



## **Rgbp: Bayesian Hierarchical Modeling and Frequentist Method Check**

**Joseph Kelly**  
Harvard University

**Carl Morris**  
Harvard University

**Hyungsuk Tak**  
Harvard University

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### **Abstract**

Bayesian-frequentist reconciliation via Bayesian hierarchical modeling for Gaussian, Binomial, and Poisson data and frequentist method check for good coverage probability.

*Keywords:* hierarchical model, multi-level model, random effects mixed model, method check, coverage probability, normal, binomial, poisson, shrinkage, R.

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## **1. Introduction**

**Rgbp** uses Bayesian machinery to estimate a two-level model (a random-effects mixed model) and allows for a check of its frequentist properties via a repeated sampling procedure (which we call a “method check”). It is found that even in small samples our procedure yields good frequency properties. Also, this package will be useful for Bayesians who want to see a non-informative reference point before and after constructing their full-Bayesian hierarchical model. For frequentists, it will provide confidence intervals of a random-effect mixed model with good repeated sampling properties.

## **2. Three Feasible Types of Data**

This package is intended to fit a multi-level model on the group-level (or unit-level) data in which each group-level (or unit-level) observation is believed to have the Normal, Poisson, or Binomial distribution. In this section, we will introduce three specific types of feasible datasets.

## 2.1. Normal: 8 School Data

Education Testing Service conducted randomized experiments in eight separate schools and obtained this dataset. It contains the coaching effects on SAT scores ( $y_j, j = 1, \dots, 8$ ) and standard errors ( $se_j, j = 1, \dots, 8$ ) of eight schools obtained after an analysis of covariance adjustment (Rubin, 1981).

```
R> y <- c(28, 8, -3, 7, -1, 1, 18, 12)
R> se <- c(15, 10, 16, 11, 9, 11, 10, 18)
```

In the original paper, each school's coaching effect has approximately Normal sampling distribution with known sampling variance, *i.e.*, standard error of each school is assumed to be known or to be accurately estimated. So, it is reasonable to think that each (group-level) coaching effect is distributed as independent Normal distribution given the unknown mean  $\mu_j$  and known standard error:  $y_j | \mu_j \stackrel{ind}{\sim} \text{Normal}(\mu_j, se_j^2)$ ,  $j = 1, \dots, 8$ . **Rgbp** includes this dataset and can be called by typing 'R> data(schools)' on R.

## 2.2. Poisson: 31 Hospital Data

This dataset is about the medical profiling evaluations for Coronary Artery Bypass Graft (CABG) surgeries of 31 New York hospitals conducted in 1992 (Morris and Lysy, 2012). It comprises of the number of deaths within a month of CABG surgeries in each hospital ( $z_j, j = 1, \dots, 31$ ) and total number of patients receiving CABG surgeries (case load) in each hospital ( $n_j, j = 1, \dots, 31$ ). The below code is an example of input based on the last ten hospital data.

```
R> z <- c( 14, 9, 15, 13, 35, 26, 25, 20, 35, 27)
R> n <- c(593, 602, 629, 636, 729, 849, 914, 940, 1193, 1340)
```

Considering the type of data, it makes sense to assume the number of deaths in each hospital has independent Poisson distribution given the unknown parameter  $\lambda_j$ :  $z_j | \lambda_j \stackrel{ind}{\sim} \text{Poisson}(n_j \lambda_j)$ ,  $j = 1, \dots, 31$ , where  $n_j$  can be interpreted as an exposure (not necessarily an interger). This dataset is also included in the package and can be called by 'R> data(hospital)' on R.

## 2.3. Binomial: 18 Baseball Data

This dataset contains information about batting averages of 18 major league players through their first 45 official at-bats of the 1970 season (Efron and Morris, 1975). Also, it has two covariates, League and Position, showing in which league and in which position each player was playing. In this paper, we will use Position for a tutorial purpose. For convenience, we transform this variable into a binary indicator, which is 1 if a player was a outfielder and 0 otherwise. The code below shows a way to make inputs. If we have more than one covariate, for example, x1 and x2, then 'R> x <- cbind(x1, x2)' will be the right input of the **gbp** function.

```
R> z <- c(18, 17, 16, 15, 14, 14, 13, 12, 11, 11, 10, 10, 10, 10, 9, 8, 7)
R> n <- c(45, 45, 45, 45, 45, 45, 45, 45, 45, 45, 45, 45, 45, 45, 45, 45, 45)
R> x <- c( 1, 1, 1, 1, 1, 0, 0, 0, 0, 1, 0, 0, 0, 1, 1, 0, 0)
```

The data indicate that independent Binomial distribution is appropriate for each player's number of hits among 45 at-bats conditioning on the unknown parameter  $p_j$ :  $z_j|p_j \stackrel{ind}{\sim}$  Binomial( $n_j, p_j$ ),  $j = 1, \dots, 18$ . This dataset is also a part of the package and can be called on R by 'R> data(baseball)'.

