



## Rgbp: An R Package for Gaussian, Poisson, and Binomial Hierarchical Modeling

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### Abstract

**Rgbp** is an R package that utilizes approximate Bayesian machinery to provide a method of estimating two-level hierarchical models for Gaussian, Poisson, and Binomial data in a fast and computationally efficient manner. The main products of this package are point and interval estimates for the true parameters, whose good frequency properties can be validated via its repeated sampling procedure called “frequency method checking.” It is found that such Bayesian-frequentist reconciliation allows **Rgbp** to have attributes desirable from both perspectives, working well in small samples and yielding good coverage probabilities for its interval estimates.

*Keywords:* multilevel model, conjugate hierarchical generalized linear models, frequency method checking, coverage probability, shrinkage.

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## 1. Introduction

**Rgbp** is an R package for estimating and validating a two-level model, also called conjugate hierarchical generalized linear model (Lee, Nelder, and Pawitan 2006; Rönnegård, Shen, and Alam 2010), producing point and interval estimates of the true parameters. The estimation procedure utilizes approximate Bayesian machinery and the validation involves checking frequency properties of the procedure via repeated sampling (which we call “frequency method checking”). It is found that even in small samples our procedure yields good frequency properties in comparison to other methods such as Maximum Likelihood Estimation (MLE).

This package will be useful for frequentists and Bayesians alike. Bayesians are able to use the package to see results for a non-informative reference prior before and after constructing their own Bayesian hierarchical model. Frequentists will have a procedure that meets or exceeds their confidence specification and repeated sampling.

## 2. Multilevel Structure

A two-level or multilevel model, also called a conditionally independent hierarchical model (Kass and Steffey 1989), is a powerful tool for exploring the hierarchical structure in data. For example, we can imagine that there exists a district-level hierarchy (bigger population) for observed school-level data, or a state-level hierarchy for observed hospital-level data in a certain state.

**gbp**, one of the functions in **Rgbp**, fits such a hierarchical model whose first-level has distributions of observed data and whose second-level has conjugate distributions on the first-level parameters. The **gbp** function allows users to choose one of three types of multilevel models, namely Normal-Normal, Poisson-Gamma, and Binomial-Beta.

### 2.1. Normal-Normal (“g”=Gaussian data)

The following is the general Normal-Normal hierarchical model assumed by **gbp**. For reference,  $V_j \equiv \sigma^2/n_j$  below is assumed to be known or to be accurately estimated, and subscript  $j$  indicates the  $j$ -th group among  $k$  groups in the dataset.

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

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

where  $\mu_{0j} = x_j^T \beta$ ,  $j = 1, \dots, k$ ,  $x_j$  is the  $j$ -th group’s covariate vector ( $m \times 1$ ),  $m$  is the number of regression coefficients and both  $\beta$  and  $A$  are unknown. Note that if there is no covariate then  $x_j = 1$  for an intercept term ( $m = 1$ ) and so  $\mu_{0j} = \mu_0 = \beta_0$  for all  $j$ , resulting in an exchangeable prior distribution. For reference, a parameter with a zero subscript, such as  $\mu_{0j}$ , represents a mean parameter of the prior (second-level) distribution, *i.e.*, a prior mean. Based on this conjugate prior distribution it is easy to derive the corresponding posterior distribution

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

where  $B_j \equiv V_j/(V_j + A)$ ,  $j = 1, \dots, k$ , are called shrinkages.

### 2.2. Poisson-Gamma (“p”=Poisson data)

**gbp** is also able to build a Poisson-Gamma multilevel model. Note that a constant,  $1/r$ , multiplied to the Gamma distribution below is a scale and a square bracket  $[, ]$  below indicates [mean, variance] of a distribution. For notational consistency, let’s define  $y_j \equiv z_j/n_j$  as the unbiased estimate of  $\lambda_j$ , where  $j = 1, \dots, k$ .

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

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

where  $\log(\lambda_{0j}) = x_j^T \beta$ ,  $j = 1, \dots, k$ , with two unknown hyper-parameters,  $r$  and  $\beta$ . The posterior distribution of this Poisson-Gamma model is

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

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

Note that the variance in (5) is linear in the mean, whereas a slightly different Poisson-Gamma specification (Christiansen and Morris 1997) has been used elsewhere e.g. that makes the variance in (5) quadratic.

### 2.3. Binomial-Beta (“b”=Binomial data)

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

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

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

where  $\log(\frac{p_{0j}}{1 - p_{0j}}) = x'_j\beta$ ,  $j = 1, \dots, k$  and  $r$  and  $\beta$  are two unknown hyper-parameters. Then corresponding posterior distribution given  $r$  and  $\beta$  is

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

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

### 2.4. Hyper-prior Distribution

A hyper-prior distribution is a distribution assigned to the second-level parameters. With the goal of objectivity in mind our choice for hyper priors with **gbp** assumes the following non-informative hyper-prior distributions:

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

where  $m$  is the number of regression coefficients. As for  $\beta$ , the flat non-informative distribution above is a common choice. In the Gaussian case, the flat prior distribution on the second level variance  $A$  is chosen to produce good repeated sampling properties for point and interval estimates of the true parameters  $\{\mu_j\}$ , and to have its posterior propriety when  $k \geq m + 3$  (Morris and Tang 2011). In the other two cases, Poisson and Binomial, the distribution of  $\frac{1}{r}$  induces the same improper prior distribution on shrinkages ( $B_j$ ) as does  $A$  with  $\text{Unif}(0, \infty)$  for the Gaussian. We will show the efficiency of this assignment in the examples in section 5.

