Parameter Estimation II: Bayesian

Prof. Edmund Lam

Department of Electrical and Electronic Engineering
The University of Hong Kong

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https://www.eee.hku.hk/~elec2844

Motivation

Suppose we have a possibly biased coin with unknown probability p that Head will show up. Our best strategy to estimate p is perhaps to experiment:

- What if we flip 1000 times and you get 500 heads?
- What if we flip 999 times and you get 500 heads?
- What if we flip once and you get head?
- What if we flip 10 times and you get 4 heads, *but the coin looks "normal" and you would normally think that it is a fair coin*?

In this lecture, we will explore how to incorporate prior belief (i.e., our view of the parameter that does not depend on the observations) in estimating probabilistic quantities based on observations.

1 Maximum a posteriori (MAP)
2 MAP estimation examples
3 Comparing MAP and ML estimations
4 Least mean square (LMS) estimate
5 Conjugate prior
6 Sequential learning with MAP
7 Hypothesis testing

A probabilistic view of the unknown parameter

In ML, the parameter θ is assumed to be *fixed*, but unknown. This is the *classical* or *frequentist* approach.

But there is an alternative approach known as Bayesian: the parameter θ is a *random variable* in itself, with a certain distribution, and our estimate is the value that gives the largest value in the distribution.

The general approach:

1. Start with a certain PMF or PDF
2. Observe data
3. Based on the observation, adjust the PMF or PDF
4. Make the estimate based on maximizing the adjusted PMF or PDF

Latin lesson

In probability, people like to use these two latin phrases:

$$\boxed{\begin{aligned} a\ priori &= \text{“beforehand”} \\ a\ posteriori &= \text{“afterwards”} \end{aligned}}$$

- *A priori* knowledge is the “prior”, which usually comes from a mathematical model;
- *A posteriori* knowledge comes from observation or empirical evidence.

Hence, our task is to morph from the *a priori* distribution (prior probability) to the *a posteriori* distribution (posterior probability) based on observations.

Bayesian

In this Bayesian approach, the key equation is the Bayes' rule:

$$\boxed{f_{\Theta|X}(\theta|x) \propto f_\Theta(\theta)\, p_{X|\Theta}(x|\theta)} \tag{1}$$

Θ is the random variable to be estimated, and $X = x$ the observation.

The interpretation is:

$$\boxed{\text{posterior} \propto \text{prior} \times \text{likelihood}} \tag{2}$$

A further interpretation:

$$\boxed{\log(\text{posterior}) = \log(\text{prior}) + \log(\text{likelihood}) + \text{constant}} \tag{3}$$

So $\log(\text{prior})$ is an *extra term* when we try to maximize the posterior as opposed to maximizing the likelihood.

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Example 1

Assuming that a certain random variable Θ has the following distribution

$$f_\Theta(\theta) = \begin{cases} 3\theta^2 & 0 < \theta < 1 \\ 0 & \text{otherwise.} \end{cases}$$

Furthermore, another random variable X is related to Θ, such that $(X|\Theta = \theta) \sim \text{Geo}(\theta)$. Given that we observe $X = 2$, find the MAP estimate of Θ.

Example 1

Because $X|\Theta$ is a geometric distribution,

$$f_{X|\Theta}(x|\theta) = (1-\theta)^{x-1}\theta$$

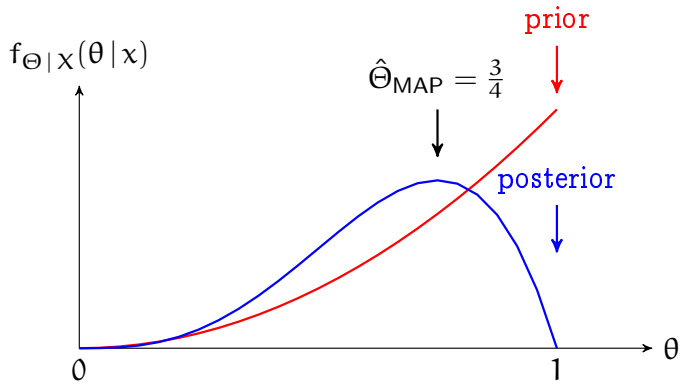
In MAP estimation,

$$\begin{aligned} f_{\Theta|X}(\theta|x=2) &\propto f_\Theta(\theta)\, p_{X|\Theta}(x=2|\theta) \\ &= (3\theta^2)\left[(1-\theta)^{2-1}\theta\right] \\ &= 3\theta^3(1-\theta) \end{aligned}$$

We need to maximize this expression, so we take the derivative w.r.t. θ and set to zero, i.e.,

$$\begin{aligned} 3\theta^2 - 4\theta^3 &= 0 \\ \theta &= \frac{3}{4} \end{aligned}$$

Example 1



Example 2: Poisson with exponential prior

Suppose random variables $X_1, X_2, \ldots, X_n$ are independently generated according to a Poisson random variable with parameter θ, but I only observe their arithmetic mean, i.e.,

$$s = \frac{1}{n}\sum_{i=1}^{n} x_i$$

where each x_i are the generated numbers. Furthermore, I know that θ itself is randomly generated, according to an exponential distribution

$$f_\Theta(\theta) = \lambda e^{-\lambda\theta}.$$

Find the MAP estimate of Θ given observation s.