### 3. Multi-level Structure

Our multi-level model, also called a conditionally independent hierarchical model (Kass and Steffey, 1989), is a very powerful tool for exploring the hierarchical structure in data. For example, we can think about a district-level hierarchy (bigger population) for 8 schools, the state-level hierarchy for 31 hospitals, and the position-level hierarchy for 18 baseball players. **gbp**, one of functions in **Rgbp**, fits such a hierarchical model whose first-level hierarchy has a distribution of observed data and second-level (bigger population hierarchy) has a conjugate prior distribution on the first-level parameter. Users can determine one of three types of multi-level models, such as Normal-Normal, Poisson-Gamma, and Binomial-Beta, based on their datasets.

#### 3.1. Normal-Normal

**gbp** can construct a two-level Normal-Normal hierarchical model on the 8 school data. For reference,  $\sigma_j^2$  below is assumed to be known or to be accurately estimated, and subscript  $j$  indicates  $j$ -th school in the dataset.

$$y_j|\mu_j \stackrel{ind}{\sim} \text{Normal}(\mu_j, \sigma_j^2), \quad (1)$$

$$\mu_j|\beta, A \stackrel{ind}{\sim} \text{Normal}(\mu_{0j}, A), \quad (2)$$

where  $\mu_{0j} = x_j^T \beta$ ,  $j = 1, \dots, 8$ ,  $x_j$  is  $j$ -th school's covariate vector ( $m \times 1$ ), and  $m$  is the number of regression coefficients. Note that if there is no covariate then  $m$  is 1 for an intercept term, making  $\mu_{0j} = \mu_0 = \beta_0$  for all  $j$ . For reference, a parameter with a zero subscript,  $\mu_{0j}$ , represents a mean parameter of the prior (second-level) distribution. Also, Based on this conjugate prior distribution, it is easy to derive corresponding posterior distribution.

$$\mu_j|y, \beta, A \stackrel{ind}{\sim} \text{Normal}((1 - B_j)y_j + B_j\mu_{0j}, (1 - B_j)\sigma_j^2), \quad (3)$$

where  $B_j \equiv \frac{\sigma_j^2}{\sigma_j^2 + A}$ ,  $j = 1, \dots, 8$ , is called a shrinkages.

#### 3.2. Poisson-Gamma

**gbp** is also able to build a Poisson-Gamma multi-level model on the 31 hospital data. Note that a constant multiplied to the notation representing Gamma distribution below is a scale and a square bracket below indicates [mean, variance] of distribution. And for notational consistency, let's define  $y_j \equiv \frac{z_j}{n_j}$  for all  $j$ .

$$z_j|\lambda_j \stackrel{ind}{\sim} \text{Poisson}(n_j\lambda_j), \quad (4)$$

$$\lambda_j | \beta, r \stackrel{ind}{\sim} \frac{1}{r} \text{Gamma}(\lambda_{0j} r) \sim \text{Gamma}[\lambda_{0j}, \frac{\lambda_{0j}}{r}], \quad (5)$$

where  $\log(\lambda_{0j}) = x'_j \beta$ , and  $j = 1, \dots, 31$ . Immediate posterior distribution of this Poisson-Gamma model is

$$\lambda_j | \mathbf{z}, \beta, r \stackrel{ind}{\sim} \frac{1}{r + n_j} \text{Gamma}(r \lambda_{0j} + n_j y_j) \sim \text{Gamma}[\lambda_j^*, \frac{\lambda_j^*}{r + n_j}], \quad (6)$$

where  $\lambda_j^* \equiv (1 - B_j) y_j + B_j \lambda_{0j}$ ,  $B_j \equiv \frac{r}{r + n_j}$ , and  $y_j \equiv \frac{z_j}{n_j}$ ,  $j = 1, \dots, 31$ .

