

An Advanced User's Guide to Stat-JR version 1.0.6

Programming and Documentation by

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WJB November 2018.

1 About Stat-JR

1.1 Stat-JR: software for scaling statistical heights.

The use of statistical modelling by researchers in all disciplines is growing in prominence. There is an increase in the availability and complexity of data sources, and an increase in the sophistication of statistical methods that can be used. For the novice practitioner of statistical modelling it can seem like you are stuck at the bottom of a mountain, and current statistical software allows you to progress slowly up certain specific paths depending on the software used. Our aim in the Stat-JR package is to assist practitioners in making their initial steps up the mountain, but also to cater for more advanced practitioners who have already journeyed high up the path, but want to assist their novice colleagues in making their ascent as well.

One issue with complex statistical modelling is that using the latest techniques can involve having to learn new pieces of software. This is a little like taking a particular path up a mountain with one piece of software, spotting a nearby area of interest on the mountainside (e.g. a different type of statistical model), and then having to descend again and take another path, with another piece of software, all the way up again to eventually get there, when ideally you'd just jump across! In Stat-JR we aim to circumvent this problem via our interoperability features so that the same user interface can sit on top of several software packages thus removing the need to learn multiple packages. To aid understanding, the interface will allow the curious user to look at the syntax files for each package to learn directly how each package fits their specific problem.

To complete the picture, the final group of users to be targeted by Stat-JR is the statistical algorithm writers. These individuals are experts at creating new algorithms for fitting new models, or better algorithms for existing models, and can be viewed as sitting high on the peaks with limited links to the applied researchers who might benefit from their expertise. Stat-JR will build links by incorporating tools to allow this group to connect their algorithmic code to the interface through template-writing, and hence allow it to be exposed to practitioners. They can also share their code with other algorithm developers, and compare their algorithms with other algorithms for the same problem. A template is a pre-specified form that has to be completed for each task: some run models, others plot graphs, or provide summary statistics; we supply a number of commonly used templates and advanced users can use their own – see the Advanced User's Guide. It is the use of templates that allows a building block, modular approach to analysis and model specification.

At the outset it is worth stressing that there a number of other features of the software that should persuade you to adopt it, in addition to interoperability. The first is flexibility – it is possible to fit a very large and growing number of different types of model. Second, we have paid particular attention to speed of estimation and therefore in comparison tests, we have found that the package compares well with alternatives. Third it is possible to embed the software's templates inside an e-book which is exceedingly helpful for training and learning, and also for replication. Fourth, it provides a very powerful, yet easy to use environment for accessing state-of-the-art Markov Chain Monte Carlo procedures for calculating model estimates and functions of model estimates, via eStat engine. The eStat engine is a newly-developed estimation engine with the advantage of being transparent in that all the algebra, and even the program code, is available for inspection.

Many of the ideas within the Stat-JR system were the brainchild of Jon Rasbash (hence the “JR” in Stat-JR). Sadly, Jon died suddenly just as we began developing the system, and so we dedicate this software to his memory. We hope that you enjoy using Stat-JR and are inspired to become part of the Stat-JR community: either through the creation of your own templates that can be shared with others, or simply by providing feedback on existing templates.

Happy Modelling,

The Stat-JR team.

1.2 About the Advanced User’s Guide

This *Advanced Guide* is meant to complement the *Beginner’s Guide to Stat-JR’s TREE interface* and we recommend that users read that guide first to get an idea of how the Stat-JR software works. A major component of the Stat-JR package is the use of (often user-written) templates. Templates are pieces of computer code (written in the Python language (Rossum); see <https://www.python.org/>) that perform a specific task. Many of the templates are used to fit a specific family of statistical models although there are other templates that perform data input, data manipulation, graphical output, and so on.

In this document it is our aim to give users who intend to write their own templates, or more generally are interested in how the Stat-JR system works, more details about how to write templates and to some degree how the system fits together. We will do this by showing the code for several of the templates we have written and giving a detailed explanation of what each function and even in places each line of code does.