Example 2: Poisson with exponential prior

In the discussion of ML estimation, we have already noted that the log-likelihood is

$$\begin{aligned} \log p_X(x_1, \ldots, x_n; \theta) &= \sum_{i=1}^{n} \log p_{X_i}(x_i; \theta) \\ &= -n\theta + \sum_{i=1}^{n} x_i \log\theta - \sum_{i=1}^{n} \log(x_i!) \\ &= -n\theta + ns\log\theta - \sum_{i=1}^{n} \log(x_i!) \end{aligned}$$

The log-prior is $\log f_\Theta(\theta) = \log\lambda - \lambda\theta$.

The log-posterior is the sum of the two, i.e., (C denoting what does not involve θ)

$$\log f_{\Theta|S}(\theta|s) = C - n\theta + ns\log\theta - \lambda\theta$$

Example 2: Poisson with exponential prior

To maximize this, we take the derivative w.r.t. θ and set to zero,

$$-n + \frac{ns}{\theta} - \lambda = 0$$
$$\theta = \frac{ns}{n+\lambda} = \frac{s}{1+\frac{\lambda}{n}}$$

So the MAP estimate is $\Theta_{\mathsf{MAP}} = \dfrac{s}{1+\frac{\lambda}{n}}$.

In the earlier discussion on ML estimate, we already know that the ML estimate of a Poisson distribution is $\Theta_{\mathsf{ML}} = s$. Here, we note two situations:

- If λ is small, the prior becomes flat, and MAP approaches ML.
- If n is large, we have more and more trust on the data, and MAP approaches ML.

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Example 1: additive noise

A signal X is transmitted through a certain wireless channel, which is corrupted by an additive noise W. Suppose we know that both are Gaussian distributed with zero mean, i.e.,

$$X \sim \mathcal{N}(0, \sigma_X^2)$$
$$W \sim \mathcal{N}(0, \sigma_W^2)$$

and that they are independent of each other. The received signal is $Y = X + W$. Given that we observe $Y = y$, find:

1. the ML estimate of X
2. the MAP estimate of X

Example 1: additive noise

In thinking about the ML estimate, we assume that X has taken on a value x, which is fixed but unknown, and we try to estimate this value based on our observation.
With a fixed x, we can see that Y is a Gaussian distribution with mean x and variance σ_W^2. The likelihood function is

$$f_Y(y; x) = \frac{1}{\sqrt{2\pi}\sigma_W} e^{-(y-x)^2/2\sigma_W^2}$$

We can maximize the log-likelihood, i.e.,

$$\log f_Y(y; x) = \log \frac{1}{\sqrt{2\pi}\sigma_W} - \frac{(y-x)^2}{2\sigma_W^2}$$

which we can see that it happens when $x = y$. So, our ML estimate is

$$\hat{X}_{\mathsf{ML}} = y$$

Example 1: additive noise

In thinking about the MAP estimate, the posterior PDF of X is

$$\begin{aligned} f_{X|Y}(x|y) &\propto f_X(x)\, f_{Y|X}(y|x) \\ &= c e^{-x^2/2\sigma_X^2} e^{-(y-x)^2/2\sigma_W^2} \end{aligned}$$

where c is a certain constant that does not depend on the value of x. Note that given $X = x$, Y is a Gaussian distribution with mean x and variance σ_W^2.

We need to maximize the *logarithm* of the above expression, which is equivalent to minimizing

$$\frac{x^2}{2\sigma_X^2} + \frac{(y-x)^2}{2\sigma_W^2}$$

Example 1: additive noise

We take the derivative (w.r.t. x) and set to zero, i.e.,

$$\begin{aligned} \frac{2x}{2\sigma_X^2} - \frac{2(y-x)}{2\sigma_W^2} &= 0 \\ \sigma_W^2 x &= \sigma_X^2 (y-x) \\ x &= \frac{\sigma_X^2}{\sigma_W^2 + \sigma_X^2} y \end{aligned}$$

So, our MAP estimate is

$$\hat{X}_{\text{MAP}} = \left(\frac{\sigma_X^2}{\sigma_W^2 + \sigma_X^2} \right) y$$

Unlike the ML estimate, the MAP estimate is saying that if the noise is large, we will simply estimate X to be close to zero (remember it's a zero-mean Gaussian) irrespective of what we have observed.

Example 2a: flipping a coin

A coin has an unknown probability θ to result in head. *We model the prior PDF as a uniform distribution, where*

$$f_\Theta(\theta) = \begin{cases} 1 & 0 < \theta < 1 \\ 0 & \text{otherwise.} \end{cases}$$

We toss the coin n times, and let $X = k$ be the number of heads observed. Find the MAP estimate.