## 3. Estimation

### 3.1. Shrinkage Estimation

Estimating the shrinkage factors  $(B_1, \dots, B_k)$  is the key estimation problem with the hierarchical models **gbp** assumes. As we can see in (3), (6), and (9), the posterior means are a linear function of the shrinkage factors ( $B_j$ ) and the posterior variances are linear (Gaussian),

quadratic (Poisson), and approximately cubic (Binomial) functions of  $B_j$ . A natural method then to estimate  $E(\mu_j|\mathbf{y})$  and  $Var(\mu_j|\mathbf{y})$  is to first estimate the shrinkage factors.

### 3.2. Approximation via Adjustment for Density Maximization

It is noted that the shrinkage factors  $(B_1, \dots, B_k)$  are a function of the second-level variance component, *i.e.*,  $B_j \equiv V_j/(V_j + A) = B_j(A)$  for Gaussian and  $B_j \equiv r/(r + n_j) = B_j(r)$  for Poisson and Binomial models. A common approach to approximate the distribution of  $B_j$  is to find its MLE  $\hat{B}_j(\hat{A}_{MLE})$  (or  $\hat{B}_j(\hat{r}_{MLE})$ ) and to use its asymptotic Normality. But MLE can result in estimates lying on the boundary of the parameter space, and its asymptotic Gaussian distribution is defined on  $(-\infty, \infty)$  whereas  $B_j$  is bounded between 0 and 1.

To continue with a maximization-based estimation procedure but to steer clear of aforementioned boundary issues we make use of adjustment for density maximization (ADM) (Morris 1988; Christiansen and Morris 1997; Morris and Tang 2011). For our purposes we approximate the posterior distribution of a shrinkage factor with a Beta distribution, which allows us to finally obtain estimates of the posterior moments, *i.e.* of  $E(B_j|\text{data})$  and  $Var(B_j|\text{data})$ , without the boundary issues that MLE encounters. See Morris and Tang (2011).

### 3.3. Posterior Moment Estimation

Using the posterior mean and variance estimates of  $B_j$ , **Rgbp** estimates the posterior mean and variance of true parameters given only the data ( $\mathbf{y}$ ). Taking the Normal-Normal model as an example, it estimates  $E(\mu_j|\mathbf{y})$  and  $Var(\mu_j|\mathbf{y})$  by the following identities

$$E(\mu_j|\mathbf{y}) = E(E(\mu_j|\mathbf{y}, \beta, A)|\mathbf{y}), \quad (11)$$

$$Var(\mu_j|\mathbf{y}) = E(Var(\mu_j|\mathbf{y}, \beta, A)|\mathbf{y}) + Var(E(\mu_j|\mathbf{y}, \beta, A)|\mathbf{y}), \quad (12)$$

where both  $E(\mu_j|\mathbf{y}, \beta, A)$  and  $Var(\mu_j|\mathbf{y}, \beta, A)$  are linear functions of the shrinkage factors as specified in (3).

### 3.4. Approximation to Posterior Distribution via Matching Moments

After estimating the two posterior moments, for example  $E(\mu_j|\mathbf{y})$  and  $Var(\mu_j|\mathbf{y})$ , **gbp** approximates a posterior distribution of the mean effects given the data by assuming a reasonable distribution and matching moments. For the Binomial-Beta model we approximate the posterior distribution of  $p_j$ ,  $\pi(p_j|\mathbf{y})$ , with a Beta distribution and for the Poisson-Gamma model we approximate  $\pi(\lambda_j|\mathbf{y})$  with a Gamma distribution. Finally for the Normal-Normal model we actually estimate the first three moments and approximate  $\pi(\mu_j|\mathbf{y})$  with a skewed-Normal distribution.

## 4. Frequency Method Checking

Like the two sides of the same coin, checking a statistical model comes hand in hand with fitting the model. If a fitted model cannot pass a validation or checking process, we usually go back and forth from estimation and checking steps iteratively. In this sense, checking a fitted model is an interactive procedure for the model justification.

There are two kinds of model justification processes; one is a model checking and the other is a method checking. The model checking is for the justification of the multilevel model on

a specific dataset. One possible question is, “Can this dataset benefit from such a multilevel modeling?” Christiansen and Morris (1997) answered this question by using the Negative-Binomial mixture model on 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 make sure that the hierarchical modeling can be appropriate for our data, the following question will be about the validity of interval estimates, the final product of this multilevel modeling. “Does the 95% (can be specified differently) confidence interval obtained via this Bayesian model-fitting process achieve 95% confidence level for any true parameter values?” **Rgbp** has a function called **coverage** to answer this question and it comprises of two parts, generating pseudo-dataset and estimating coverage probability.