### 3.3. Binomial-Beta

Binomial-Beta hierarchical model is the last model that **gbp** can fit. Again, a square bracket below indicates [mean, variance] of distribution.

$$z_j | p_j \stackrel{ind}{\sim} \text{Binomial}(n_j, p_j), \quad (7)$$

$$p_j | \beta, r \stackrel{ind}{\sim} \text{Beta}(r p_{0j}, r(1 - p_{0j})) \sim \text{Beta}[p_{0j}, \frac{p_{0j}(1 - p_{0j})}{r + 1}], \quad (8)$$

where  $\log(\frac{p_{0j}}{1 - p_{0j}}) = x'_j \beta$  and  $j = 1, \dots, 18$ . Then posterior distribution is

$$p_j | \mathbf{z}, \beta, r \stackrel{ind}{\sim} \text{Beta}(r p_{0j} + n_j y_j, r(1 - p_{0j}) + n_j(1 - y_j)) \sim \text{Beta}\left[p_j^*, \frac{p_j^*(1 - p_j^*)}{r + n_j + 1}\right], \quad (9)$$

where  $p_j^* \equiv (1 - B_j) y_j + B_j p_{0j}$ ,  $B_j \equiv \frac{r}{r + n_j}$ , and  $y_j \equiv \frac{z_j}{n_j}$ ,  $j = 1, \dots, 18$ .

### 3.4. Hyper-prior Distribution

Hyper-prior distribution indicates a distribution of the second-level parameters, which plays an important role in deriving a full posterior distribution of all the parameters. **gbp** sets a non-informative distribution on second-level parameters to let the data speak more about their estimation.

$$\beta \sim \text{Uniform on } \mathbf{R}^m, \quad A \text{ (or } \frac{1}{r}) \sim \text{Uniform}(0, \infty), \quad (10)$$

where  $m$  is the number of regression coefficients. For  $\beta$ , it is reasonable choice to take flat (non-informative) distribution because information about the location gets informative as number of groups increases. Another flat prior on the hyper-parameter  $A$  (or  $1/r$ ) that we suggest here will guarantee a posterior propriety under the moderate conditions and will give users a good repeated sampling property.

## 4. Estimation

### 4.1. Shrinkage Estimation

Estimating shrinkage is a key part of our work because as we can see the posterior means in (3), (6), and (9) are a linear function of shrinkage and the posterior variances are also a

linear (Gaussian), quadratic (Poisson), or cubic (Binomial) function of shrinkage. Once we estimate it, we can approximate the posterior moments given only data by Adam's law, for example,  $E(\mu_j|\mathbf{y}) = E(E(\mu_j|\mathbf{y}, r, A)|\mathbf{y})$  for Gaussian model and by Eve's law, for instance,  $Var(\mu_j|\mathbf{y}) = E(Var(\mu_j|\mathbf{y}, r, A)|\mathbf{y}) + Var(E(\mu_j|\mathbf{y}, r, A)|\mathbf{y})$

## 4.2. Adjustment for Density Maximization

When it comes to estimating a shrinkage, we can notice that it is a function of the second-level variance component, *i.e.*,  $B_j \equiv \frac{\sigma^2}{\sigma^2 + A} = B_j(A)$  for Gaussian and  $B_j \equiv \frac{r}{r + n_j} = B_j(r)$  for Poisson and Binomial models.

In this case, one way is to obtain an MLE of the variance component with its asymptotic Normal distribution and then to use Delta method for asymptotic Normal distribution of shrinkage. But is the Normal approximation a good approximation for shrinkage that takes on a value between 0 and 1?

Here the adjustment for density maximization (Morris and Tang, 2011), called ADM, comes. It assumes the Beta distribution for shrinkage, which the authors believe is a much better approximation for it, and estimates its posterior moments, *i.e.*,  $E(B_j|\text{data})$  and  $Var(B_j|\text{data})$ .

## 4.3. Approximation to Posterior Distribution via Matching Moments

After estimating two posterior moments, `gbp` reasonably approximates posterior distribution given only data, *i.e.*,  $(\mu_j|\text{data})$ ,  $(\lambda_j|\text{data})$ , or  $(p_j|\text{data})$ , by matching two moments with its parameters. The reason we said 'reasonably approximates' is that it is hard to find a closed form of posterior distribution given only data unless it is a Gaussian model. So, we assumed  $(p_j|\text{data})$  had also Beta( $a_1$ ,  $a_0$ ) distribution and matched two estimated moments,  $E(p_j|\text{data})$  and  $Var(p_j|\text{data})$ , with two parameters,  $a_1$  and  $a_0$ , of this Beta distribution.