ANS: The number of heads given $\Theta = \theta$ is given by

$$p_{X|\Theta}(k|\theta) = \binom{n}{k} \theta^k (1-\theta)^{n-k} \qquad k = 0, 1, 2, \ldots, n$$

From Bayes' rule, the posterior probability of Θ is

$$f_{\Theta|X}(\theta|k) \propto f_\Theta(\theta)\, p_{X|\Theta}(k|\theta) = c\theta^k (1-\theta)^{n-k}$$

where c is a constant independent of θ.

Example 2a: flipping a coin

We obtain the MAP estimate by maximizing

$$f_{\Theta|X}(\theta|k) = c\theta^k (1-\theta)^{n-k}$$

Taking the derivative w.r.t. θ and setting it to zero,

$$0 = ck(1-\theta)^{n-k}\theta^{k-1} - c(n-k)(1-\theta)^{n-k-1}\theta^k$$

which yields the MAP estimator $\hat{\Theta} = \dfrac{k}{n}$.

This is exactly the same as the ML estimator! The reason is because we have an uninformative prior.

Example 2b: flipping a coin

A coin has an unknown probability θ to result in head. *We model the prior PDF as*

$$f_\Theta(\theta) = \begin{cases} 2 - 4 \cdot \left|\frac{1}{2} - \theta\right| & 0 < \theta < 1 \\ 0 & \text{otherwise.} \end{cases}$$

We toss the coin n times, and let $X = k$ be the number of heads observed. Find the MAP estimate.

Example 2b: flipping a coin

ANS: From Bayes' rule, the posterior PDF of Θ is

$$\begin{aligned} f_{\Theta|X}(\theta|k) &\propto f_\Theta(\theta)\, p_{X|\Theta}(k|\theta) \\ &= c\left(2 - 4 \cdot \left|\frac{1}{2} - \theta\right|\right) \theta^k (1-\theta)^{n-k} \end{aligned}$$

How do we maximize this w.r.t. θ? We divide into three cases: (a) maximum is at $\theta < 1/2$; (b) maximum is at $\theta > 1/2$; (c) maximum is at $\theta = 1/2$.

For (a) and (b), we need the derivative to be zero; for (c), note that the function is not differentiable.

Example 2b: flipping a coin

(a) For $\theta < 1/2$: We have $f_{\Theta|X}(\theta|k) \propto \theta^{k+1}(1-\theta)^{n-k}$. Taking the derivative w.r.t. θ and setting it to zero, similar calculations as above would yield the MAP estimator

$$\hat{\Theta} = \frac{k+1}{n+1}.$$

(b) For $\theta > 1/2$: We have $f_{\Theta|X}(\theta|k) \propto \theta^{k}(1-\theta)^{n-k+1}$. Taking the derivative w.r.t. θ and setting it to zero, similar calculations as above would yield the MAP estimator

$$\hat{\Theta} = \frac{k}{n+1}.$$

(c) Situations other than (a) or (b) would be (c).

Example 2b: flipping a coin

Summarizing, the MAP estimate is given by

$$\hat{\Theta} = \begin{cases} \frac{k+1}{n+1} & \text{if } \frac{k+1}{n+1} < \frac{1}{2} \\ \frac{1}{2} & \text{if } \frac{k}{n+1} \leqslant \frac{1}{2} \leqslant \frac{k+1}{n+1} \\ \frac{k}{n+1} & \text{if } \frac{1}{2} < \frac{k}{n+1} \end{cases}$$

For example, if $n = 9$, then

k	0	1	2	3	4	5	6	7	8	9
$\hat{\Theta}$	0.1	0.2	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.9

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MAP and LMS

Bayesian approach actually gives us another possible esimate. Consider the posterior probability

$$f_{\Theta|X}(\theta|x) \propto f_\Theta(\theta)\, p_{X|\Theta}(x|\theta)$$

where Θ is the random variable to be estimated, and $X = x$ the observation.

- MAP estimate:
$$\hat{\Theta}_{\text{MAP}} = \arg\max_{\Theta} f_{\Theta|X}(\theta|x)$$
- Least mean squares (LMS) estimate:

$$\boxed{\hat{\Theta}_{\text{LMS}} = \mathbb{E}(\Theta|X)} \tag{4}$$

MAP and LMS

Comparison of MAP and LMS:

- MAP finds the *maximum*, or mode of the posterior distribution
- LMS finds the *conditional expectation* of the posterior distribution. It minimizes the mean squared error over all estimators.
- The conditional variance $\text{var}(\Theta|X)$ also gives us information about how reliable the estimator is.
- If the posterior distribution is symmetric around its conditional mean and unimodal, then MAP = LMS.

