22S:138
Bayes factors

Lecture 19
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Bayes factors for model comparison and hypothesis testing

- simplest case: null and alternative hypotheses both simple
- equivalently: comparing two models that differ according to point values of one parameter

Bayes' rule applied to the example (from lectures 1)

You take the blood test and the result is positive (+). This is the data or observation.

MODEL	Prior	Like for +	Product	Posterior
Have disease	.001	.95	.00095	.019
Don't have disease	.999	.05	.04995	.981
			.05090	1

Hypothesis-testing view:

$$H_0: \ p = 0.05$$
$$H_A: \ p = 0.95$$

"simple hypotheses" regarding probability of positive test

Model	description	prior probability
M_0	don't have disease	.999
M_1	have disease	.001

Equivalently

Hypothesis	description	prior probability
H_0	p = .05	.999
H_1	p = .95	.001

Prior odds in favor of Model 1 vs. Model 0:

$$\frac{Pr(M_1)}{Pr(M_0} = \frac{.001}{.999} = \frac{1}{999}$$

Bayes factor in favor of Model 1 vs. Model 0

$$BF_{10} = \frac{Pr(data|M_1)}{Pr(data|M_0)} = \frac{.95}{.05} = 19$$

where "data" is positive test

Bayes factor in simple/simple case

- BF_{10} is weight of evidence contained *in the data* in favor of M_1 vs M_0
- usually reported on $\log_{10}$ scale
- interpretation (Kass and Raftery, JASA, 1995)

$\log_{10}(B_{10})$	B_{10}	Evidence against H_0 (or M_0)
0 to 1/2	1 to 3.2	Not worth more than bare mention
1/2 to 1	3.2 to 10	Substantial
1 to 2	10 to 100	Strong
> 2	> 100	Decisive

Posterior probabilities and posterior odds

- posterior odds in example
$$\frac{Pr(M_1|data)}{Pr(M_0|data)} = \frac{.019}{.981} = .0194$$
- relationship among BF, posterior odds and prior odds in simple/simple case
$$BF_{10} = \frac{\frac{Pr(M_1|data)}{Pr(M_0|data)}}{\frac{Pr(M_1)}{Pr(M_0)}}$$

  BF is ratio of posterior odds to prior odds

Before considering more general case, recall Bayes' rule:

$$p(\boldsymbol{\theta}|\mathbf{y}) = \frac{p(\boldsymbol{\theta})p(\mathbf{y}|\boldsymbol{\theta})}{\int p(\boldsymbol{\theta})p(\mathbf{y}|\boldsymbol{\theta})d\boldsymbol{\theta}}$$

Denominator is:

$$\begin{aligned} & \int p(\boldsymbol{\theta})p(\mathbf{y}|\boldsymbol{\theta})d\boldsymbol{\theta} \\ = & \int p(\boldsymbol{\theta}, \mathbf{y})d\boldsymbol{\theta} \\ = & \; p(\mathbf{y}) \end{aligned}$$

- the "marginal likelihood" of the data
- depends on
  - data
  - model (*form* of likelihood and prior)

More general case

To compare two competing models, M_1 and M_0:

- Compute the marginal likelihood of the data under each model
  - let $\boldsymbol{\theta}_1$ = parameters under M_1
  - let $\boldsymbol{\theta}_0$ = parameters under M_0

$$\begin{aligned} p(\mathbf{y}|M_1) &= \int p(\boldsymbol{\theta}_1)p(\mathbf{y}|\boldsymbol{\theta}_1)d\boldsymbol{\theta}_1 \\ p(\mathbf{y}|M_0) &= \int p(\boldsymbol{\theta}_0)p(\mathbf{y}|\boldsymbol{\theta}_0)d\boldsymbol{\theta}_0 \\ BF_{10} &= \frac{p(\mathbf{y}|M_1)}{p(\mathbf{y}|M_0)} \end{aligned}$$

More general case

$$H_0 : \theta \in \Theta_0$$
$$H_1 : \theta \in \Theta_1$$

Bayesian hypothesis test involves calculating posterior probabilities:

$$P(\Theta_0|\mathbf{y})$$
$$P(\Theta_1|\mathbf{y})$$

Example

- Child is given intellignce test, with resulting score Y.
- $Y \sim N(\theta, 100)$
  - where θ represents child's own true IQ
  - 100 is variance if same child takes repeated IQ tests of the same kind
- in population as a whole, IQ scores are distributed as:

$$\theta \sim N(100, 225)$$

- if child scores $y = 115$, then posterior distribution of θ is:

$$(\theta|y) \sim N(110.4, 69.2)$$

Example continued

$$H_0 : \theta \leq 100$$
$$H_1 : \theta > 10$$

Prior probabilities and prior odds:

$$\begin{aligned} p(\theta) &= N(100, 225) \\ -> & Pr(\theta \leq 100) = .5 \\ & Pr(\theta > 100) = .5 \end{aligned}$$