From now on, the explanation will be based on Normal-Normal model because the idea can be easily applied to the other two models.

#### 4.1. Pseudo-data Generation Process

Figure 1 will be helpful to understand this process. As we can see in (3), the distribution of each true parameter ( $\mu_j$ ,  $j = 1, \dots, k$ ) is completely determined by two hyper-parameters,  $A$  and  $\beta_{(m \times 1)}$ . So, once we fix these hyper-parameters at specific values, we can generate true parameters. Suppose we generated 500 ( $= N_{sim}$ )  $\mu_{(k \times 1)}$ 's, *i.e.*,  $\{\mu_{(k \times 1)}^{(i)}, i = 1, \dots, 500\}$  from the prior distribution in (2), where  $A$  and  $\beta$  are given. Then using (1), we can also generate  $\{y_{(k \times 1)}^{(i)}, i = 1, \dots, 500\}$  given each  $\mu_{(k \times 1)}^{(i)}$ , where  $i$  indicates the  $i$ -th simulation.

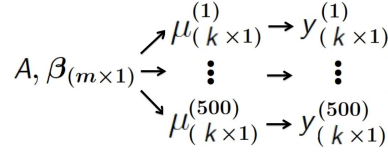


Figure 1: Pseudo-data generating process

#### 4.2. Coverage Estimation Process

Next, **coverage** fits the Normal-Normal model 500 times using the 500 pseudo-datasets in order to obtain  $500 \times k$  interval estimates,  $\{(\hat{\mu}_{j, low}^{(i)}, \hat{\mu}_{j, upp}^{(i)}), j = 1, \dots, k, i = 1, \dots, 500\}$ . And then within each group, it will check simply how often the interval estimates include true parameters, or calculate Rao-Blackwellized coverage estimate.

##### *Simple Unbiased Estimates of Coverage Probabilities*

Let's define an indicator variable,  $I_j^{(i)}$ , which is 1 if the  $j$ -th group's interval estimate from the  $i$ -th pseudo-dataset includes  $\mu_j^{(i)}$  and 0 otherwise. Then **coverage** estimates the coverage probability via the sample mean of these indicator variables for each group  $j$ , averaging over all the possible  $\mu_j^{(i)}$  and  $y_j^{(i)}$  for given  $A$  and  $\beta$ . This provides a simple unbiased estimate of the  $k$  coverage probabilities. For example,  $\frac{1}{500} \sum_{i=1}^{500} I_1^{(i)}$  is the simple unbiased estimate of

coverage probability for the first group ( $j = 1$ ), accounting for possible randomness in  $\mu_1^{(i)}$  and  $y_1^{(i)}$ ,  $i = 1, \dots, 500$ , given a specific  $(A, \beta)$ . As the number of pseudo-datasets increases, this simple estimate converges to the true coverage probability of the first group given  $A$  and  $\beta$ .

### *Rao-Blackwellized Unbiased Estimates of Coverage Probabilities*

Rao-Blackwellization improves accuracy of an unbiased estimator by taking a conditional expectation given a sufficient statistic. Based on this idea, we use  $E(I_j^{(i)} | y_j^{(i)}, A, \beta)$ , where  $A$  and  $\beta$  are given and  $y_j^{(i)}$  is the sufficient statistic for the  $j$ -th group in the  $i$ -th pseudo-dataset. This expectation is the same as  $\Pr(\hat{\mu}_{j,low}^{(i)} \leq \mu_j^{(i)} \leq \hat{\mu}_{j,upp}^{(i)} | y_j^{(i)}, A, \beta)$ , where  $(\hat{\mu}_{j,low}^{(i)}, \hat{\mu}_{j,upp}^{(i)})$  is the  $j$ -th group's interval estimate on the  $i$ -th dataset. We can calculate this probability because we know the distribution of  $(\mu_j^{(i)} | y_j^{(i)}, A, \beta)$  in (3). Note that conditioning on  $y_j^{(i)}$  is equivalent to conditioning on  $\mathbf{y}_{(k \times 1)}^{(i)}$  as long as  $A$  and  $\beta$  are known. Then, we estimate the first group's coverage probability by  $\frac{1}{500} \sum_{i=1}^{500} E(I_1^{(i)} | y_1^{(i)}, A, \beta)$ , which is also unbiased but with smaller variance than the previous simple estimator,  $\frac{1}{500} \sum_{i=1}^{500} I_1^{(i)}$ .

## 5. Examples

### 5.1. 31 Hospitals: Known Second-level Mean

Suppose a person living in the New York state (NY) has been suffering from severe coronary heart disease. If this person is supposed to receive the coronary artery bypass graft (CABG) surgery soon, he or she might want to find the most reliable hospital for dealing with such a surgery. On top of that, if this person can figure out each hospital's ability to handle this surgery, it will be useful for choosing a hospital.