LMS example

Assuming that a certain random variable Θ has the following distribution

$$f_\Theta(\theta) = \begin{cases} 3\theta^2 & 0 < \theta < 1 \\ 0 & \text{otherwise.} \end{cases}$$

Furthermore, another random variable X is related to Θ, such that $(X|\Theta = \theta) \sim \text{Geo}(\theta)$. Given that we observe $X = 2$, find the LMS estimate of Θ.

LMS example

We had looked into this problem with MAP estimation, and note that the posterior is (except for the constant)

$$f_{\Theta|X}(\theta|x=2) \propto \theta^3(1-\theta)$$

Let K be the proportionality constant. Since this is a PDF, it must integrate to unity,

$$\int_0^1 K\theta^3(1-\theta)d\theta = 1$$

$$K\left[\frac{1}{4}\theta^4 - \frac{1}{5}\theta^5\right]_0^1 = 1$$

$$K = 20$$

LMS example

Hence, the LMS estimate (conditional expectation) is

$$\mathbb{E}(\Theta|X=2) = \int_0^1 \theta \cdot 20\theta^3(1-\theta)d\theta$$

$$= 20\left[\frac{1}{5}\theta^5 - \frac{1}{6}\theta^6\right]_0^1 = \frac{2}{3}$$

Also, for the conditional variance,

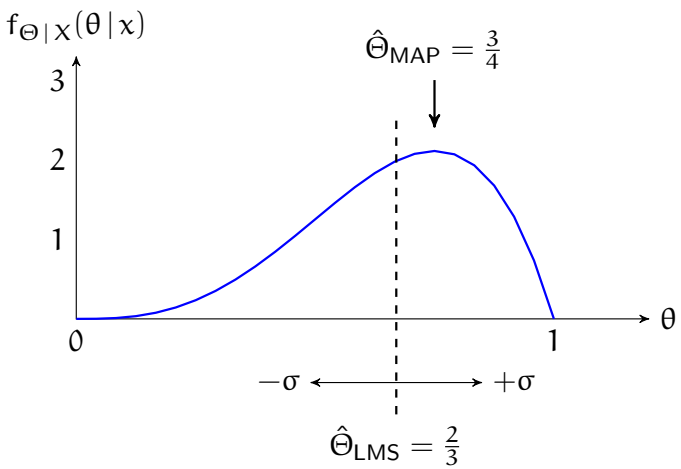
$$\mathbb{E}(\Theta^2|X=2) = \int_0^1 \theta^2 \cdot 20\theta^3(1-\theta)d\theta$$

$$= 20\left[\frac{1}{6}\theta^6 - \frac{1}{7}\theta^7\right]_0^1 = \frac{10}{21}$$

$$\mathrm{var}(\Theta|X) = \frac{10}{21} - \left(\frac{2}{3}\right)^2 = \frac{2}{63}$$

LMS example

Putting things in perspective:



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Example

A coin has an unknown probability θ to result in head. *We model the prior PDF as a beta distribution, where*

$$f_\Theta(\theta) \sim \text{Beta}(\theta; \alpha, \beta) = \begin{cases} \frac{1}{B(\alpha,\beta)}\theta^{\alpha-1}(1-\theta)^{\beta-1} & 0 < \theta < 1 \\ 0 & \text{otherwise,} \end{cases}$$

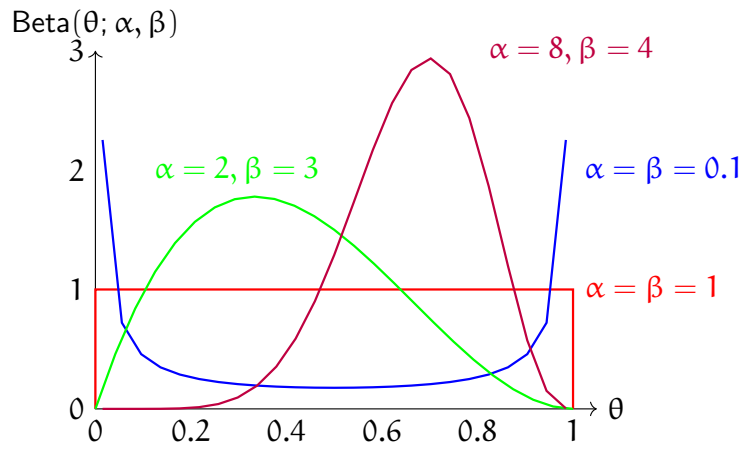
where $B(\alpha, \beta)$ *is a normalizing constant, known as the beta function, given by*

$$B(\alpha, \beta) = \frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha+\beta)} = \frac{(\alpha-1)!(\beta-1)!}{(\alpha+\beta-1)!}$$

(We can use the factorial notation if the quantity is a nonnegative integer.) We toss the coin n times, and let $X = k$ be the number of heads observed. Find the MAP estimate.

Beta distribution

The beta distribution takes on different shapes for various values of α and β, which are not necessarily integers. Specifically, when $\alpha = \beta = 1$, we get the uniform distribution.



