

Examples from Multilevel Software Comparative Reviews

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Abstract

The Center for Multilevel Modelling at the Institute of Education, London maintains a web site of “Software reviews of multilevel modeling packages”. The data sets discussed in the reviews are available at this web site. We have incorporated these data sets in the `lme4` package for R and, in this vignette, provide the results of fitting several models to these data sets.

1 Introduction

2 Two-level normal models

The `Exam` data set is used in fitting examples of two-level normal multilevel models.

```
> data(Exam)
> str(Exam)
`data.frame`:      4059 obs. of  10 variables:
 $ school  : Factor w/ 65 levels "1","2","3","4",...: 1 1 1 1 1 1 1 1 1 1 ...
 $ normexam: num   0.261  0.134 -1.724  0.968  0.544 ...
 $ schgend : Factor w/ 3 levels "mixed","boys",...: 1 1 1 1 1 1 1 1 1 1 ...
 $ schavg  : num   0.166  0.166  0.166  0.166  0.166 ...
 $ vr      : Factor w/ 3 levels "bottom 25%","mi..",...: 2 2 2 2 2 2 2 2 2 2 ...
 $ intake  : Factor w/ 3 levels "bottom 25%","mi..",...: 1 2 3 2 2 1 3 2 2 3 ...
 $ standLRT: num   0.619  0.206 -1.365  0.206  0.371 ...
 $ sex     : Factor w/ 2 levels "F","M": 1 1 2 1 1 2 2 1 2 ...
 $ type    : Factor w/ 2 levels "Mxd","Sngl": 1 1 1 1 1 1 1 1 1 1 ...
 $ student : Factor w/ 650 levels "1","2","3","4",...: 143 145 142 141 138 155 158 115 117 113 ...
```

```

> sysgc.time(Eml <- lme(normexam ~ standLRT + sex + schgend,
+   Exam, ~1 | school), gc = TRUE)
[1] 0.05 0.00 0.06 0.00 0.00
> summary(Eml)

Linear mixed-effects model fit by REML
Fixed: normexam ~ standLRT + sex + schgend
Data: Exam
      AIC      BIC    logLik
9361.673 9405.834 -4673.837

Random effects:
Groups   Name             Variance Std.Dev.
school   (Intercept) 0.085829 0.29297
Residual                   0.562534 0.75002
# of obs: 4059, groups: school, 65

Fixed effects:
              Estimate Std. Error   DF t value Pr(>|t|)
(Intercept) -1.0493e-03 5.5569e-02 4054 -0.0189  0.98494
standLRT      5.5975e-01 1.2450e-02 4054 44.9601 < 2.2e-16
sexM          -1.6739e-01 3.4100e-02 4054 -4.9089 9.519e-07
schgendboys   1.7769e-01 1.1347e-01 4054  1.5659  0.11745
schgendgirls  1.5900e-01 8.9403e-02 4054  1.7784  0.07541

Correlation of Fixed Effects:
              (Intr) stnLRT sexM   schgndb
standLRT      -0.014
sexM          -0.316  0.061
schgendboys   -0.395 -0.003 -0.145
schgendgrls   -0.622  0.009  0.197  0.245

> sysgc.time(Em2 <- lme(normexam ~ standLRT * sex + schgend,
+   Exam, ~1 | school), gc = TRUE)
[1] 0.05 0.00 0.07 0.00 0.00
> summary(Em2)

Linear mixed-effects model fit by REML
Fixed: normexam ~ standLRT * sex + schgend
Data: Exam
      AIC      BIC    logLik
9369.204 9419.673 -4676.602

Random effects:
Groups   Name             Variance Std.Dev.
school   (Intercept) 0.085856 0.29301
Residual                   0.562666 0.75011
# of obs: 4059, groups: school, 65

Fixed effects:
              Estimate Std. Error   DF t value Pr(>|t|)
(Intercept) -8.4349e-04 5.5586e-02 4053 -0.0152  0.98789
standLRT      5.5745e-01 1.6662e-02 4053 33.4572 < 2.2e-16
sexM          -1.6733e-01 3.4105e-02 4053 -4.9064 9.638e-07
schgendboys   1.7765e-01 1.1349e-01 4053  1.5653  0.11759
schgendgirls  1.5879e-01 8.9422e-02 4053  1.7757  0.07586
standLRT:sexM  5.1121e-03 2.4584e-02 4053  0.2079  0.83528