# 5. Method Check

Like the two sides of the same coin, checking a statistical model always comes with fitting a model. If a fitted model cannot pass a checking process, we usually go back to the fitting process and come back to checking process iteratively. In this sense, checking a fitted model is an interactive procedure for the model justification.

There are two kinds of model justification process; one is a model check and the other is a method check. The model check is for the justification of a hierarchical modeling on a specific dataset. One possible question is, "Can this dataset benefit from such a modeling?" Christiansen and Morris (1996) answered this question by using a mixture model,  $(z_j|\beta, r) \sim \text{Negative-Binomial}$ , for Poisson data to justify the second-level hierarchy. They found that their data had more variation than expected of the first-level Poisson distribution and Poisson hierarchical model could successfully account for such additional variation.

Once we are sure that the hierarchical modeling can be appropriate for our data, the following question will be about the validity of interval estimates. "Does the confidence interval obtained

via this Bayesian model-fitting process achieve pre-specified  $100(1 - \alpha)\%$  confidence level for any true parameter values?” Our answer is “yes” and **Rgbp** has a function to assure this point. From now on, all the explanations will be based on the Binomial model.

### 5.1. Pseudo-data Generation Process

Figure 1 will be helpful to understand this process. As we can see in (8), the distribution of each true parameter ( $p_j$ ,  $j = 1, \dots, 18$ ) depends on two hyper-parameters,  $r$  and  $\beta_{(m \times 1)}$ , where  $m$  is the number of regression coefficients. Once we fix these hyper-parameters at specific values, we can generate true parameters. Suppose we sampled 500  $\mathbf{p}_{(18 \times 1)}$ 's, *i.e.*,  $\{\mathbf{p}_{(18 \times 1)}^{(i)}, i = 1, \dots, 500\}$ . Then, we can also generate  $\{\mathbf{z}_{(18 \times 1)}^{(i)}, i = 1, \dots, 500\}$  given each  $p_{ij}$ , where  $i$  indicates  $i$ -th pseudo-dataset and  $j$  does  $j$ -th player. Next, **coverage** fits the Binomial hierarchical model 500 times on  $\{(\mathbf{z}_{(18 \times 1)}^{(i)}, \mathbf{n}_{(18 \times 1)}), i = 1, \dots, 500\}$  to obtain  $500 \times 18$  interval estimates. Taking the first player as an example, we have 500 pairs of  $(z_{i1}, p_{i1})$ ,  $i = 1, \dots, 500$ , and 500 interval estimates.

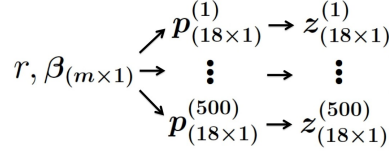


Figure 1: Pseudo-data generating process

### 5.2. Unbiased Coverage Probability

Based on the generated pseudo-datasets, let's define an indicator variable,  $I_{ij}$ , which is 1 if  $j$ -th player's interval estimate from  $i$ -th pseudo-dataset includes  $p_{ij}$  and 0 otherwise. One way to estimate the coverage probability is taking average over these indicator variables. We call it an unbiased coverage probability estimate. For example,  $\bar{I}_1 = \sum_{i=1}^{500} I_{i1} / 500$  is the estimated coverage probability for the first player.

### 5.3. Rao-Blackwellized Coverage Probability

Based on the definition of Rao-Blackwellization, we define  $E(I_{ij} | z_{ij}, r, \beta)$ , where  $r$  and  $\beta$  were fixed at first (see 5.1) and  $z_{ij}$  is a sufficient statistic. This expectation is the same as  $\Pr(\hat{p}_{ij,low} \leq p_{ij} \leq \hat{p}_{ij,upp} | z_{ij}, r, \beta)$ , where  $(\hat{p}_{ij,low}, \hat{p}_{ij,upp})$  is  $j$ -th player's interval estimates (numeric values) on the  $i$ -th dataset. We can calculate this probability exactly because we know the distribution of  $(p_{ij} | z_{ij}, r, \beta)$  in (9). Then, we can estimate the first player's coverage probability, for instance, by  $\sum_{i=1}^{500} E(I_{i1} | z_{i1}, r, \beta) / 500$ .