Example

ANS: From Bayes' rule, the posterior PDF of Θ is

$$\begin{aligned} f_{\Theta|X}(\theta|k) &\propto f_\Theta(\theta)\, p_{X|\Theta}(k|\theta) \\ &= \left(\frac{1}{B(\alpha,\beta)}\theta^{\alpha-1}(1-\theta)^{\beta-1}\right)\theta^k(1-\theta)^{n-k} \\ &= c\theta^{k+\alpha-1}(1-\theta)^{n-k+\beta-1} \end{aligned}$$

Taking the derivative w.r.t. θ and setting it to zero,

$$0 = (k+\alpha-1)(1-\theta)^{n-k+\beta-1}\theta^{k+\alpha-2} - (n-k+\beta-1)(1-\theta)^{n-k+\beta-2}\theta^{k+\alpha-1}$$

which yields the MAP estimator $\hat{\Theta} = \dfrac{k+(\alpha-1)}{n+(\alpha+\beta-2)}$.

Designing the prior

The beta distribution is called a conjugate prior of the Bernoulli, because they have the same form

$$\theta^{\gamma_1}(1-\theta)^{\gamma_2}$$

for some γ_1 and γ_2.

The parameters of the prior are called hyper-parameters. We can set them to encode our prior beliefs.

Designing the prior

Example: Suppose we want $\mathbb{E}(\theta) = 0.7$ and $\text{var}(\theta) = 0.04$.

With a bit of mathematical derivations, we can show that the beta distribution has the following expressions for mean and variance:

$$\mathbb{E}(\theta) = \frac{\alpha}{\alpha+\beta}$$
$$\text{var}(\theta) = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$$

Plugging in $\frac{\alpha}{\alpha+\beta} = 0.7$, we find $\alpha = \frac{7}{3}\beta$.

We then use the expression for the variance, and after some calculations, we have $\beta = \frac{51}{40} = 1.275$. Hence, $\alpha = 2.975$.

Multinomial and conjugate prior

We have seen that the discrete binomial random variable or likelihood

$$X \sim \text{Bin}(n, \theta) = p_{X|\Theta}(k|\theta) = \binom{n}{k}\theta^k(1-\theta)^{n-k} \qquad k = 0, 1, \ldots, n$$

has a conjugate prior given by the continuous beta distribution

$$f_\Theta(\theta) \sim \text{Beta}(\theta; \alpha, \beta) = \frac{1}{B(\alpha,\beta)}\theta^{\alpha-1}(1-\theta)^{\beta-1} \qquad 0 < \theta < 1$$

which can encode a range of possibilities of prior information, and make it relatively easy to calculate the posterior. Together, we call this the beta-binomial model. We can generalize to cases with multiple outcomes (i.e., from a coin to a die).

Multinomial distribution

Generalizing the binomial distribution, for each event with K possible outcomes, we let

$$x = (x_1, \ldots, x_K) \qquad ; \qquad \theta = (\theta_1, \ldots, \theta_K)$$

where x_j denotes the number of times event j has occurred, with probability θ_j.

The *random vector* X follows a multinomial distribution

$$\boxed{X \sim \text{Mult}(n, \theta) = \binom{n}{x_1, \ldots, x_k}\prod_{j=1}^{K}\theta_j^{x_j}} \tag{5}$$

where $\sum_{k=1}^{K} x_k = n$, and $\binom{n}{x_1, \ldots, x_k} = \frac{n!}{x_1! \cdots x_K!}$ are partitions.

Multinomial distribution

When $n = 1$, binomial becomes Bernoulli.

Similarly, when $n = 1$, multinomial becomes a "categorical" distribution: random vector x denotes a *one-hot encoding* of event j that has occurred, with

$$x = (0, \ldots, \underbrace{1}_{j\text{th}}, \ldots, 0)$$

This is very useful for classification problems.

Dirichlet distribution

Generalizing the beta distribution, we have the Dirichlet distribution, defined over the *probability simplex*

$$S_k = \left\{ \theta : 0 \leqslant \theta_k \leqslant 1, \sum_{k=1}^{K} \theta_k = 1 \right\}$$

such that

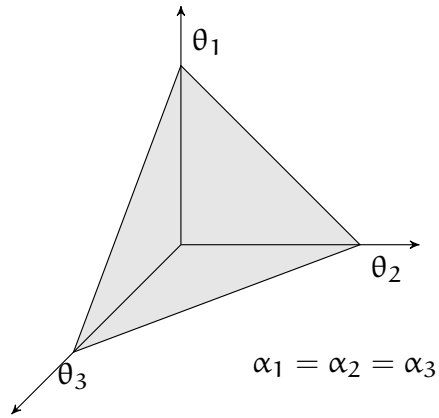
$$\boxed{\mathrm{Dir}(\theta; \alpha) = \frac{1}{B(\alpha)} \prod_{k=1}^{K} \theta_k^{\alpha_k - 1}} \tag{6}$$

with $\alpha_0 = \sum_{k=1}^{K} \alpha_K$, and $B(\alpha) = \frac{\prod_{k=1}^{K} \Gamma(\alpha_k)}{\Gamma(\alpha_0)}$.