```

```

Correlation of Fixed Effects:
              (Intr) stnLRT sexM   schgndb schgndg
standLRT      -0.022
sexM           -0.316  0.040
schgendboys   -0.395 -0.001 -0.145
schgendgrls   -0.622  0.014  0.196  0.245
stndLRT:sexM   0.018 -0.664  0.008 -0.002  -0.011

> sysgc.time(Em3 <- lme(normexam ~ standLRT * sex + schgend,
+   Exam, ~standLRT | school), gc = TRUE)

[1] 0.07 0.00 0.09 0.00 0.00

> summary(Em3)

Linear mixed-effects model fit by REML
Fixed: normexam ~ standLRT * sex + schgend
Data: Exam
      AIC      BIC    logLik
9328.242 9391.329 -4654.121

Random effects:
Groups   Name      Variance Std.Dev. Corr
school   (Intercept) 0.083723 0.28935
          standLRT    0.015250 0.12349  0.575
Residual              0.550374 0.74187
# of obs: 4059, groups: school, 65

Fixed effects:
              Estimate Std. Error  DF t value Pr(>|t|)
(Intercept)  -2.1277e-02  5.3279e-02 4053 -0.3993  0.68966
standLRT      5.5713e-01  2.4349e-02 4053 22.8812 < 2.2e-16
sexM          -1.6859e-01  3.3844e-02 4053 -4.9814 6.576e-07
schgendboys   1.7751e-01  1.0211e-01 4053  1.7384  0.08221
schgendgirls  1.7790e-01  8.2104e-02 4053  2.1668  0.03031
standLRT:sexM -6.8757e-03  2.9540e-02 4053 -0.2328  0.81596

Correlation of Fixed Effects:
              (Intr) stnLRT sexM   schgndb schgndg
standLRT      0.200
sexM           -0.337  0.026
schgendboys   -0.354 -0.048 -0.148
schgendgrls   -0.600  0.116  0.225  0.218
stndLRT:sexM   0.067 -0.559  0.010  0.094  -0.181

```

There are some interesting aspects of data management that show up in the analysis of these data. The `student` variable is an identifier of the student within the `school`. It would be best to combine the indicators of school and student to get a unique identifier of the student.

```

> Exam$ids <- interaction(Exam$school, Exam$student, drop = TRUE)
> str(Exam)

`data.frame`:      4059 obs. of  11 variables:
 $ school : Factor w/ 65 levels "1","2","3","4",...: 1 1 1 1 1 1 1 1 1 1 ...
 $ normexam: num  0.261  0.134 -1.724  0.968  0.544 ...
 $ schgend : Factor w/ 3 levels "mixed","boys",...: 1 1 1 1 1 1 1 1 1 1 ...
 $ schavg  : num  0.166  0.166  0.166  0.166  0.166 ...
 $ vr      : Factor w/ 3 levels "bottom 25%","mi...",...: 2 2 2 2 2 2 2 2 2 2 ...

```

```

$ intake : Factor w/ 3 levels "bottom 25%","mi...",...: 1 2 3 2 2 1 3 2 2 3 ...
$ standLRT: num 0.619 0.206 -1.365 0.206 0.371 ...
$ sex : Factor w/ 2 levels "F","M": 1 1 2 1 1 2 2 2 1 2 ...
$ type : Factor w/ 2 levels "Mxd","Sngl": 1 1 1 1 1 1 1 1 1 1 ...
$ student : Factor w/ 650 levels "1","2","3","4",...: 143 145 142 141 138 155 158 115 117 113 ...
$ ids : Factor w/ 4055 levels "1.143","1.145",...: 1 2 3 4 5 6 7 8 9 10 ...