## 6. Example

### 6.1. 31 Hospitals: Known Second-level Mean

If you, living in the New York state (NY), were suffering from severe coronary heart dis-

ease (hopefully not), and were supposed to receive the coronary artery bypass graft (CABG) surgery, your concern might be each hospital's ability to handle this surgery.

For this purpose, you gathered data of 31 hospitals in NY composed of the number of deaths within a month of CABG surgeries and total number of patients receiving CABG surgeries in each hospital. In addition, suppose you could obtain the state-level death rate of this surgery while you were looking for such information, which was 0.02. From this point, there are a lot of ways to explore those data to have an idea about each hospital's ability.

One way we suggest here is a hierarchical modeling assuming that there is a bigger population-level hierarchy. In this case, for example, we presume that there is a state-level (NY) hierarchy governing the true death rates of CABG surgery of all the hospitals in NY. Then, we can consider the true death rates of those 31 hospitals were sampled from this state-level population distribution whose mean is 0.02. The validity of such an assumption can be checked (Christiansen and Morris, 1996).

Once we are sure that the assumption of an additional hierarchy is reasonable, we start a model-fitting process. Since the true death rate after CABG surgery might be small and caseloads ( $n_j$ ) look relatively much bigger than the number of deaths ( $z_j$ ), the Poisson distribution would be our first choice to describe the uncertainty in our data. Next, `gbp` will help us fit a multi-level model with the Gamma conjugate distribution for  $\lambda_j$  on the second-level hierarchy whose mean is 0.02 ( $\lambda_0 = 0.02$ ) as described in the section 3.2.

```
R> p <- gbp(z, n, mean.PriorDist = 0.02, model = "pr")
R> p
```

Summary for whole observations:

	obs.mean	n	prior.mean	shrinkage	intv.low	post.mean	intv.upp	post.sd
1	0.045	67	0.02	0.834	0.011	0.024	0.042	0.008
2	0.029	68	0.02	0.832	0.010	0.022	0.038	0.007
3	0.024	210	0.02	0.616	0.011	0.021	0.035	0.006
4	0.043	256	0.02	0.568	0.017	0.030	0.046	0.008
5	0.033	269	0.02	0.556	0.015	0.026	0.041	0.007
6	0.044	274	0.02	0.551	0.018	0.031	0.047	0.008
7	0.043	278	0.02	0.548	0.018	0.030	0.047	0.007
8	0.014	295	0.02	0.533	0.008	0.017	0.029	0.005
9	0.029	347	0.02	0.492	0.014	0.024	0.038	0.006
10	0.037	349	0.02	0.491	0.017	0.029	0.043	0.007
11	0.039	358	0.02	0.484	0.018	0.030	0.045	0.007
12	0.018	396	0.02	0.459	0.010	0.019	0.030	0.005
13	0.028	431	0.02	0.438	0.015	0.024	0.037	0.006
14	0.025	441	0.02	0.433	0.013	0.023	0.035	0.005
15	0.027	477	0.02	0.414	0.015	0.024	0.036	0.006
16	0.045	484	0.02	0.410	0.023	0.035	0.050	0.007
17	0.030	494	0.02	0.405	0.016	0.026	0.039	0.006

18	0.022	501	0.02	0.402	0.012	0.021	0.032	0.005
19	0.028	505	0.02	0.400	0.015	0.025	0.036	0.005
20	0.020	540	0.02	0.384	0.012	0.020	0.031	0.005
21	0.028	563	0.02	0.374	0.016	0.025	0.037	0.005
22	0.024	593	0.02	0.362	0.014	0.022	0.033	0.005
23	0.015	602	0.02	0.358	0.010	0.017	0.026	0.004
24	0.024	629	0.02	0.348	0.014	0.023	0.033	0.005
25	0.020	636	0.02	0.346	0.012	0.020	0.030	0.005
26	0.048	729	0.02	0.316	0.027	0.039	0.053	0.007
27	0.031	849	0.02	0.284	0.019	0.028	0.038	0.005
28	0.027	914	0.02	0.269	0.017	0.025	0.035	0.005
29	0.021	940	0.02	0.264	0.014	0.021	0.030	0.004
30	0.029	1193	0.02	0.220	0.020	0.027	0.036	0.004
31	0.020	1340	0.02	0.201	0.014	0.020	0.027	0.003
colMeans	0.029	517	0.02	0.438	0.015	0.025	0.037	0.006

For reference, we need to type ‘R> print(p, sort = FALSE)’ instead of ‘R> p’ to list the above output by the order of data input. ‘R> p’ will automatically sort the output by the increasing order of  $n_j$ .