Dirichlet distribution

Remember for $K = 2$ (beta distribution), $\alpha_1 = \alpha_2 = 1$ gives a uniform distribution.

For $K = 3$, The probability simplex is the surface:



$\alpha_1 = \alpha_2 = \alpha_3 = 1$ is a uniform distribution

Dirichlet-multinomial model

Using the Dirichlet as prior, and multinomial as the likelihood, the posterior is given by

$$\begin{aligned} f_{\Theta|X}(\theta | x_1, \ldots, x_k) &\propto f_\Theta(\theta)\, p_{X|\Theta}(x_1, \ldots, x_k | \theta) \\ &\propto \left(\prod_{k=1}^{K} \theta_k^{\alpha_k - 1} \right) \left(\prod_{j=1}^{K} \theta_j^{x_j} \right) \\ &= \prod_{k=1}^{K} \theta_k^{\alpha_k + x_k - 1} \\ &\propto \mathrm{Dir}(\theta; \alpha_1 + x_1, \ldots, \alpha_K + x_k) \end{aligned}$$

Dirichlet-multinomial model

We compute the MAP estimate by maximizing the (log) posterior.

$$\begin{aligned} \text{maximize} \quad & \log \prod_{k=1}^{K} \theta_k^{\alpha_k + x_k - 1} \\ \text{subject to} \quad & \sum_{k=1}^{K} \theta_k = 1 \end{aligned}$$

We solve by using $\lambda =$ Lagrange multipler,

$$L = \sum_{k=1}^{K} (\alpha_k + x_k - 1) \log \theta_k + \lambda \sum_{k=1}^{K} \theta_k$$

$$\frac{\partial L}{\partial \theta_k} = 0 \qquad \Rightarrow \qquad \theta_k = -\frac{\alpha_k + x_k - 1}{\lambda}$$

Dirichlet-multinomial model

We next solve for λ by summing over k:

$$1 = \sum_{k=1}^{K} \theta_k = -\frac{1}{\lambda} \sum_{k=1}^{K} (\alpha_k + x_k - 1) = -\frac{1}{\lambda}(\alpha_0 + n - K)$$

Thus, $\lambda = -(\alpha_0 + n - K)$. Hence, the MAP estimate is

$$\hat{\Theta}_k = \frac{\alpha_k + x_k - 1}{\alpha_0 + n - K}$$

In case of uninformative prior (uniform distribution), $\alpha_k = 1$,

$$\hat{\Theta}_k = \frac{x_k}{n}$$

i.e., the empirical fraction of time event k occurs.

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Recursive learning

The Bayesian estimation technique can be adapted to a successive refinement procedure *as data come in*. This is known as recursive learning or online learning.

Example: Suppose we believe our data come from a uniform distribution

$$f_X(x) \sim U(0, \theta)$$

but θ is something you need to estimate, based on successive appearance of new data. Before seeing any data, we can only assume that $0 \leqslant \theta \leqslant 10$. The data that we subsequently observe are, in order, $\{4, 7, 2, 8\}$. Show how our understanding of θ changes.

Recursive learning

ANS: Let the data be labeled $x_1 = 4$, $x_2 = 7$, $x_3 = 2$, $x_4 = 8$. We make use of Bayes' rule (and ignore normalization throughout):

$$f_{\Theta \mid X_1}(\theta \mid x_1) \propto f_{X_1 \mid \Theta}(x_1 \mid \theta)\, f_\Theta(\theta)$$

- Since $0 \leqslant \theta \leqslant 10$, without further information, we assume it is a uniform distribution. Hence,

$$f_\Theta(\theta) = \begin{cases} \frac{1}{10} & 0 \leqslant \theta \leqslant 10 \\ 0 & \text{otherwise.} \end{cases}$$

- $f_{X_1 \mid \Theta}(x_1 \mid \theta) = 1/\theta$, *provided* $x_1 < \theta$.
- Putting the two together, with $x_1 = 4$,

$$f_{\Theta \mid X_1}(\theta \mid x_1) \propto \begin{cases} 1/\theta & 4 \leqslant \theta \leqslant 10 \\ 0 & \text{otherwise.} \end{cases}$$

Recursive learning

We apply Bayes' rule again, noting that X_1 *and* X_2 *are conditionally independent given* Θ:

$$\begin{aligned} f_{\Theta|X_1,X_2}(\theta|x_1,x_2) &\propto f_{X_1,X_2|\Theta}(x_1,x_2|\theta)\, f_\Theta(\theta) \\ &= f_{X_2|\Theta}(x_2|\theta)\, f_{X_1|\Theta}(x_1|\theta)\, f_\Theta(\theta) \\ &= f_{X_2|\Theta}(x_2|\theta)\, f_{\Theta|X_1}(\theta|x_1) \end{aligned}$$

