The normal-normal model

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Bayesian Data Analysis and Probabilistic Programming

Credits

- Chap. 5 of *Bayes Rules! An Introduction to Applied Bayesian Modeling*
    - https://www.bayesrulesbook.com/chapter-5.html

The Normal model

- Let Y be a continuous random variable which can take values in $(-\infty,\infty)$
- The variability of Y might be well represented by a Normal model

$$Y \sim N(\mu, \sigma^2)$$

The Normal model

- The Normal pdf is

$$f(y) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(y-\mu)^2}{2\sigma^2}\right]$$

- With:

$$\begin{aligned} E(Y) &= Mode(Y) = \mu \\ Var(Y) &= \sigma^2 \\ SD(Y) &= \sigma \end{aligned}$$

Standard deviation σ

- σ provides a sense of scale for Y.
- Roughly 95% of Y values are within 2 standard deviations of μ:

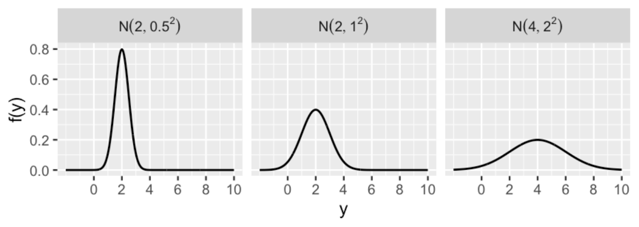
$$\mu \pm 2\sigma$$

- Roughly 99% of Y values are within 3 standard deviations of μ:

$$\mu \pm 3\sigma$$

The normal model

- The Normal model is bell-shaped and symmetric around μ.
- As σ gets larger, the pdf becomes more spread out.
- Though a Normal variable is defined in $(-\infty, \infty)$, the plausibility of values that are more than 3 standard deviations σ from the mean μ is negligible.



Example

- The volume of the hippocampus (a part of the brain) is researched in studies about the effect of concussions.
- In the general population, both halves of the hippocampus have a volume between 3.0 and 3.5 cm^3.
- Thus, the hippocampal volume is thought to vary, within the population, between 6 and 7 cm^3.
- The average volume μ is thought to be between 6.4 and 6.6 cm^3.

Normal prior

- Assuming symmetry, we formalize our prior information about μ as:

$$\mu \sim N(\mu', \sigma_\mu)$$

which in this example yields :

$$\mu \sim N(6.5, 0.05)$$

- μ' is our prior guess on the value of μ.
- σ_μ represents our uncertainty on the guess μ'.
- According to this prior, μ lies with 95% probability in (6.4, 6.6).
- We allow the volume to range over $(-\infty, \infty)$, but values beyond $\mu \pm 3\sigma$ are given negligible probability.

Normal prior

- There is no single right prior, but different reasonable priors.

Normal likelihood

- We now define a model for the distribution of the observations.
- We make a *second* assumption of normality.
- The hyppocampal volumes observed in n subjects ($y_1, y_2, ..., y_n$) are normally distributed $N(\mu, \sigma)$.

Normal likelihood

- μ is the mean volume in the population.
- σ expresses the spread of the measures within the population.
- We expect y to vary in (6-7); we interpret this interval as $\mu \pm 2\sigma$, hence it has length of 4σ.
- We thus set σ=0.25.

Independence

- We morever assume the observations $y_1, ..., y_n$ to be *independent* samples from $N(\mu, \sigma)$.
- This is realistic: the measure y_i tells us nothing about the measure y_{i+1} (assuming they refer to different subjects)

Assuming independence, the joint pdf of the n measures $(y_1, y_2, ..., y_n)$ is the product of the unique Normal pdfs $f(y_i \mid \mu)$:

$$f(\vec{y}|\mu) = \prod_{i=1}^{n} f(y_i|\mu) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(y_i - \mu)^2}{2\sigma^2}\right].$$

- $\vec{y}$ is the vector containing the measures $y_1, ...y_n$.

The Normal-Normal model

$$\mu \sim N(\mu', \sigma_\mu)$$
$$\vec{y} \sim N(\mu, \sigma)$$

- We treat μ', σ_μ and σ as fixed numbers.
- The only parameter of the model is μ.
- Later we will treat also σ as a parameter.