Prior odds - $\frac{0.5}{0.5} = 1$

Posterior probabilities and odds:

$$Pr(\theta \leq 100|y) = .106$$
$$Pr(\theta > 100|y) = .894$$

posterior odds

$$\frac{0.106}{0.894} = 0.119$$

Bayes factor in favor of H_0 vs H_1 is

$$BF_{01} = \frac{\frac{0.106}{0.894}}{\frac{0.5}{0.5}} = 0.119$$

Baeys factor in favor of H_1 vs H_0 is

$$BF_{10} = 8.44$$

Bayesian hypothesis testing and frequentist p-values

- In one-sided testing situations like this, frequentist p-value will sometimes have a Bayesian justification.
- Example:
  - normal likelihood, variance known
$$Y \sim N(\theta, \sigma^2)$$
  - noninformative prior
$$p(\theta) \propto 1$$
  - posterior
$$p(\theta|y) \sim N(y, \sigma^2)$$

- Hypotheses
$$H_0 : \theta \leq \theta_0$$
$$H_1 : \theta > \theta_0$$
- posterior probability of H_0
$$Pr(\theta \leq \theta_0|y) = \Phi\left(\frac{\theta_0 - y}{\sigma}\right)$$
- classical p-value
$$pval = Pr(Y \geq y|\theta = \theta_0) = 1 - \Phi\left(\frac{y - \theta_0}{\sigma}\right)$$
- By symmetry of normal distribution, $Pr(\theta \leq \theta_0|y) =$ p-value against H_0

Testing a point null hypothesis

- common in frequentist practice
$$H_0 : \theta = \theta_0$$
$$H_1 : \theta \neq \theta_0$$
- where θ could have any value on a continuum
- Bayesian answers may differ radically from frequentist answers
- almost never do we seriously consider that $\theta = \theta_0$ exactly
- more reasonable:
$$H_0 : \theta \in (\theta_0 - b, \theta_0 + b)$$
  for some small b
  "region of indifference"

Consider Bayesian test of point null so as to compare with frequentist

$$H_0 : \theta = \theta_0$$
$$H_1 : \theta \neq \theta_0$$

- cannot use a continuous prior on θ
  Why?
- reasonable approach to constructing a prior
  - put positive prior *probability* on θ_0
$$Pr(\theta = \theta_0) = \pi_0 > 0$$
  - give $\{\theta : \theta \neq \theta_0\}$ the prior
$$(1 - \pi_1)g_1(\theta)$$
    where
    - g_1 is a proper density

Bayesian analysis

- let $f(\mathbf{y}|\theta)$ denote the sampling density of $\mathbf{y}$
- then the marginal likelihood is

$$m(\mathbf{y}) = f(\mathbf{y}|\theta_0)\pi_0 + m_1(\mathbf{y})(1-\pi_0)$$

where

$$m_1(\mathbf{y}) = \int_{\theta \neq \theta_0} f(\mathbf{y}|\theta) g_1(\theta) d\theta$$

- so posterior probability of H_0 is

$$Pr(\theta = \theta_0|\mathbf{y}) = \frac{f(\mathbf{y}|\theta_0)\pi_0}{f(\mathbf{y}|\theta_0)\pi_0 + m_1(\mathbf{y})(1-\pi_0)}$$

- posterior odds in favor of H_0 vs H_1

$$\frac{\pi_0}{1-\pi_0}\frac{f(\mathbf{y}|\theta_0)}{m_1(\mathbf{y})}$$

- and the Bayes factor in favor of H_0 vs H_1 is

$$BF_{01} = \frac{f(\mathbf{y}|\theta_0)}{m_1(\mathbf{y})}$$

Example: child's intelligence

- sampling distribution of data

$$f(y|\theta) = N(\theta, \sigma^2 = 100)$$

- hypotheses to be tested

$$H_0: \theta = 100$$
$$H_1: \theta \neq 100$$

- priors

$$Pr(\theta = 100) = \pi_0 = 0.5$$
$$g_1(\theta) = N(\mu_0, \sigma_0^2) = N(100, 100)$$

  - note: prior mean $\mu_0 = \theta_0$ (value from H_0)
  - prior variance σ_0^2 equals variance of sampling distribution

Example continued

- What statistical test would a frequentist use when sampling distribution is assumed to be normal with known variance?
- results for frequentist test with different possible data values y

y	z	frequentist p-value	$Pr(H_0\|y)$
116.45	1.645	0.1	0.42
119.60	1.960	0.05	0.35
125.76	2.576	0.01	0.21
132.91	3.291	0.001	0.086

Similar table for different sample sizes

- Table 4.2, p. 151 from
  Berger, JO (1985) *Statistical Decision Theory and Bayesian Analysis, 2nd ed.*, New York, Springer-Verlag
- applies when σ^2 is assumed known, $\mu_0 = \theta_0$, $\pi_0 = 0.5$, $\sigma_0^2 = \sigma^2$