```

Notice that there are 4059 observations but only 4055 unique levels of student within school. We can check the ones that are duplicated

```

> Exam$ids[which(duplicated(Exam$ids))]
[1] 43.86 50.39 52.2 52.21
4055 Levels: 1.143 1.145 1.142 1.141 1.138 1.155 1.158 1.115 1.117 ... 65.56

```

One of these duplicated cases is particularly interesting. One of the students with the duplicated student id 86 in school 43 is the only male student in this mixed school. This is probably a case of a misrecorded school.

3 Three-level Normal Models

Data from the 1997 A-level Chemistry exam are available as Chem97.

```

> data(Chem97)
> str(Chem97)
`data.frame`:      31022 obs. of  8 variables:
 $ lea      : Factor w/ 131 levels "1","2","3","4",...: 1 1 1 1 1 1 1 1 1 1 ...
 $ school   : Factor w/ 2410 levels "1","2","3","4",...: 1 1 1 1 1 1 1 1 1 1 ...
 $ student  : Factor w/ 31022 levels "1","2","3","4",...: 1 2 3 4 5 6 7 8 9 10 ...
 $ score    : num 4 10 10 10 8 10 6 8 4 10 ...
 $ gender   : Factor w/ 2 levels "M","F": 2 2 2 2 2 2 2 2 2 2 ...
 $ age      : num 3 -3 -4 -2 -1 4 1 4 3 0 ...
 $ gcsecore: num 6.62 7.62 7.25 7.50 6.44 ...
 $ gcsecnt  : num 0.339 1.339 0.964 1.214 0.158 ...
> sysgc.time(mC1 <- lme(score ~ 1, Chem97, ~1 | lea/school))
[1] 0.42 0.01 0.54 0.00 0.00
> summary(mC1)
Linear mixed-effects model fit by REML
Fixed: score ~ 1
Data: Chem97
      AIC      BIC    logLik
157881.8 157915.2 -78936.9

Random effects:
Groups   Name      Variance Std.Dev.
school   (Intercept) 2.74872  1.65793
lea      (Intercept) 0.15349  0.39178
Residual                   8.51609  2.91823
# of obs: 31022, groups: school, 2410; lea, 131

Fixed effects:
              Estimate Std. Error    DF t value Pr(>|t|)
(Intercept) 5.3190e+00 5.8108e-02 31021  91.536 < 2.2e-16

```

```

> sysgc.time(mC2 <- lme(score ~ gcsecnt, Chem97, ~1 | lea/school))
[1] 1.07 0.01 1.36 0.00 0.00
> summary(mC2)
Linear mixed-effects model fit by REML
Fixed: score ~ gcsecnt
Data: Chem97
      AIC      BIC    logLik
141707 141748.7 -70848.5

Random effects:
Groups   Name             Variance Std.Dev.
school   (Intercept)  1.166198  1.07991
lea      (Intercept)  0.014766  0.12151
Residual                    5.154202  2.27029
# of obs: 31022, groups: school, 2410; lea, 131

Fixed effects:
              Estimate Std. Error    DF t value Pr(>|t|)
(Intercept)  5.6355e+00  3.1235e-02 31020  180.42 < 2.2e-16
gcsecnt      2.4726e+00  1.6904e-02 31020  146.27 < 2.2e-16

Correlation of Fixed Effects:
      (Intr)
gcsecnt  0.058

