An Introduction to Bayesian Statistics - I

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Overview

1. Big idea behind Bayesian statistics
   - Bayes' theorem
   - Terminology explanation
   - Bayesian vs frequentist
2. Prior types
   - By reasoning
   - By mathematical property
3. Three examples in R
   - Coin flip example
   - Logistic regression example
   - Linear regression example

Big Idea behind Bayesian Statistics

Figure 1: Thomas Bayes, 1701-1761

- Treat probability as a **degree of belief**

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- Treat probability as a **degree of belief**
- Continually update our prior beliefs about events as new evidence is presented
- Probabilistic reasoning leads to probabilistic results

Bayes Reasoning

Bayes' Theorem

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

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Posterior Distribution

$$P(A|B) \propto P(B|A) \times P(A)$$

$$P(\text{parameter}|\text{data}) \propto P(\text{data}|\text{parameter}) \times P(\text{parameter})$$

$$\text{Posterior} \propto \text{Likelihood} \times \text{Prior}$$

Terminology

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- **Posterior**: the probability distribution of parameters given evidence

Bayesian vs Frequentist

Table 1: Comparison between frequentist and Bayesian

Characteristic	Frequentist	Bayesian
Probability	limiting relative frequency	degree of belief
Parameter	fixed constant	random variable
Probability statement	procedure	parameter

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  - Conjugate prior: leads to a posterior from the same parametric family as the prior
  - Non-conjugate prior: does not result in a posterior from the same parametric family as the prior

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- Let θ be the probability of heads, n be the number of tosses, and y be the number of heads in n tosses
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- What's the estimate of θ?
- Frequentist: $\hat{\theta}_{\text{ML}} = y/n$
- Bayesian:
  (1) choose a prior of θ
  (2) calculate posterior distribution
  (3) $\hat{\theta}_{\text{Bayes}} =$ posterior mean

Coin Flip Example - Conjugate Prior

- Consider a conjugate prior $\theta \sim \text{Beta}(\alpha, \beta)$ and the likelihood $y|\theta \sim \text{Bin}(n, \theta)$, then

$$\begin{aligned}
\theta|y &\propto \text{prior} \times \text{likelihood} \\
&\propto \text{Beta}(\alpha, \beta) \times \text{Bin}(n, \theta) \\
&\propto \theta^{\alpha-1}(1-\theta)^{\beta-1} \times \theta^{y}(1-\theta)^{n-y} \\
&= \theta^{\alpha+y-1}(1-\theta)^{\beta+n-y-1}.
\end{aligned}$$

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- The posterior distribution $\theta|y \sim \text{Beta}(\alpha + y, \beta + n - y)$.
- The Bayes estimator is the posterior mean, $\hat{\theta}_{\text{Bayes}} = \frac{\alpha+y}{\alpha+\beta+n}$.

Coin Flip Example - Conjugate Prior

- Set up

```
##Coin flip
set.seed(98712)
n        <- n_post <- 10^5
y        <- rbinom(1,n,.48)
alpha    <- 2
beta     <- 2
```

- Specify prior and likelihood

```
set.seed(3878)
th_pror   <- rbeta(n_post,alpha,beta)
plot(density(th_pror),xlab=expression(theta[prior]),main="")

y_like    <- rbinom(n_post,n,y/n)
plot(density(y_like),xlab="y, number of heads",main="")
```

Coin Flip Example - Conjugate Prior

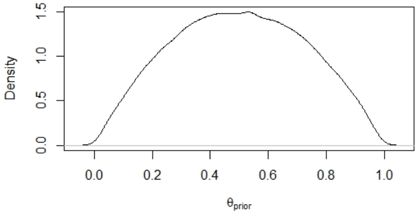

Figure 2: Prior density of θ

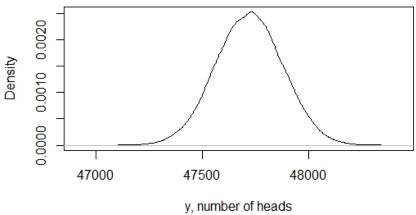

Figure 3: Likelihood of $y|\theta$

Coin Flip Example - Conjugate Prior

- Draw a posterior sample

```
th_post  <- rbeta(n_post,alpha+y,beta+n-y)
plot(density(th_post),xlab=expression(theta[post]),main="")
abline(v=y/n,col="darkgreen",lty=2,lwd=2)
abline(v=(alpha+y)/(alpha+beta+n),col="blue",lwd=2)
legend(.471,250,c("ML","Bayes"),col=c("darkgreen","blue"),
       pch=rep(19,2),bty="n")
legend(.478,250,"ML and Bayes estimates \n almost the same",bty="n")
```