Your turn: normal likelihood functions

- For a Normal random sample $y_i \sim N(\mu, \sigma)$ with σ=10 we observe:

$$y_1, y_2, y_3 = (-4.3, 0.7, -19.4)$$

- Specify and plot the corresponding likelihood function of μ.

Conjugacy of the normal-normal model

- Denote the sample mean as $\bar{y} = \frac{1}{n}\sum_i y_i$.
- The posterior density of μ is normal with updated parameters:

$$\mu|\vec{y} \;\sim\; N\Bigg(\underbrace{\mu' \frac{\sigma^2}{n\sigma_\mu^2 + \sigma^2} + \bar{y}\frac{n\sigma_\mu^2}{n\sigma_\mu^2 + \sigma^2}}_{\text{posterior mean}}, \underbrace{\frac{\sigma_\mu^2 \sigma^2}{n\sigma_\mu^2 + \sigma^2}}_{\text{posterior variance}}\Bigg).$$

Posterior mean

$$\mu|\vec{y} \;\sim\; N\left(\mu' \frac{\sigma^2}{n\sigma_\mu^2 + \sigma^2} + \bar{y}\frac{n\sigma_\mu^2}{n\sigma_\mu^2 + \sigma^2},\; \frac{\sigma_\mu^2\sigma^2}{n\sigma_\mu^2 + \sigma^2}\right).$$

- The posterior mean is a weighted average of the prior mean μ' and the sample mean $\bar{y}$.
- As n increases, the posterior mean converges to $\bar{y}$.
- As n increases, the posterior variance decreases.

Your turn

- Which is the posterior mean, if we did 5 measures with $\bar{y} = 6.7$?
- Which is the posterior mean, if we did 35 measures with $\bar{y} = 6.7$?

Treating σ as a parameter

- A more sophisticated approach is to treat σ as a parameter.
- We assigning a prior to it; it should cover a wide range of plausible values for σ, leaving out however values that make no sense.
- In this case there is no closed-form expression of the posterior.

Half-normal distribution

- σ is strictly positive; a suitable prior is the *half-normal* distribution.
- The half-normal is a Gaussian restricted to positive values.
- Sample s from a half-normal are obtained by:
  - sampling from a normal distribution
  - applying the absolute value to the sampled values
  - $s \sim |N(0, \xi)|$, where ξ is the standard deviation of the underlying normal. It is referred to as the *scale* of the half-normal.

The half-normal distribution

- The HN pdf is asymmetric and right-skewed.
- It has long tails which are much larger than the median.

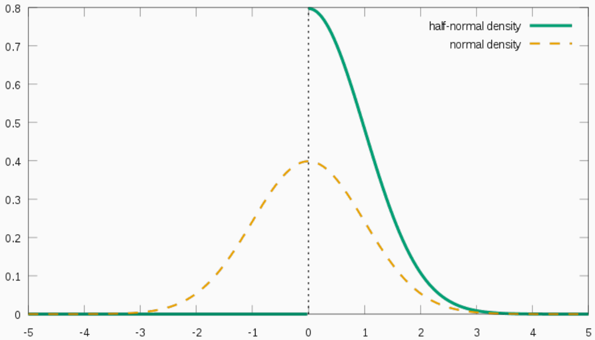
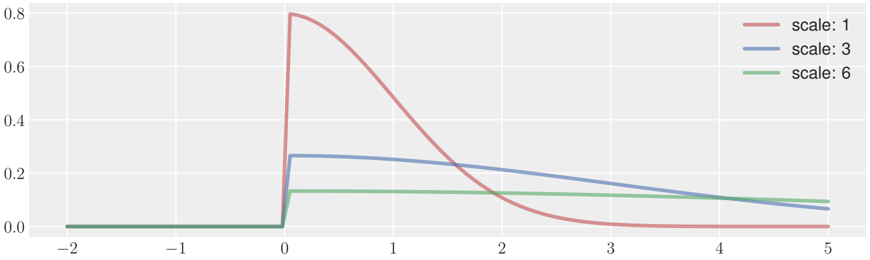


Figure 1: from wikipedia

Effect of the scale parameter

- The half-normal pdf is characterized by a scale parameter (the standard deviation of the underlying normal).