An initial question posed by potential template writers has been what language are templates written in and when told ‘Python’ then ask whether we are providing an introductory chapter on this language. We are not specifically writing an introductory chapter on Python (good books include Hetland (Hetland, 2005) and Lutz and Ascher (Lutz & Ascher, 2005), as well as the many online resources available) as it has a vast language and we will mainly be interested in specific aspects of the language, some of which are non-standard and specific to Stat-JR. In fact many of the functions that make up a template in Stat-JR are designed to create text blocks in other languages, for example C++ (Stroustrup, 2013), BUGS or any of the other macro languages associated with the software packages supported via inter-operability. This is not to say that reading up on Python is without merit and certainly Python experts will find writing templates initially easier than others (though more because of their programming skills than their Python skills *per se*).

Our advice is therefore to work through this guide first and try the exercises and have a Python book as a backstop for when you are stuck writing your own templates. We will now give instructions into how to install all the software needed to run Stat-JR before moving on to our first example template.

2 Installation instructions

Stat-JR has a dedicated website for requests for a copy of the software and which contains instructions for installation. This is currently located at <http://www.bristol.ac.uk/cmm/software/statjr/index.html>

To run the software:

Stat-JR runs in a web browser; whilst it will work in most web browsers we suggest not using Internet Explorer, although it is hoped support for more browsers will be added in future. To start Stat-JR, select the *Stat-JR TREE* link from the *Centre for Multilevel Modelling* suite on the start up menu; this should bring up a web browser.

When you open *TREE*, this action starts a Command prompt window in the background to which commands are printed out. This window is useful for viewing what the system is doing: for example, on the machine on which I have run *TREE* I can see the following commands:

```
WARNING:root:Failed to load package GenStat_model (GenStat not found)
WARNING:root:Failed to load package Minitab_model (Minitab not found)
WARNING:root:Failed to load package Minitab_script (Minitab not found)
WARNING:root:Failed to load package SABRE (Sabre not found)
INFO:root:Trying to locate and open default web browser
```

The last line quoted here (although more lines will appear beneath it on start-up) indicates that Stat-JR is locating the default web browser on your machine; once it has done so it will open that web browser and display *TREE*'s welcome page. The lines such as "WARNING:root:Failed to load package GenStat model (GenStat not found)" are not necessarily problematic but are warning you that the Genstat (VSN International, 2015) statistical package – one of the third-party statistical packages with which Stat-JR can interoperate – has not be found (where Stat-JR expects to find it if it is installed) on your particular machine.