For this purpose, data were gathered from 31 hospitals in NY composed of the number of deaths ( $z$ ) within a month of CABG surgeries and total number of patients ( $n$ ) receiving CABG surgeries in each hospital. Using these data, **Rgbp** provides point and interval estimates of the true death ratio for each hospital so that one can choose the safest hospital. The following code is an example of input based on the last ten hospital data ( $j = 22, 23, \dots, 31$ ). Throughout this paper, the symbol 'R>' represents a command prompt that you should not type on R.

```
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)
```

In addition, while one looks for such information, suppose one knows that the state-level death rate per exposure of this surgery is 0.020.

The multilevel modeling that assumes a bigger population-level hierarchy will be insightful in this problem. Here, we presume a state-level (NY) hierarchy governing the true death rates ( $\lambda$ ) of CABG surgery of all the hospitals in NY. This perspective is to view the true death rates of those 31 hospitals as sampled from the state-level population distribution whose mean is 0.020.

Assuming an additional hierarchy is reasonable, a model-fitting process begins. We know the true death rate per exposure after CABG surgery might be small and the caseload ( $n_j$ ) is much bigger than the number of deaths ( $z_j$ ) in each hospital. Then the independent Poisson distribution, *i.e.*,  $z_j|\lambda_j \stackrel{ind}{\sim} \text{Poisson}(n_j\lambda_j)$ ,  $j = 1, \dots, 31$ , would be the first choice to describe the uncertainty in these data. Note that caseload ( $n_j$ ) can be interpreted as an exposure, which is not necessarily an integer.

Next, `gbp` will help us fit the Poisson multilevel model with the Gamma conjugate prior distribution on the true death rate  $\lambda_j$  whose mean is 0.020 ( $\lambda_0 = 0.020$ ) as described in the section 2.2. For reference, the number of regression coefficients ( $m$ ) is 0 because we do not need to estimate the prior mean via log-linear regression (see section 3.2).

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

Summary for each unit (sorted by n):

	obs.mean	n	prior.mean	shrinkage	low.intv	post.mean	upp.intv	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’ in order to list hospitals by the order of data input in the above output. ‘R> p’ automatically sorts the output by the increasing order of caseload ( $n_j$ ).

The output contains information about observed death ratio ( $y_j$ ), caseload ( $n_j$ ), known prior mean ( $\lambda_0$ ), shrinkage estimate ( $\hat{B}_j$ ), lower bound of interval estimate ( $\hat{\lambda}_{j,low}$ ), posterior mean ( $\hat{\lambda} = E(\lambda_j|\mathbf{y})$ ), upper bound of interval estimate ( $\hat{\lambda}_{j,upp}$ ), and standard deviation of posterior distribution ( $sd(\lambda_j|\mathbf{y})$ ).

As we can see in (6), the posterior mean,  $(1 - B_j)y_j + B_j\lambda_0$ , is a linear function of shrinkage,  $B_j \equiv r/(r + n_j)$ , 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 and  $n_j$  as the amount of observed information. If the second level has more information than the first level, then the sample mean shrinks towards the prior mean more than 50%. This point is clear in the above output because, as caseload increases, shrinkage decreases, depending less on the second level information.

A function `summary` shows selective information on hospitals and more detailed estimation result as below. To be specific, it displays some hospitals (not all as above) with minimum, median, and maximum caseloads ( $n_j$ ). On top of that, more specific estimation results, such as the estimation result of  $\alpha \equiv \log(1/r)$ , follow. Note that when we do not know the prior mean in advance unlike this hospital problem, `gbp` fits a linear regression for the Normal model, a log-linear regression for the Poisson model, or a logistic regression for the Binomial model and a summary of regression fit will appear.

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

Main summary:

	obs.mean	n	prior.mean	shrinkage	low.intv	post.mean
Unit w/ min(n)	0.045	67	0.02	0.834	0.011	0.024
Unit w/ median(n)	0.045	484	0.02	0.410	0.023	0.035
Unit w/ max(n)	0.020	1340	0.02	0.201	0.014	0.020
Overall Mean	0.029	517	0.02	0.438	0.015	0.025

	upp.intv	post.sd
	0.042	0.008
	0.050	0.007
	0.027	0.003
	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  $\hat{r} = \exp(5.818) = 336$ , which is a good indicator of how valuable and informative the hypothetical second-level hierarchy is. It means that observed sample means of hospitals whose caseloads are less than 336 will shrink toward the prior mean (0.020) more than 50%. For example, the shrinkage estimate of the first hospital ( $\hat{B}_1 = 0.834$ ) was calculated by  $336 / (336 + 67)$ , where 67 is its caseload ( $n_1$ ), and its posterior mean is  $(1 - 0.834) * 0.045 + 0.834 * 0.020 = 0.024$ . As for this hospital, using more information from the prior distribution is an appropriate choice because its observed amount of information (67) is far less than the amount of state-level information (336).