```

4 Two-level models for binary data

The data frame `Contraception` provides data from the Bangladesh fertility survey.

```

> data(Contraception)
> str(Contraception)
`data.frame`:      1934 obs. of  6 variables:
 $ woman   : Factor w/ 1934 levels "1","2","3","4",...: 1 2 3 4 5 6 7 8 9 10 ...
 $ district: Factor w/ 60 levels "1","2","3","4",...: 1 1 1 1 1 1 1 1 1 1 ...
 $ use      : Factor w/ 2 levels "N","Y": 1 1 1 1 1 1 1 1 1 1 ...
 $ livch    : Factor w/ 4 levels "0","1","2","3+": 4 1 3 4 1 1 4 4 2 4 ...
 $ age      : num  18.44 -5.56  1.44  8.44 -13.56 ...
 $ urban    : Factor w/ 2 levels "N","Y": 2 2 2 2 2 2 2 2 2 2 ...

> summary(Contraception[, -1])
      district      use      livch      age      urban
14      : 118    N:1175    0 :530    Min.   :-13.560000    N:1372
1       : 117    Y: 759    1 :356    1st Qu.: -7.559900    Y: 562
46      : 86                2 :305    Median : -1.559900
25      : 67                3+:743    Mean   :  0.002198
6       : 65                      3rd Qu.:  6.440000
30      : 61                      Max.   : 19.440000
(Other):1420

> sysgc.time(mB1 <- GLMM(use ~ urban + age + livch, binomial,
+   Contraception, ~1 | district))
[1] 0.73 0.01 0.99 0.00 0.00
> summary(mB1)

```

Generalized Linear Mixed Model

Family: binomial family with logit link

Fixed: use ~ urban + age + livch

Data: Contraception

	AIC	BIC	logLik
	2429.664	2474.203	-1206.832

Random effects:

Groups	Name	Variance	Std.Dev.
	district (Intercept)	0.21518	0.46387

of obs: 1934, groups: district, 60

Estimated scale (compare to 1) 0.9844111

Fixed effects:

	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-1.6606460	0.1452147	-11.4358	< 2.2e-16
urbanY	0.7193097	0.1183317	6.0788	1.211e-09
age	-0.0261558	0.0078152	-3.3468	0.0008176
livch1	1.0921026	0.1565011	6.9782	2.989e-12
livch2	1.3545533	0.1729641	7.8314	4.824e-15
livch3+	1.3241531	0.1773558	7.4661	8.262e-14

Correlation of Fixed Effects:

	(Intr)	urbanY	age	livch1	livch2
urbanY		-0.300			
age		0.446	-0.046		
livch1		-0.589	0.059	-0.211	
livch2		-0.631	0.094	-0.378	0.488
livch3+		-0.748	0.098	-0.674	0.539

```
> sysgc.time(mB2 <- GLMM(use ~ urban + age + livch, binomial,  
+ Contraception, ~1 | district, method = "Laplace"))
```

Using optimizer nlm

```
[1] 28.79 0.12 35.99 0.00 0.00
```

```
> summary(mB2)
```

Generalized Linear Mixed Model

Family: binomial family with logit link

Fixed: use ~ urban + age + livch

Data: Contraception

	AIC	BIC	logLik
	2417.616	2428.750	-1206.808

Random effects:

Groups	Name	Variance	Std.Dev.
	district (Intercept)	0.21239	0.46086

of obs: 1934, groups: district, 60

Estimated scale (compare to 1) 0.985962

Fixed effects:

	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-1.6897183	0.1459302	-11.5789	< 2.2e-16
urbanY	0.7329919	0.1192191	6.1483	7.833e-10
age	-0.0265959	0.0078772	-3.3763	0.0007347

```

livch1      1.1091870  0.1576911  7.0339 2.008e-12
livch2      1.3764020  0.1743348  7.8952 2.899e-15
livch3+     1.3452475  0.1787111  7.5275 5.172e-14

Correlation of Fixed Effects:
      (Intr) urbanY age    livch1 livch2
urbanY  -0.301
age      0.448 -0.046
livch1   -0.589  0.059 -0.210
livch2   -0.631  0.094 -0.378  0.487
livch3+  -0.749  0.099 -0.674  0.538  0.618

> sysgc.time(mB3 <- GLMM(use ~ urban + age + livch, family = binomial,
+   data = Contraception, random = ~urban | district))
[1] 0.53 0.00 0.80 0.00 0.00

> summary(mB3)

Generalized Linear Mixed Model

Family: binomial family with logit link
Fixed: use ~ urban + age + livch
Data: Contraception
      AIC      BIC    logLik
2225.720 2281.394 -1102.860

Random effects:
Groups   Name             Variance Std.Dev. Corr
district (Intercept) 0.38774  0.62269
          urbanY      0.66745  0.81698  -0.793
# of obs: 1934, groups: district, 60

Estimated scale (compare to 1)  0.9759564

Fixed effects:
      Estimate Std. Error z value Pr(>|z|)
(Intercept) -1.6665200  0.1572532 -10.5977 < 2.2e-16
urbanY       0.7914232  0.1681257  4.7073 2.510e-06
age         -0.0258502  0.0079082 -3.2688 0.00108
livch1       1.0987723  0.1580051  6.9540 3.550e-12
livch2       1.3342511  0.1745854  7.6424 2.132e-14
livch3+      1.3227367  0.1795440  7.3672 1.743e-13

Correlation of Fixed Effects:
      (Intr) urbanY age    livch1 livch2
urbanY  -0.481
age      0.416 -0.036
livch1   -0.548  0.038 -0.211
livch2   -0.586  0.068 -0.378  0.487
livch3+  -0.695  0.062 -0.674  0.537  0.616

```

5 Growth curve model for repeated measures data

```

> data(Oxboys)
> str(Oxboys)

```

```

Formal class 'groupedData' [package "lme4"] with 6 slots
..@ data :`data.frame`:      234 obs. of  4 variables:
.. ..$ Subject : Ord.factor w/ 26 levels "10"<"26"<"25"<...: 13 13 13 13 13 13 13 13 13 13 5 ...
.. ..$ age      : num [1:234] -1.0000 -0.7479 -0.4630 -0.1643 -0.0027 ...
.. ..$ height   : num [1:234] 140 143 145 147 148 ...
.. ..$ Occasion: Ord.factor w/ 9 levels "1"<"2"<"3"<"4"<...: 1 2 3 4 5 6 7 8 9 1 ...
.. ..- attr(*, "FUN")=function (x)
.. .. ..- attr(*, "source")= chr "function (x) max(x, na.rm = TRUE)"
..@ formula:Class 'formula' length 3 height ~ age | Subject
.. .. ..- attr(*, ".Environment")=length 31 <environment>
..@ outer :Class 'formula' length 2 ~0
.. .. ..- attr(*, ".Environment")=length 3 <environment>
..@ inner :Class 'formula' length 2 ~0
.. .. ..- attr(*, ".Environment")=length 3 <environment>
..@ labels :List of 2
.. ..$ y: chr "Height"
.. ..$ x: chr "Centered age"
..@ units :List of 1
.. ..$ y: chr "(cm)"
> sysgc.time(mX1 <- lme(height ~ age + I(age^2) + I(age^3) +
+ I(age^4), Oxboys, ~age + I(age^2) | Subject), gc = TRUE)
[1] 0.19 0.00 0.22 0.00 0.00
> summary(mX1)

Linear mixed-effects model fit by REML
Fixed: height ~ age + I(age^2) + I(age^3) + I(age^4)
Data: Oxboys
      AIC      BIC    logLik
651.9081 693.372 -313.9541

Random effects:
Groups Name Variance Std.Dev. Corr
Subject (Intercept) 64.03464 8.00216
      age      2.86418 1.69239 0.614
      I(age^2) 0.67429 0.82115 0.215 0.658
Residual      0.21737 0.46623
# of obs: 234, groups: Subject, 26

Fixed effects:
      Estimate Std. Error DF t value Pr(>|t|)
(Intercept) 149.01887 1.57036 229 94.8946 < 2.2e-16
age          6.17418 0.35650 229 17.3187 < 2.2e-16
I(age^2)     1.12823 0.35144 229 3.2103 0.001516
I(age^3)     0.45385 0.16246 229 2.7937 0.005653
I(age^4)    -0.37690 0.30018 229 -1.2556 0.210552

Correlation of Fixed Effects:
      (Intr) age      I(g^2) I(g^3)
age      0.572
I(age^2) 0.076 0.264
I(age^3) -0.001 -0.340 0.025
I(age^4) 0.021 0.016 -0.857 -0.021

> sysgc.time(mX2 <- lme(height ~ poly(age, 4), Oxboys, ~age +
+ I(age^2) | Subject), gc = TRUE)
[1] 0.10 0.00 0.13 0.00 0.00
> summary(mX2)