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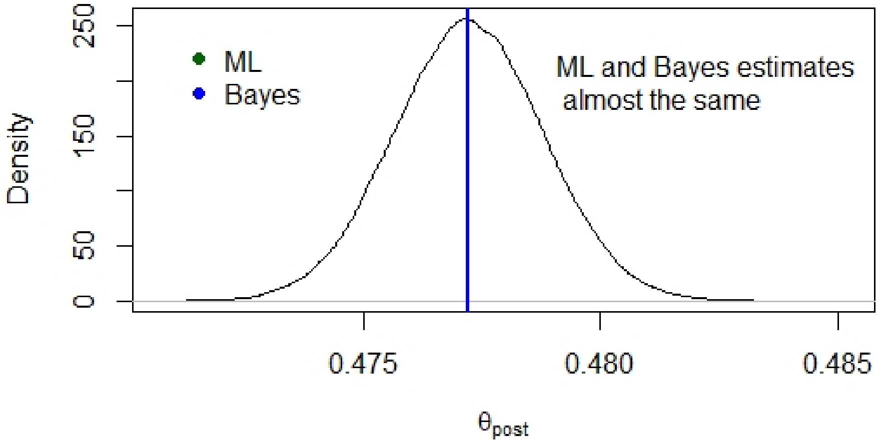

Figure 4: Posterior density of θ

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- The posterior $P(\beta_k|y) \propto p^y(1-p)^{(n-y)} \times exp^{-\frac{1}{2\sigma^2}\beta_k^2}$ doesn't lead to a recognizable distribution.

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- How can we conduct inference with this beast of a posterior distribution?

Moving Away From a Conjugate Prior

Basic Bayesian Steps

1. Select a model and priors
2. Approximate the posterior via Markov chain Monte Carlo
3. Check the posterior approximation (e.g. sufficient samples)
4. Use the MCMC samples to conduct inference

You can either code it yourself or use one of the MANY packages on CRAN.

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     1. Propose new values based on the current parameter values
     2. Move to the proposed values with some probability, or stay at the current position with the complementary probability
- The exact method of selecting proposed values and calculating the probability of moving depends on the exact MCMC sampler.

Approximating the Posterior via MCMC

- Some packages (such as `mcmc`) focus on the MCMC (independent of the model/context) and are therefore **more general**.
- `mcmc` simulates using a user-inputted log unnormalized posterior density.

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- `mcmc` simulates using a user-inputted log unnormalized posterior density.
- Some packages (such as `MCMCpack`) contain functions to perform **specific methods of Bayesian inference**.
- `MCMCpack` does MCMC in the context of specific statistical models.

Logistic Regression Example - Non-conjugate Prior

- Set up

```
library(mcmc)
data(logit)
out <- glm(y~x1,data=logit,family=binomial,x=TRUE)

lupost_factory <- function(x,y)function(beta){
   eta  <- as.numeric(x%*%beta)
   logp <- ifelse(eta<0,eta-log1p(exp(eta)),-log1p(exp(-eta)))
   logq <- ifelse(eta<0,-log1p(exp(eta)),-eta-log1p(exp(-eta)))
   logl <- sum(logp[y==1])+sum(logq[y==0])
   return(logl-sum(beta^2)/8)
   }
lupost <- lupost_factory(out$x,out$y)
```

- Construct the log posterior density

```
set.seed(317)
beta.init <- as.numeric(coefficients(out))
out <- metrop(lupost,beta.init,1e3)
names(out)
out$accept
```