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)
```

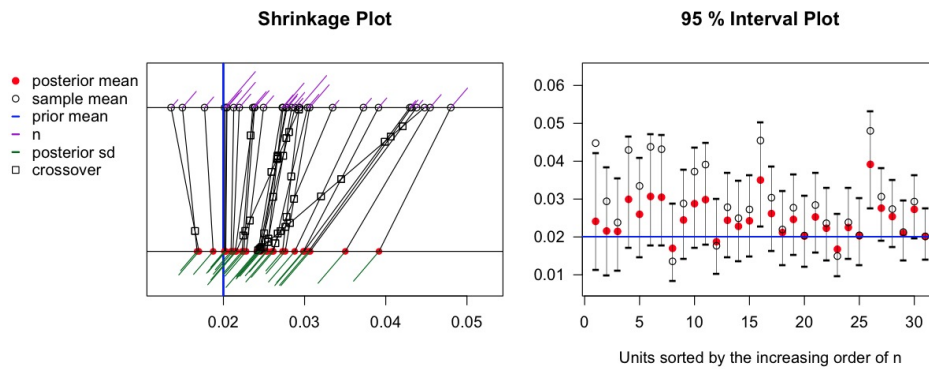


Figure 2: Shrinkage plot and 95% interval plot

In Figure 2 the regression towards the mean (RTTM) is obvious in the left-side graph; the observed sample means, empty dots on the upper horizontal line, are shrinking towards the known second-level mean (a blue vertical line at 0.02) to the different extents. Note that some hospitals' ranks have changed by shrinking much harder towards 0.02 than others. For example, the empty square symbol at the crossing point of the two left-most lines (8th and 23rd hospitals on the list above) indicates that seemingly the safest hospital among 31 hospitals in terms of the observed death ratio is not actually safer than seemingly the second safest hospital.

Intuitively, the result of multilevel modeling makes more sense than that of naive sample mean. For example, suppose there are two hospitals, whose observed death ratios ( $y_j$ ) are 0 and 0.001 and caseloads ( $n_j$ ) are 10 and 1000 each. Do you believe that the former hospital, whose observed death rate is 0, is better than the latter and are you going to choose the former hospital? Borrowing information from state-level hierarchy seems reasonable for the former hospital because it is hard to judge its true death rate per exposure with just ten caseloads. Though somewhat extreme, this is what happened to the two left-most hospitals in the first plot and this is why hierarchical modeling is a reasonable choice for this dataset.

The estimated 95% intervals are displayed on the right-side plot. We can clearly see that all the posterior means (red dots) are between sample mean (empty dots) and second-level mean (a blue horizontal line). For reference, if we want to draw this plot by the order of data input, `plot(p, sort = FALSE)` is the right adjustment.

This interval plot can give us one more valuable insight, which we could not have noticed. Let's look at the 8th and the 31st hospitals on the graph (or on the outcome for numeric reference). The point estimate of the true death rate per exposure of the 31st hospital is higher than the one of the 8th. But, the upper bound of interval estimate of this 31st hospital is lower than that of the 8th. This interval plot makes the 31st hospital emerge as one of your candidates.

Also it reveals that the 23rd hospital, whose estimated true rate was the smallest, has also the smallest upper bound. If you are a risk-averse, this hospital will attract you most strongly. And if you already chose this 23rd hospital compared to the 8th from the shrinkage plot, your decision might become stronger at this point, excluding the 8th hospital with more certainty.

Then, how reliable are these intervals? Does our procedure to generate interval estimates have good repeated sampling property? The following method checking will answer this question. The `coverage` function below generates 10,000 pseudo-datasets regarding the estimated  $r$  ( $= 336.37$ ) as a given true value. For reference, we can try any other value of  $r$ , for example  $r = 200$ , by replacing below code with `'R> pcv <- coverage(p, A.or.r = 200, mean.PriorDist = 0.02, nsim = 10000).'`

Also, `gbp` can give us interval estimates with different confidence level, for example 90%, and the appropriate code adjustment is `'R> p <- gbp(z, n, Alpha = 0.9, mean.PriorDist = 0.02, model = "pr").'` Then, the below code will evaluate whether interval estimates achieve 90% confidence level.

```
R> pcv <- coverage(p, nsim = 10000)
```

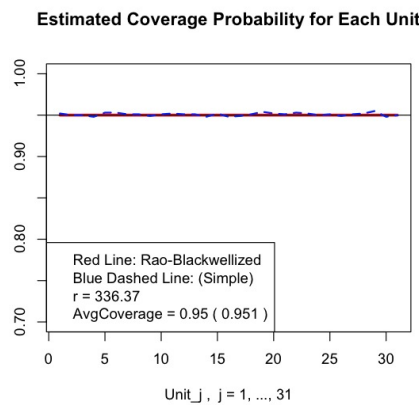


Figure 3: Coverage plot via frequency method checking for 31 hospitals

In Figure 3 we see two estimated coverage probabilities: a simple unbiased estimate (a blue dashed line) and an Rao-Blackwellized unbiased estimate (a red line). Both lines are indistinguishable from the horizontal line at 0.95 and the estimated overall average coverage rate

is 0.950 from the Rao-Blackwellized estimate. This result shows that the interval estimates from the suggested multilevel modeling on this particular dataset have nice repeated sampling property. For reference, it took 10 seconds for MacBook Pro with a 2.3 GHz dual-core Intel i5 CPU to run 10,000 simulations.

It is noted that [Morris and Christiansen \(1995\)](#) also investigated a similar ranking problem in hierarchical modeling, taking shrinkage into account.

## 5.2. 8 Schools: Unknown Second-level Mean and No Covariate

The Education Testing Service (ETS) conducted randomized experiments in eight separate schools (group) to test whether students (unit) SAT scores are effected by coaching. The dataset contains the estimated coaching effects on SAT scores ( $y_j, j = 1, \dots, 8$ ) and standard errors ( $se_j, j = 1, \dots, 8$ ) of the eight schools ([Rubin 1981](#)).

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

Due to the nature of the test each school's coaching effect has an 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. Hence, we can use `gbp` to fit a Normal-Normal hierarchical model to produce point and interval estimates of the true coaching effect for each school:

```
R> data(schools)
R> attach(schools)
R> g <- gbp(y, se, model = "gr")
R> g
```

Summary for each unit (sorted by se):

	obs.mean	se	prior.mean	shrinkage	low.intv	post.mean	upp.intv	post.sd
5	-1.00	9.0	8.168	0.408	-13.297	2.737	16.692	7.634
2	8.00	10.0	8.168	0.459	-7.255	8.077	23.361	7.810
7	18.00	10.0	8.168	0.459	-1.289	13.484	30.821	8.176
4	7.00	11.0	8.168	0.507	-8.780	7.592	23.602	8.257
6	1.00	11.0	8.168	0.507	-13.027	4.633	20.131	8.441
1	28.00	15.0	8.168	0.657	-2.315	14.979	38.763	10.560
3	-3.00	16.0	8.168	0.685	-17.130	4.650	22.477	10.096
8	12.00	18.0	8.168	0.734	-10.208	9.189	29.939	10.227
colMeans	8.75	12.5	8.168	0.552	-9.163	8.168	25.723	8.900

The output from `gbp` provides an easy way to read summary of the results of the estimation. From this there seems to be little evidence that the training provided much of an added benefit with every school's 95% posterior interval containing 0. **Rgbp** also provides functionality to plot the results of the analysis as seen in [Figure 4](#).

```
R> plot(g)
```

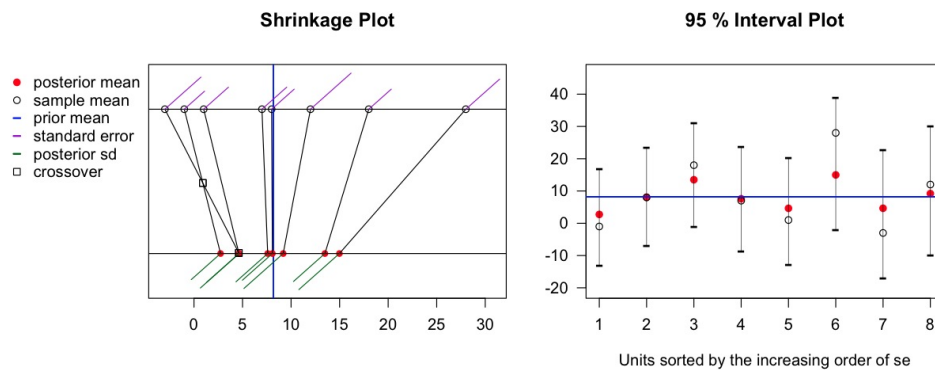


Figure 4: Shrinkage plot and 95% interval plot for 8 schools

Plotting the results provides a visual aid to understanding but is only largely beneficial when the number of groups ( $k$ ) is small. In the case where the number of groups is large **Rgbp** provides a summary feature:

```
R> summary(g)
```

Main summary:

	obs.mean	se	prior.mean	shrinkage	low.intv	post.mean
Unit w/ min(se)	-1.00	9.0	8.168	0.408	-13.297	2.737
Unit w/ median(se)1	1.00	11.0	8.168	0.507	-13.027	4.633
Unit w/ median(se)2	7.00	11.0	8.168	0.507	-8.780	7.592
Unit w/ max(se)	12.00	18.0	8.168	0.734	-10.208	9.189
Overall Mean	8.75	12.5	8.168	0.552	-9.163	8.168

	upp.intv	post.sd
	16.692	7.634
	20.131	8.441
	23.602	8.257
	29.939	10.227
	25.723	8.900

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	4.768	1.139

Regression Summary:

	estimate	se	z.val	p.val
beta0	8.168	5.73	1.425	0.154

An integral part of fitting any model is to check the method of estimation. Namely we can generate new pseudo-data from our assumed model by fixing the hyper-parameter values ( $A$  and  $\mu_0$  in this example) at their estimates. It is then possible to simulate “true”  $\theta_i$  for each group  $i$  and re-fit the model many times to estimate the coverage probabilities of our procedure.