- $f_{X_2|\Theta}(x_2|\theta) = 1/\theta$, *provided* $x_2 < \theta$.
- Putting it together with our previous result, with $x_2 = 7$,

$$f_{\Theta|X_1,X_2}(\theta|x_1,x_2) \propto \begin{cases} 1/\theta^2 & 7 \leqslant \theta \leqslant 10 \\ 0 & \text{otherwise.} \end{cases}$$

Recursive learning

We apply Bayes' rule once again,

$$f_{\Theta|X_1,X_2,X_3}(\theta|x_1,x_2,x_3) \propto f_{X_3|\Theta}(x_3|\theta)\, f_{\Theta|X_1,X_2}(\theta|x_1,x_2)$$

With $x_3 = 2$, we do not shrink the range of θ, and therefore

$$f_{\Theta|X_1,X_2,X_3}(\theta|x_1,x_2,x_3) \propto \begin{cases} 1/\theta^3 & 7 \leqslant \theta \leqslant 10 \\ 0 & \text{otherwise.} \end{cases}$$

We apply Bayes' rule for one more time,

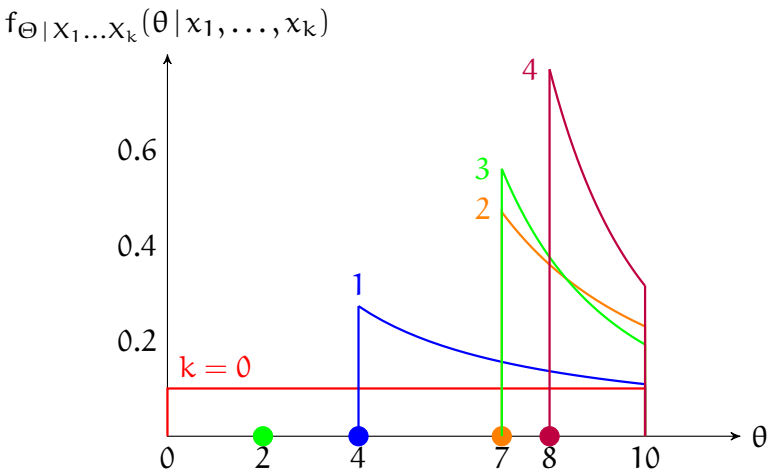
$$f_{\Theta|X_1,X_2,X_3,X_4}(\theta|x_1,x_2,x_3,x_4) \propto f_{X_4|\Theta}(x_4|\theta)\, f_{\Theta|X_1,X_2,X_3}(\theta|x_1,x_2,x_3)$$

With $x_4 = 8$, we have

$$f_{\Theta|X_1,X_2,X_3,X_4}(\theta|x_1,x_2,x_3,x_4) \propto \begin{cases} 1/\theta^4 & 8 \leqslant \theta \leqslant 10 \\ 0 & \text{otherwise.} \end{cases}$$

Recursive learning

Visualizing the results in plots:



Recursive learning

MAP rule is to maximize $f_{\Theta|X_1\ldots X_k}(\theta|x_1,\ldots,x_k)$.

- With only x_1, the maximum is at $\theta = 4$.
- With x_1 and x_2, the maximum is at $\theta = 7$.
- With x_1 to x_3, the maximum is at $\theta = 7$.
- With x_1 to x_4, the maximum is at $\theta = 8$.
- Every additional data point changes our belief about the random variable Θ.

1. Maximum a posteriori (MAP)
2. MAP estimation examples
3. Comparing MAP and ML estimations
4. Least mean square (LMS) estimate
5. Conjugate prior
6. Sequential learning with MAP
7. Hypothesis testing

Hypothesis testing as an estimation problem

Binary hypothesis testing involves deciding between two "hypotheses", e.g., $\mathbb{P}(H) = 0.5$ versus $\mathbb{P}(H) = 0.1$ for a particular coin, based on observations of outcomes.

We can look at this as a special case of parameter estimation, where θ takes on two possible values. Both ML and MAP can be used. Nevertheless, we'll introduce the specific terminologies relating to hypothesis testing.

Hypothesis testing terminology

We use H_0 and H_1 to denote the two hypotheses.

H_0 :	null hypothesis
H_1 :	alternative hypothesis

$X = (X_1, \ldots, X_n)$ is a vector of random variables whose distribution depends on the hypothesis. Certain set (or acceptance region) of X will lead us to decide on H_0; outside that set (or rejection region), we will conclude on H_1.

We are interested to find a rule to determine where the regions are.

