{\hat{\mathbf{t}}'^2 - \hat{\mathbf{t}}^2 + 2\hat{\mathbf{t}}\mathbf{w}^T \hat{\mathbf{x}} - 2\hat{\mathbf{t}}'\mathbf{w}^T \hat{\mathbf{x}}}{\sigma^2})} \frac{q(\hat{\mathbf{t}}', \hat{\mathbf{t}})}{q(\hat{\mathbf{t}}, \hat{\mathbf{t}}')}\end{aligned}$$

**Pure Gibbs on blocks  $\mathbf{w}$  and  $\hat{\mathbf{t}}$ :**

$\mathbf{w}$  block

$$\begin{aligned}
\log p(\mathbf{w} \mid \mathbf{t}, \mathbf{x}, \sigma^2, \alpha) &\propto \log p(\mathbf{w}, \mathbf{t}, \mathbf{x}, \sigma^2, \alpha) \\
&= \log \prod_{n=1}^N p(t_n \mid \mathbf{w}, \mathbf{x}_n, \sigma^2) p(\mathbf{w} \mid 0, \alpha \mathbf{I}) \\
&\propto -\frac{\sum_{n=1}^N (t_n - \mathbf{w}^T \mathbf{x}_n)^2}{2\sigma^2} - \frac{1}{2} \mathbf{w}^T (\alpha \mathbf{I})^{-1} \mathbf{w} \\
&\propto -\frac{1}{2\sigma^2} (\|\mathbf{t} - \mathbf{x}^T \mathbf{w}\|^2) - \frac{1}{2} \mathbf{w}^T (\alpha \mathbf{I})^{-1} \mathbf{w} \\
&= -\frac{1}{2\sigma^2} (\mathbf{t}^T \mathbf{t} - 2\mathbf{t}^T \mathbf{x}^T \mathbf{w} + \mathbf{w}^T \mathbf{x} \mathbf{x}^T \mathbf{w}) - \frac{1}{2} \mathbf{w}^T (\alpha \mathbf{I})^{-1} \mathbf{w} \\
&= -\frac{1}{2} (\mathbf{w} - \boldsymbol{\mu}) \boldsymbol{\Sigma}^{-1} (\mathbf{w} - \boldsymbol{\mu}) \sim N(\boldsymbol{\mu}, \boldsymbol{\Sigma}) \\
\boldsymbol{\mu} &= \sigma^{-2} \boldsymbol{\Sigma} \mathbf{x}^T \mathbf{t} \qquad \boldsymbol{\Sigma}^{-1} = \sigma^{-2} \mathbf{x} \mathbf{x}^T + (\alpha \mathbf{I})^{-1}
\end{aligned}$$

$\hat{\mathbf{t}}$  block

$$p(\hat{\mathbf{t}} \mid \mathbf{t}, \mathbf{x}, \sigma^2, \mathbf{w}, \alpha) \propto e^{-\frac{1}{2}(\frac{\hat{\mathbf{t}} - \mathbf{w}^T \hat{\mathbf{x}}}{\sigma})^2} \sim \text{Normal}(\mathbf{w}^T \hat{\mathbf{x}}, \sigma^2)$$

**Posterior Predictive:**

$$\begin{aligned}
p(\hat{\mathbf{t}} \mid \hat{\mathbf{x}}, \mathbf{t}) &= \int p(\hat{\mathbf{t}} \mid \hat{\mathbf{x}}, \mathbf{w}) p(\mathbf{w} \mid \mathbf{t}) d\mathbf{w} \\
&= \int N(\mathbf{w}^T \hat{\mathbf{x}}, \sigma^2) N(\mathbf{w} \mid \boldsymbol{\mu}, \boldsymbol{\Sigma}) d\mathbf{w}
\end{aligned}$$

Bye the linear combination rules for Gaussian random variables, we have that,

$$p(\hat{\mathbf{t}} \mid \hat{\mathbf{x}}, \mathbf{t}) \sim N(\boldsymbol{\mu}', \sigma'^2)$$

$$\begin{aligned}
\boldsymbol{\mu}' &= \boldsymbol{\mu}^T \hat{\mathbf{x}} \\
\sigma'^2 &= \hat{\mathbf{x}}^T \boldsymbol{\Sigma} \hat{\mathbf{x}} + \sigma^2
\end{aligned}$$

## Exercise 5

$M$  = number of documents,  $K$  = number of topics,  $V$  = vocabulary size

$N_{w,i}$  = number of times word  $w$  is assigned to topic  $i$

$N_i$  = number of words assigned to topic  $i$

$N_{j,i}$  = number of words in document  $j$  assigned to topic  $i$

$x_{lj}$  =  $l^{th}$  word in document  $j$  (observed)

$z_{lj}$  = topic assignment for the  $l^{th}$  word in document  $j$

Joint log likelihood:

$$\begin{aligned} \log p(z, w \mid \alpha, \beta) \propto & \sum_{j=1}^M \left( \sum_{i=1}^K \log \Gamma(N_{ji} + \alpha_i) \right) - \log \Gamma\left(\sum_{i=1}^K N_{ji} + \alpha_i\right) \\ & + \sum_{i=1}^K \left( \sum_{w=1}^V \log \Gamma(N_{wi} + \beta_w) \right) - \log \Gamma\left(\sum_{w=1}^V N_{wi} + \beta_w\right) \end{aligned}$$

Conditional:

$$p(z_{lj} = k \mid z^{-lj}, x, \alpha, \beta) = \frac{1}{Z} a_{ji} b_{wi}$$

$$a_{ji} = N_{ji}^{-lj} + \alpha \qquad b_{wi} = \frac{N_{wi}^{-lj} + \beta}{N_i^{-lj} + V\beta} \qquad Z = \sum_i^K a_{ji} b_{wi}$$