```
R> gcv <- coverage(g, nsim = 10000)
```

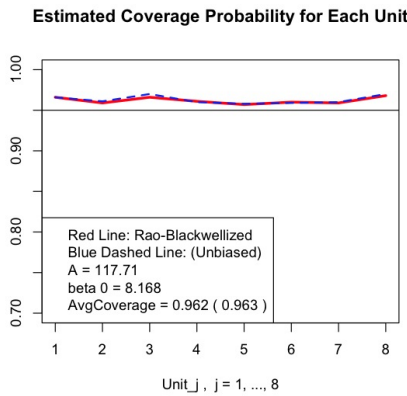


Figure 5: Coverage plot via frequency method checking for 8 schools

As seen in Figure 5 the desired 95% confidence (horizontal line at 0.95) is achieved (actually, exceeded) for each school in this example. For reference, it took 188 seconds for 10,000 simulations on one of authors’ MacBook Pro with a 2.3 GHz dual-core Intel i5 CPU. In MCMC, the exact simulation would be too time-consuming. One could compare curve in Figure 5 with a curve from MCMC.

### 5.3. 18 Baseball Players: Unknown Second-level Mean and One Covariate

The following dataset from the New York Times published on 26 April 1970 contains information on the batting averages of 18 major league baseball players through their first 45 official at-bats of the 1970 season (Efron and Morris 1975). In addition one covariate relating to the position of each player was observed and for illustrative purposes, we transform this variable into a binary indicator (1 if a player was an outfielder and 0 otherwise).

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

The data indicate that independent Binomial distribution is appropriate probability distribution for describing each player’s number of hits ( $z_j$ ) among 45 at-bats conditioning on the unknown true batting average, *i.e.*,  $z_j|p_j \stackrel{ind}{\sim} \text{Binomial}(45, p_j)$ ,  $j = 1, \dots, 18$ . Our goal is to estimate point and interval estimates of true batting average for each player. For reference, we can also assume the Normal distribution using  $y_j = z_j/n_j$  and  $V_j = \bar{y}(1 - \bar{y})/n$ , where  $\bar{y} = \sum_j z_j / \sum_j n_j$ ,  $j = 1, \dots, 18$ .

Suppose we believe that the outfielder's batting averages are different from other positions' ones. So, it is desirable to assume two different second-level hierarchies for outfielders and for other positions, within each of which sharing information and regressing toward the mean (RTTM) occur. Our multilevel modeling provides a way to incorporate such information (position) seamlessly into the second-level hierarchy.

```
R> b <- gbp(z, n, x, model = "br")
R> b
```

Summary for each unit (sorted by n):

	obs.mean	n	X1	prior.mean	shrinkage	low.intv	post.mean	upp.intv	post.sd
1	0.400	45	1.00	0.310	0.715	0.248	0.335	0.429	0.046
2	0.378	45	1.00	0.310	0.715	0.244	0.329	0.420	0.045
3	0.356	45	1.00	0.310	0.715	0.240	0.323	0.411	0.044
4	0.333	45	1.00	0.310	0.715	0.236	0.316	0.403	0.043
5	0.311	45	1.00	0.310	0.715	0.230	0.310	0.396	0.042
6	0.311	45	0.00	0.233	0.715	0.179	0.256	0.341	0.041
7	0.289	45	0.00	0.233	0.715	0.175	0.249	0.331	0.040
8	0.267	45	0.00	0.233	0.715	0.171	0.243	0.323	0.039
9	0.244	45	0.00	0.233	0.715	0.166	0.237	0.315	0.038
10	0.244	45	1.00	0.310	0.715	0.210	0.291	0.379	0.043
11	0.222	45	0.00	0.233	0.715	0.161	0.230	0.308	0.038
12	0.222	45	0.00	0.233	0.715	0.161	0.230	0.308	0.038
13	0.222	45	0.00	0.233	0.715	0.161	0.230	0.308	0.038
14	0.222	45	1.00	0.310	0.715	0.202	0.285	0.375	0.044
15	0.222	45	1.00	0.310	0.715	0.202	0.285	0.375	0.044
16	0.200	45	0.00	0.233	0.715	0.155	0.224	0.302	0.038
17	0.178	45	0.00	0.233	0.715	0.148	0.218	0.297	0.038
18	0.156	45	0.00	0.233	0.715	0.140	0.211	0.292	0.039
colMeans	0.265	45	0.44	0.267	0.715	0.191	0.267	0.351	0.041

Our model reflects on the additional information, *i.e.*, indicator covariate (1 for outfielder and 0 for other positions), estimating two different prior means, 0.310 and 0.233. Also note that shrinkage estimates are the same for all players. It makes sense because shrinkage ( $B_j \equiv r/(r + n_j)$ ) is determined solely by the relative amount of information between the first-level and the second-level hierarchies. The fact that all players have the same amount of observed information ( $n_j = 45$ ) and  $\hat{r} = \exp(4.727) = 113$  from below summary tell why the estimated shrinkage is 0.715 ( $=113 / (113 + 45)$ ).

The below summary includes the result of logistic regression fit because we did not know prior means in advance. We had to estimate them via this logistic regression model. Let's look at the p-value of the indicator covariate. It shows that the two prior means distinguishing outfielders from other positions were significantly different (p-value = 0.038), supporting our initial belief. The positive sign of  $\hat{\beta}_1$  indicates that the mean batting average for all the outfielders tends to be higher than that for those in the other positions.