```

```

Linear mixed-effects model fit by REML
Fixed: height ~ poly(age, 4)
Data: Oxboys
      AIC      BIC    logLik
640.8686 682.3324 -308.4343

Random effects:
Groups   Name             Variance Std.Dev. Corr
Subject  (Intercept)  64.03464  8.00216
          age          2.86418  1.69239   0.614
          I(age^2)     0.67429  0.82115   0.215 0.658
Residual                    0.21737  0.46623
# of obs: 234, groups: Subject, 26

Fixed effects:
              Estimate Std. Error  DF t value  Pr(>|t|)
(Intercept)   149.51976    1.59031 229 94.0194 < 2.2e-16
poly(age, 4)1   64.54095    3.32787 229 19.3941 < 2.2e-16
poly(age, 4)2    4.20322    1.02361 229  4.1063 5.597e-05
poly(age, 4)3    1.29077    0.46628 229  2.7682 0.006098
poly(age, 4)4   -0.58547    0.46630 229 -1.2556 0.210552

Correlation of Fixed Effects:
              (Intr) p(,4)1 p(,4)2 p(,4)3
poly(ag,4)1  0.631
poly(ag,4)2  0.230  0.583
poly(ag,4)3  0.000  0.000  0.000
poly(ag,4)4  0.000  0.000  0.000  0.000

```

6 Cross-classification model

```

> data(ScotsSec)
> str(ScotsSec)
`data.frame':      3435 obs. of  6 variables:
 $ verbal : num  11 0 -14 -6 -30 -17 -17 -11 -9 -19 ...
 $ attain : num  10 3 2 3 2 2 4 6 4 2 ...
 $ primary: Factor w/ 148 levels "1","2","3","4",...: 1 1 1 1 1 1 1 1 1 1 ...
 $ sex    : Factor w/ 2 levels "M","F": 1 2 1 1 2 2 2 1 1 1 ...
 $ social : num   0 0 0 20 0 0 0 0 0 0 ...
 $ second : Factor w/ 19 levels "1","2","3","4",...: 9 9 9 9 9 9 1 1 9 9 ...

> sysgc.time(mS1 <- lme(attain ~ sex, ScotsSec, ~1 | primary +
+   second))
[1] 0.08 0.00 0.09 0.00 0.00

> summary(mS1)

Linear mixed-effects model fit by REML
Fixed: attain ~ sex
Data: ScotsSec
      AIC      BIC    logLik
17137.91 17168.62 -8563.956

Random effects:
Groups   Name             Variance Std.Dev.
primary  (Intercept)  1.10962  1.0534
second   (Intercept)  0.36966  0.6080

```

```

Residual          8.05511  2.8382
# of obs: 3435, groups: primary, 148; second, 19

Fixed effects:
      Estimate Std. Error   DF t value  Pr(>|t|)
(Intercept) 5.2552e+00 1.8432e-01 3433 28.5108 < 2.2e-16
sexF        4.9851e-01 9.8255e-02 3433  5.0737 4.109e-07

Correlation of Fixed Effects:
      (Intr)
sexF -0.264

```