The output contains information about sample mean (`obs.mean`), total number of trials (`n`), prior mean ( $\lambda_0$ ), shrinkage, lower interval, posterior mean ( $E(\lambda_j|\mathbf{z})$ ), upper interval, and standard deviation of posterior distribution ( $sd(\lambda_j|\mathbf{z})$ ).

As we can see in (6), the posterior mean  $((1 - B_j)y_j + B_j\lambda_0)$  is a linear function of shrinkage ( $\equiv r/(r + n_j)$ ), locating between the sample mean and prior mean ( $\lambda_0 = 0.02$ ). It makes sense because  $r$  can be interpreted as the amount of prior information; if the second level has more information than the first level, then the sample mean shrinks towards the prior mean more than 50%.

A function “`summary`” shows selective information on hospitals and more detailed estimation result as below. To be specific, it selectively displays estimation result of hospitals with minimum, median, and maximum values of  $n_j$ . Also, more specific estimation results, such as estimation result of  $\alpha = \log(1/r)$ , will follow. Note that if we fit a regression when we do not know the second-level mean unlike this example, the regression summary will appear.

```
R> summary(p)
```

Main summary:

	obs.mean	n	prior.mean	shrinkage	intv.low	post.mean	intv.upp	post.sd
Unit w/ min(n)	0.045	67	0.02	0.834	0.011	0.024	0.042	0.008
Unit w/ median(n)	0.045	484	0.02	0.410	0.023	0.035	0.050	0.007
Unit w/ max(n)	0.020	1340	0.02	0.201	0.014	0.020	0.027	0.003
Overall Mean	0.029	517	0.02	0.438	0.015	0.025	0.037	0.006



Second-level Variance Component Estimation Summary:

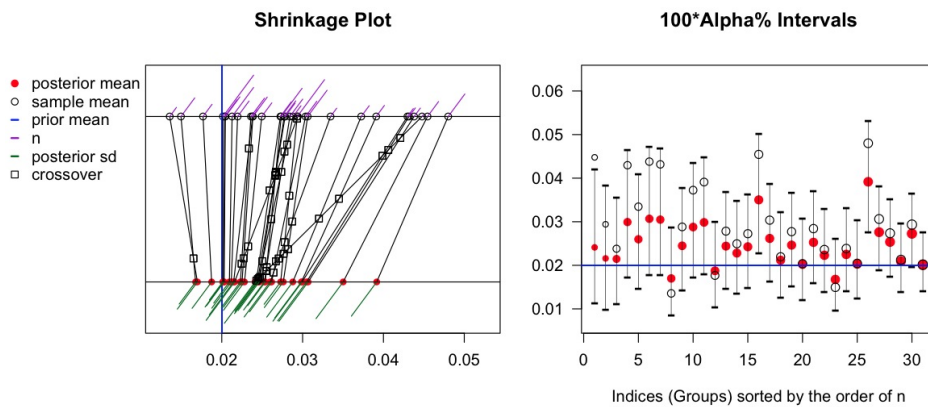
$\alpha = \log(A)$  for Gaussian and  $\log(1/r)$  for Binomial and Poisson data:

```
post.mode.alpha post.sd.alpha
1             -5.818           0.411
```

Since estimated  $\alpha$  is -5.818, we can easily calculate  $r = \exp(5.818) = 336$ , which will be helpful for understanding how each shrinkage of hospital was determined by comparing this value to the amount of observed information ( $n_j$ ).

But bunch of numbers can sometimes distract us from the important point. In this sense, we also need a graphical summary that can give us valuable insight buried in pile of numbers and a function ‘plot’ is exactly for this purpose.

```
R> plot(p)
```



The regression towards the mean (RTTM) is obvious in the left-side graph; the observed sample means are shrinking towards the known second-level mean (a blue vertical line at 0.02) to the different extents. And note that some hospitals' ranks have changed by shrinking much harder towards 0.02 than others. For example, the empty square at the crossing point of the first two lines indicates that seemingly safest hospital among 31 hospitals in terms of the observed sample mean was not actually safer than the second safest hospital. Without this hierarchical modeling, we might have made a wrong decision in choosing a hospital.