```
R> summary(b)
```

Main summary:

	obs.mean	n	X1	prior.mean	shrinkage	low.intv
Unit w/ min(obs.mean)	0.156	45	0.00	0.233	0.715	0.140
Unit w/ median(obs.mean)1	0.244	45	0.00	0.233	0.715	0.166
Unit w/ median(obs.mean)2	0.244	45	1.00	0.310	0.715	0.210
Unit w/ max(obs.mean)	0.400	45	1.00	0.310	0.715	0.248
Overall Mean	0.265	45	0.44	0.267	0.715	0.191

	post.mean	upp.intv	post.sd
	0.211	0.292	0.039
	0.237	0.315	0.038
	0.291	0.379	0.043
	0.335	0.429	0.046
	0.267	0.351	0.041

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	-4.727	0.957

Regression Summary:

	estimate	se	z.val	p.val
beta0	-1.194	0.131	-9.129	0.000
beta1	0.389	0.187	2.074	0.038

Now, let's see following shrinkage and 95% interval plots for more intuition. It is obvious that sample means (empty dots) on the upper horizontal line shrink towards two different means, 0.310 and 0.233. For reference, the red line symbols on dots are for when two or more points have the same mean and are plotted over each other. For example, five players (from the 11th player to the 15th) have the same sample mean (0.222) and at this point on the upper horizontal line, there are short red lines toward five directions.

`R> plot(b)`

In Figure 6 the 95% interval plot shows us range of true batting average for each player, which clarifies the regression toward the mean (RTTM) within two groups. Let's see the 10th, 14th, and 15th players on the graph for example. They are outfielders but their observed batting averages are far lower than the first five outfielders. RTTM means that it can happen by their bad luck though in the long run their batting averages will come back to their expected ones as outfielders (blue horizontal lines). So, their posterior means (red dots) can be interpreted as their RTTM.

Then, how much can we trust these interval estimates? The following frequency method checking that regards the estimated values,  $\hat{r}$  ( $=112.95$ ) and  $\hat{\beta}$  ( $=(-1.194, 0.389)^T$ ), as

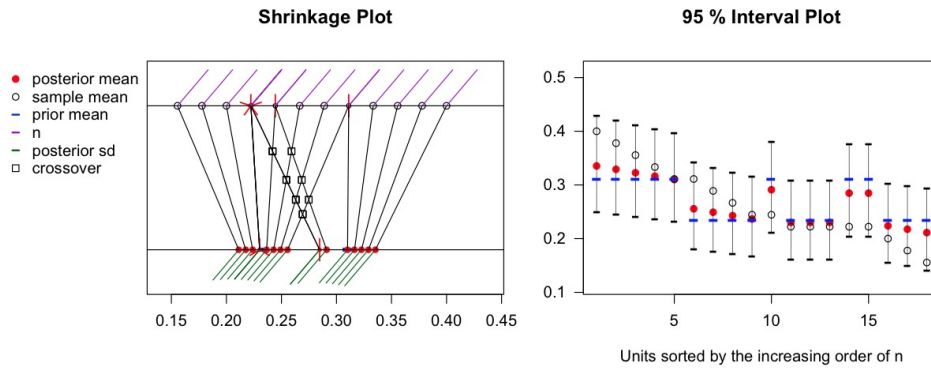


Figure 6: Shrinkage plot and 95% interval plot

true values when it generates pseudo-datasets will answer it. For reference, if we want to try different true parameters, the appropriate code will be `coverage(b, A.or.r = 100, reg.coef = c(-1, 0.2), nsim = 10000)` instead of below one.

```
R> bcv <- coverage(b, nsim = 10000)
```

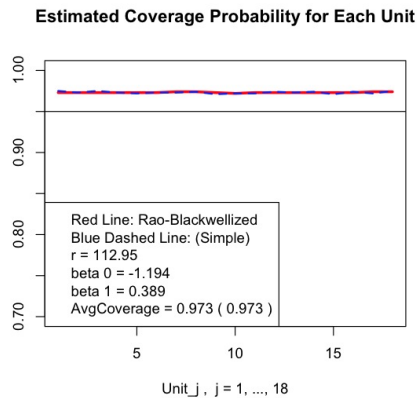


Figure 7: Coverage plot via frequency method checking for 18 players

Finally, in Figure 7, we see that the estimated average coverage probability is 0.973 based on the Rao-Blackwellization, conservatively satisfying the definition of the 95% confidence interval. As for the running time, it took 243 seconds for MacBook Pro equipped with a 2.3 GHz dual-core Intel i5 CPU to execute 10,000 simulations.

## 6. Discussion

**Rgbp** is an R package for estimating and validating a two-level hierarchical model. The package aims to provide a procedure that is not only fast and easy to use but has good frequency properties and can be used in many scenarios. The package provides “frequency



method checking” functionality to examine repeated sampling properties and test that the method is valid at given hyper-parameter values.

In addition to good frequency properties Bayesians will be able to use the package to see the results from a non-informative reference point. This allows the user to examine whether it is worth to implement a full Bayesian model (which is often more time consuming).

Due to the fact that the estimation procedures in **Rgbp** rely on differentiation the package is extremely quick in fitting the available models. This makes the package ideal to be used in simulation studies where a hierarchical model needs to be fitted at every iteration and where running a full Bayesian model (via MCMC) would be computationally impractical.

## 7. Acknowledgments

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