Logistic Regression Example - Non-conjugate Prior

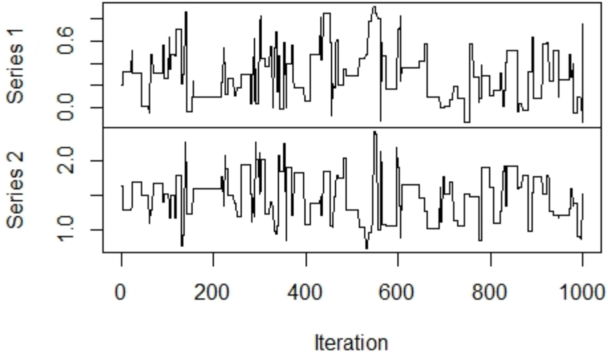

Figure 5: Trace plot of $\hat{\beta}_0$ and β_1

Linear Regression Example

- **Bikeshare dataset**: contains the hourly and daily count of rental bikes between years 2011 and 2012 in Capital bikeshare system with the corresponding weather and seasonal information.

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- **Objective**: investigate if feel like temperature is significantly related to number of registered riders.

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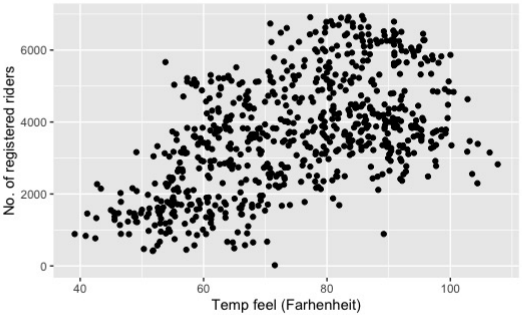

Figure 6: Scatter plot of feel like temperature and number of registered riders

Linear Regression Example

- Let Y_i be the number of registered riders and x_i be the feels like temperature (Fahrenheit) on date $i = 1, ..., n$, then the linear regression model is
$$y_i = \beta_0 + \beta_1 x_i + \epsilon_i.$$

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$$y_i = \beta_0 + \beta_1 x_i + \epsilon_i.$$
- Random error: $\epsilon_i \overset{iid}{\sim} N(0, \sigma^2)$
- Prior specification: $\beta_0, \beta_1 \overset{indep}{\sim} N(0, 10^2), \sigma^2 \sim \text{InvGamma}(a, b)$

Linear Regression Example

- Fit the model in two ways:

```
#fit a regression model
freq.fit  <- lm(riders_registered ~ temp_feel, data=bikes)

bayes.fit <- MCMCregress(riders_registered~temp_feel,b0=0,B0=.01,
                         sigma.mu=100,sigma.var=100,data=bikes,
                         burnin=10^3,mcmc=10^5)
```

Linear Regression Example

- Bayesian: $\hat{y} = -665.6 + 57.9x$, frequentist: $\hat{y} = -667.9 + 57.9x$

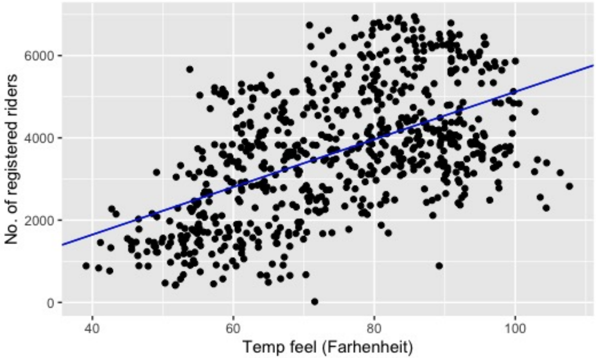

Figure 7: Regression lines and scatter plot of feel like temperature and number of registered riders

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```
Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) -667.916    251.608  -2.655  0.00811 **
temp_feel     57.892      3.306  17.514  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1310 on 729 degrees of freedom
Multiple R-squared:  0.2961,    Adjusted R-squared:  0.2952
F-statistic: 306.7 on 1 and 729 DF,  p-value: < 2.2e-16
```

Figure 8: Coefficient summary of ordinary least square estimates

Linear Regression Example

```
Iterations = 1001:101000
Thinning interval = 1
Number of chains = 1
Sample size per chain = 1e+05