Hypothesis testing terminology

We can have two types of errors:

Type I (false rejection) :	reject H_0 even though it is true
Type II (false acceptance) :	accept H_0 even though it is false

Type I error means X lies in the rejection region R, even when the reality should follow H_0. This occurs with probability

$$\alpha(R) = \mathbb{P}(X \in R; H_0) \tag{7}$$

Type II error means X does not lie in the rejection region R, even when the reality should follow H_1. This occurs with probability

$$\beta(R) = \mathbb{P}(X \notin R; H_1) \tag{8}$$

We often have to tradeoff between the two types of errors.

Hypothesis testing and ML

We define the likelihood ratio $L(x)$ for both discrete and continuous r.v.:

$$\boxed{L(x) = \frac{p_X(x; H_1)}{p_X(x; H_0)} \qquad \text{or} \qquad L(x) = \frac{f_X(x; H_1)}{f_X(x; H_0)}} \tag{9}$$

ML says we pick H_1 if $L(x) > 1$, and H_0 otherwise.

Hypothesis testing and MAP

Let H_0 means $\Theta = \theta_0$ with prior probability $p_\Theta(\theta_0)$, and H_1 means $\Theta = \theta_1$ with prior probability $p_\Theta(\theta_1)$. The MAP rule for $\Theta = \theta_1$ is

$$p_\Theta(\theta_0)\, p_{X|\Theta}(x|\theta_0) < p_\Theta(\theta_1)\, p_{X|\Theta}(x|\theta_1)$$

We define the likelihood ratio $L(x)$ for both discrete and continuous r.v.:

$$\boxed{L(x) = \frac{p_{X|\Theta}(x|\theta_1)}{p_{X|\Theta}(x|\theta_0)} \qquad \text{or} \qquad L(x) = \frac{f_{X|\Theta}(x|\theta_1)}{f_{X|\Theta}(x|\theta_0)}} \tag{10}$$

MAP says we pick H_1 if $L(x) > \zeta$, and H_0 otherwise, with

$$\zeta = \frac{p_\Theta(\theta_0)}{p_\Theta(\theta_1)} \tag{11}$$

Example

We have a die and have two hypotheses about its fairness:

$$H_0(\text{fair die}): \quad p_X(x; H_0) = \tfrac{1}{6} \qquad x = 1, \ldots, 6$$

$$H_1(\text{loaded die}): \quad p_X(x; H_1) = \begin{cases} \frac{1}{4} & x = 1, 2 \\ \frac{1}{8} & x = 3, 4, 5, 6 \end{cases}$$

1. For $x = 1, 2$: $L(x) = \dfrac{1/4}{1/6} = \dfrac{3}{2}$
2. For $x = 3, 4, 5, 6$: $L(x) = \dfrac{1/8}{1/6} = \dfrac{3}{4}$

If we use ML, observing 1 or 2 will lead us to H_1, and observing 3 to 6 will lead us to H_0.

Example

If we use "MAP", we are more flexible to set ζ.

- If we set $\zeta < \frac{3}{4}$: we will reject H_0 for all x.

$$\alpha(\zeta) = 1 \qquad \beta(\zeta) = 0$$

- If we set $\zeta > \frac{3}{2}$: we will accept H_0 for all x.

$$\alpha(\zeta) = 0 \qquad \beta(\zeta) = 1$$

- If we set $\frac{3}{4} < \zeta < \frac{3}{2}$: we will accept H_0 for $x = 3, 4, 5, 6$ and reject it for $x = 1, 2$.

$$\alpha(\zeta) = \mathbb{P}(X = 1, 2; H_0) = \tfrac{1}{3}$$
$$\beta(\zeta) = \mathbb{P}(X = 3, 4, 5, 6; H_1) = \tfrac{1}{2}$$

Tradeoff

Choosing ζ represents a tradeoff in Type I and Type II errors. In fact, using the likelihood ratio as a means of deciding on the acceptance and rejection regions, reducing one type of error leads to an increase in another, given by the Neyman-Pearson Lemma.

Consider using the likelihood ratio $L(X)$ for testing, with error probabilities

$$\mathbb{P}(L(X) > \zeta; H_0) = \alpha \qquad \text{and} \qquad \mathbb{P}(L(X) \leqslant \zeta; H_1) = \beta$$

Suppose some other test results in a rejection region R achieving a smaller (or equal) false rejection probability $\mathbb{P}(X \in R; H_0) \leqslant \alpha$, then we must have

$$\mathbb{P}(X \notin R; H_1) \geqslant \beta$$

with strict inequality $\mathbb{P}(X \notin R; H_1) > \beta$ when $\mathbb{P}(X \in R; H_0) < \alpha$.

Conclusions

Parameter estimation based on observations has increasingly widespread use, especially because we are in a *data-driven* era.

Conclusions

Pierre-Simon Laplace (1749–1827) once said:
"Les questions les plus importantes de la vie ne sont en effet, pour la plupart, que des problèmes de probabilité."

Pierre-Simon Laplace

The most important questions of life are indeed, for the most part, really only problems of probability.

Maybe this is true on 20 May 2025?