The estimated 95% intervals are displayed on the right-side plot. We can clearly see that all the posterior mean (red dots) are between sample mean (empty dots) and second-level mean (a blue horizontal line). Although the first interval does not include the observed sample mean, it can happen by chance considering these are 95% intervals. Overall, this plot shows that as the sample size increases (size of dots) and as the posterior mean gets close to 0, the length of interval gets shorter.

## 6.2. 8 Schools: Unknown Second-level Mean and No Covariate

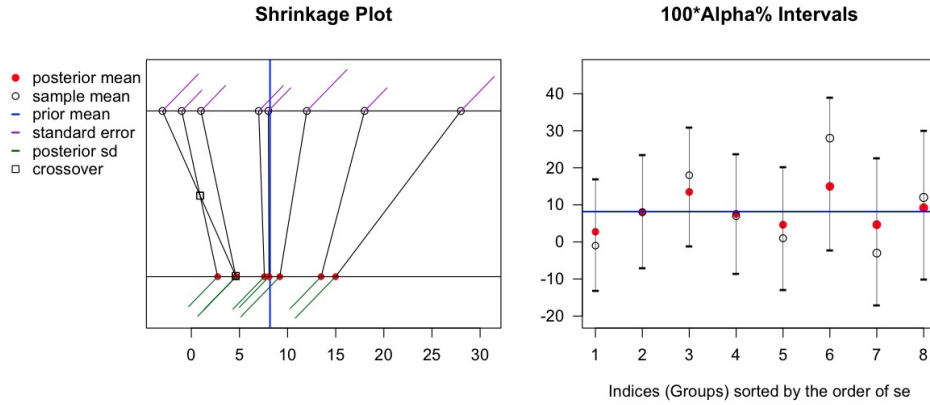


Figure 2: Shrinkage and interval plots of 8 schools

### 6.3. 18 Baseball Players: Unknown Prior Mean and One Covariate

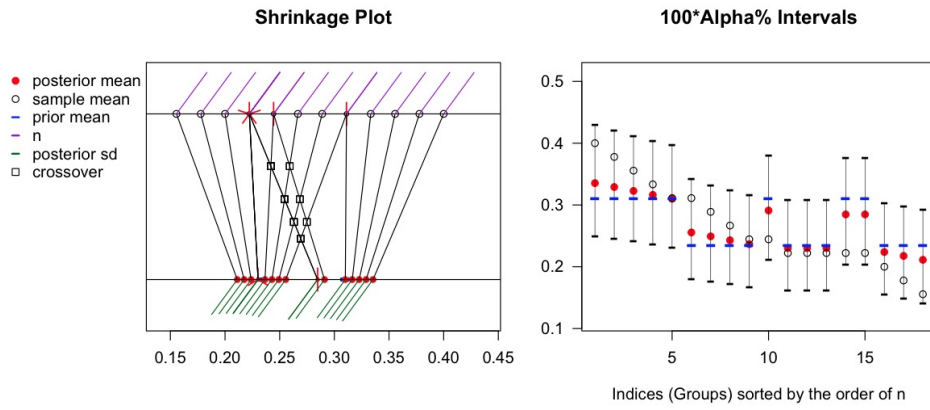


Figure 3: Shrinkage and interval plots of 18 baseball players

## 7. Discussion

## 8. Acknowledgments

## 9. Reference

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**Affiliation:**

Joseph Kelly  
Department of Statistics  
Harvard University  
1 Oxford Street, Cambridge, MA  
E-mail: [kelly2@fas.harvard.edu](mailto:kelly2@fas.harvard.edu)  
URL: <http://www.people.fas.harvard.edu/~kelly2/>

Carl Morris  
Department of Statistics  
Harvard University  
1 Oxford Street, Cambridge, MA  
E-mail: [morris@fas.harvard.edu](mailto:morris@fas.harvard.edu)

Hyungsuk Tak  
Department of Statistics  
Harvard University  
1 Oxford Street, Cambridge, MA  
E-mail: [hyungsuk.tak@gmail.com](mailto:hyungsuk.tak@gmail.com)