1. Empirical mean and standard deviation for each variable,
   plus standard error of the mean:

                  Mean        SD  Naive SE Time-series SE
(Intercept) -6.824e-01 9.974e+00 3.154e-02      3.154e-02
temp_feel    4.913e+01 5.783e-01 1.829e-03      1.829e-03
sigma2       1.355e+06 6.309e+04 1.995e+02      1.995e+02
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Figure 9: Coefficient summary of Bayesian estimates

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```

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```
2. Quantiles for each variable:

                  2.5%        25%        50%       75%     97.5%
(Intercept)     -20.24 -7.426e+00 -6.621e-01 6.014e+00 1.892e+01
temp_feel        48.00  4.874e+01  4.913e+01 4.952e+01 5.027e+01
sigma2      1237345.01  1.312e+06  1.353e+06 1.397e+06 1.484e+06
```

Figure 10: Quantile summary of Bayesian estimates

Linear Regression Example

- In frequentist method, the 95% confidence interval of β_1 is $\hat{\beta}_1 \pm t_{0.025,729}\mathrm{SE}(\hat{\beta}_1) \approx (51.4, 64.4)$.
- In Bayesian statistics, the 95% credible set of β_1 is (51.4, 64.3).

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- Different interpretations:

	Term	Meaning
Frequentist	confidence interval	95% certain $\beta_1 \in (51.4, 64.4)$
Bayesian	credible set	$P(51.4 \leq \beta_1 \leq 64.3) = 0.95$

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Bayesian	credible set	$P(51.4 \leq \beta_1 \leq 64.3) = 0.95$

- Both classic and Bayesian methods indicate feel like temperature has a significant association with number of registered riders.

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Summary

- Bayesian statistics treats probability as a **degree of belief** and incorporates probabilistic reasoning into analysis.
- The biggest difference between frequentist and Bayesian is that frequntist views a parameter **fixed** while it's a **random variable** in Bayesian.
- There are various choices of priors. **Domain knowledge** and **sensitivity analysis** are crucial to obtain reasonable and consistent results.
- R is your good friend!

Thank you!

Happy Friday:)

Q&A

References

James M. Flegal, John Hughes, Dootika Vats, and Ning Dai. (2018). mcmcse: Monte Carlo Standard Errors for MCMC. R package version 1.3-3. Riverside, CA, Denver, CO, Coventry, UK, and Minneapolis, MN.

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Appendix

- Data link: `https://www.macalester.edu/~dshuman1/data/155/bike_share.csv`
- Posterior derivation in linear regression example:

$$
\begin{aligned}
P(\beta_0|\cdot) &\propto \text{likelihood} \times \text{prior} \\
&\propto \prod_{i=1}^{n} P(y_i|\beta_0) \times P(\beta_0) \\
&\propto \prod_{i=1}^{n} \exp^{-\frac{1}{2\sigma^2}(y_i-\beta_0-\beta_1 x_i)^2} \times \exp^{-\frac{1}{2\cdot 10^2}\beta_0^2} \\
&\propto \exp^{-\frac{1}{2}\left[\left(\frac{n}{\sigma^2}+\frac{1}{10^2}\right)\beta_0^2-\frac{2}{\sigma^2}\sum_{i=1}^{n}(y_i-\beta_1 x_i)\beta_0\right]} \\
\Rightarrow \beta_0|\cdot &\sim N\left(\frac{\frac{\sum_{i=1}^{n}(y_i-\beta_1 x_i)}{\sigma^2}}{\frac{n}{\sigma^2}+\frac{1}{10^2}}, \frac{1}{\frac{n}{\sigma^2}+\frac{1}{10^2}}\right).
\end{aligned}
$$

Appendix

- Following the same technique,

$$\beta_0|\cdot \sim N\left(\frac{\frac{\sum_{i=1}^{n}(y_i-\beta_0)x_i}{\sigma^2}}{\frac{n}{\sigma^2}+\frac{1}{10^2}}, \frac{1}{\frac{n}{\sigma^2}+\frac{1}{10^2}}\right),$$

$$\sigma^2|\cdot \sim \text{InvGamma}\left(a+\frac{n}{2}, b+\frac{1}{2}\sum_{i=1}^{n}(y_i-\beta_0-\beta_1 x_i)^2\right).$$