Tuning the half-normal distribution

- You can tune the scale of the HN by considering a plausible value of σ, and choose the scale so that it is close to the median of the HN.
- E.g., assume a plausible value of σ is 7.5.
- With 95% probability the measures are lie in an interval of ± 15 around the mean.
- But we are uncertain about this statement, as the interval could be well of ± 30 .

Tuning the half-normal distribution

- We try different scales, until the median is about 7.5.
- Notice the long tails of the distribution, which allows to model to correct if our prior median guess (7.5) is underestimated.

```
pd.DataFrame(halfnorm.rvs(size=1000, scale=11)).describe()
```

```
##                  0
## count  1000.000000
## mean      8.537373
## std       6.460674
## min       0.016756
## 25%       3.421440
## 50%       7.163258
## 75%      12.232990
## max      37.524301
```

Probabilistic model with σ as parameter

$\mu \sim N(\mu_\mu, \sigma_\mu)$	prior beliefs about μ
$\sigma \sim \text{Half-Normal}(\sigma_\sigma)$	prior beliefs about σ
$y \sim N(\mu, \sigma)$	the observation are normally distributedσ

- We cannot treat this model analytically, as the prior are no longer conjugates.
- We will implement it later via probabilistic programming.

Conceptual exercise

- Try to define a probabilistic model of the distribution of height of adult males in Switzerland

Prior for μ

- The mean height of the population could be 175.
- Keeping our prior broad, we state the mean height of the population to lie with 99% probability between 160 and 190 cm (the 99% interval roughly corresponds to $\mu \pm 3\sigma$).
  - $\mu \sim N(175, 5)$

Prior for σ

- We shall now assign a prior to σ. Within the population, we assume the height to lie with 99% probability between 100 and 250 (broad but realistic range).

- Hence the corresponding value of the standard deviation is (250-100)/6 = 25.

Tuning the half-normal

- A half-normal distribution with scale 35 has roughly median 25:

```
pd.DataFrame(halfnorm.rvs(size=1000, scale=35)).describe()
```

```
##                  0
## count  1000.000000
## mean     27.274481
## std      20.789165
## min       0.039510
## 25%      10.467055
## 50%      22.829115
## 75%      39.262192
## max     106.729979
```

Likelihood (distribution of the data)

- Under the assumption of normality and independence, the likelihood is:

$$y \sim \mathcal{N}(\mu, \sigma)$$

- No further specification is required.

The resulting model

$$\mu \sim N(175, 5)$$
$$\sigma \sim \text{half-normal}(35)$$
$$\vec{y} \sim N(\mu, \sigma)$$

Solution for the exercise on normal likelihood functions

- Compute the likelihood as a function of μ for a normal sample with σ=10, given the observations:

$$y_1, y_2, y_3 = (-4.3, 0.7, -19.4)$$

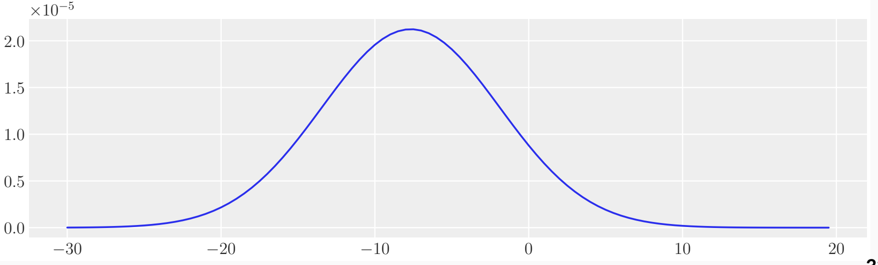
Solution

```
#based on the observations, plausible values of mu
#range between -30 and 20.
mu = np.arange(-30, 20, 0.5)
sigma = 10

#a likelihood value for each value of mu
lik = norm.pdf(-4.3, loc=mu, scale=sigma)

#under independence, the likelihood of each observation multiplies
lik = lik * norm.pdf(0.7, loc=mu, scale=sigma)
lik = lik * norm.pdf(-19.4, loc=mu, scale=sigma)

plt.figure(figsize=(10, 3))
plt.plot(mu, lik)
```



Solution

- The values in the previous slide are numerically small. With more data, and more likelihood multiplication, it will become numerically untractable.
- For this reason it is numerically better to work with the log of the likelihood (log-likelihood).