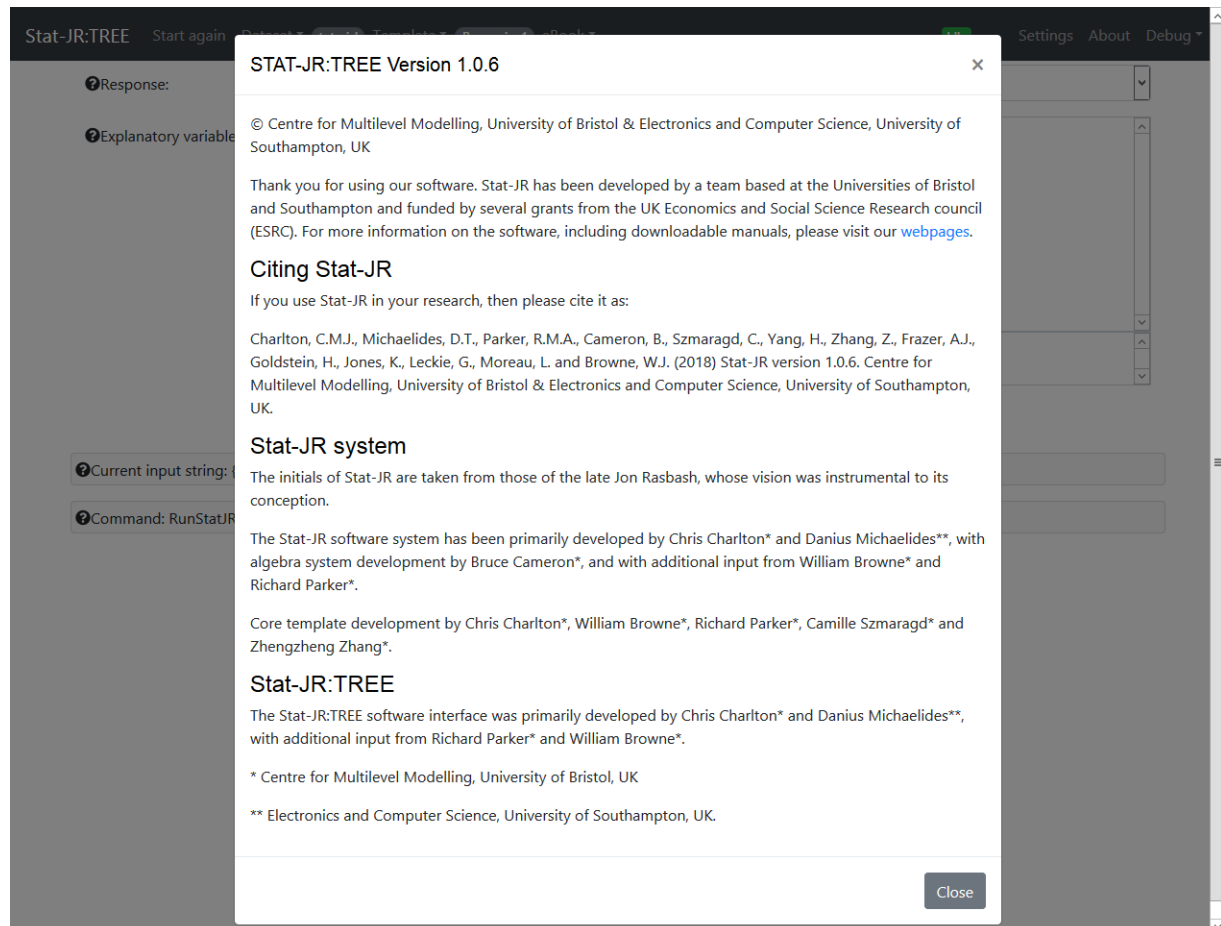
Stat-JR works best with either Chrome or Firefox, so if the default browser on your machine is Internet Explorer it is best to open a different browser and copy the html path to it; this will be something like localhost:52228 (although the number will likely differ each time you run Stat-JR).

TREE is short for *Template Reading and Execution Environment* and is an interface into Stat-JR that allows the user to look at a single template and dataset at a time. There are also an eBook interface (called DEEP), a Python command line interface, and a workflow interface called LEAF (*Logging and Execution of Analysis Flows*), but in this manual we stick with the *TREE* interface.

3 A simple regression template example

3.1 Running a first template

We will firstly consider a very simple template that is included in the core model templates distributed with Stat-JR which has the title *Regression1*. This template is used in the Beginner's Guide and perhaps before looking at the code it would be good to run the template again in the TREE interface to see what it does. To do this start up the Stat-JR package as directed in Section 0. If you refresh the screen and click on the About button to the top left you should be greeted by the following display:



If you click on **Close** then the software will move from this information to the general working page. Here you will see that the template *Regression1* is the default template on start up and the default dataset is called *tutorial* (see the Beginner's Guide for more information on the dataset). The screen will look as shown below:

Stat-JR:TREE Start again Dataset **tutorial** Template **Regression1** eBook Idle Settings About Debug

? Response:

? Explanatory variables:

- school
- student
- normexam
- cons
- standlrt
- girl
- schgend
- avslrt
- schav
- vrband

Next

? Current input string: {}

? Command: RunStatJR(template='Regression1', dataset='tutorial', invars = {}, estoptions = {})

Here you will see a **main pane** which is looking for inputs for a response (a single select list) and explanatory variables (a multiple select list). We will here select *normexam* as the response and *cons* and *standlrt* as the explanatory variables as shown below:

Stat-JR:TREE Start again Dataset **tutorial** Template **Regression1** eBook Idle Settings About Debug

? Response: normexam

? Explanatory variables:

- school
- student
- normexam
- girl
- schgend
- avslrt
- schav
- vrband
- cons
- standlrt

☐ treat cons as categorical
☐ treat standlrt as categorical

Next

? Current input string: {}

? Command: RunStatJR(template='Regression1', dataset='tutorial', invars = {}, estoptions = {})

Next we click on the **Next** button and fill in the input boxes that appear as follows (NB the input string is `{'burnin': '500', 'defaultsv': 'Yes', 'outdata': 'out', 'thinning': '1', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'y': 'normexam', 'x': 'cons,standlrt', 'seed': '1', 'makepred': 'No'}`; this can be entered into the input string box via **Template > Set Inputs** to populate the input values as an alternative to pointing and clicking through):

Stat-JR:TREE
Start again
Dataset ▾
tutorial
Template ▾
Regression1
eBook ▾
Idle
Settings
About
Debug ▾

Response:	normexam remove
Explanatory variables:	cons,standlrt remove
Number of chains:	3 remove
Random Seed:	1 remove
Length of burnin:	500 remove
Number of iterations:	2000 remove
Thinning:	1 remove
Use default algorithm settings:	Yes remove
Generate prediction dataset:	No remove
Use default starting values:	Yes remove
Name of output results:	<input type="text" value="out"/>

Next

Current input string: {'burnin': '500', 'defaultsv': 'Yes', 'thinning': '1', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'y': 'normexam', 'x': 'cons,standlrt', 'seed': '1', 'makepred': 'No'}

Command: RunStatJR(template='Regression1', dataset='tutorial', invars = {'y': 'normexam', 'x': 'cons,standlrt'}, estoptions = {'burnin': '500', 'defaultsv': 'Yes', 'thinning': '1', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'seed': '1', 'makepred': 'No'})

Note that when all boxes on the screen are filled in, clicking the **Next** button will show further inputs if there are any. Here we have given a name of the object/dataset where the results are to be stored. The other inputs are for the MCMC estimation methods we are using. When you click **Next** again the software will perform some procedures in the background and after a short while the screen will expand to include a lower pane with an accompanying pull down list in which various objects generated by Stat-JR can be selected and displayed thus:

Stat-JR:TREE
Start again
Dataset ▾
tutorial
Template ▾
Regression1
eBook ▾
Ready (6s)
Settings
About
Debug ▾

Name of output results:
out
remove

Run

Current input string: {'burnin': '500', 'defaults': 'Yes', 'outdata': 'out', 'thinning': '1', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'y': 'normexam', 'x': 'cons,standlrt', 'seed': '1', 'makepred': 'No'}

Command: RunStatJR(template='Regression1', dataset='tutorial', invars = {'y': 'normexam', 'x': 'cons,standlrt'}, estoptions = {'burnin': '500', 'defaults': 'Yes', 'thinning': '1', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'outdata': 'out', 'seed': '1', 'makepred': 'No'})

Edit
equation.tex
Popout

$$\begin{aligned}
\text{normexam}_i &\sim N(\mu_i, \sigma^2) \\
\mu_i &= \beta_0 \text{cons}_i + \beta_1 \text{standlrt}_i \\
\beta_0 &\propto 1 \\
\beta_1 &\propto 1 \\
\tau &\sim \Gamma(0.001, 0.001) \\
\sigma^2 &= 1/\tau
\end{aligned}$$

The pull-down list contains several objects including the model code which looks a bit like WinBUGS (Lunn, Thomas, Best, & Spiegelhalter, 2000) code which the system uses to create code that will fit the model. Currently a nicely formatted mathematical description of the model (in LaTeX code) is shown in the pane and named **equation.tex**. Objects can be displayed in their own tab by clicking on the word *Popout* to the right of the pull-down list:

Stat-JR:TREE

$$\begin{aligned}
\text{normexam}_i &\sim N(\mu_i, \sigma^2) \\
\mu_i &= \beta_0 \text{cons}_i + \beta_1 \text{standlrt}_i \\
\beta_0 &\propto 1 \\
\beta_1 &\propto 1 \\
\tau &\sim \Gamma(0.001, 0.001) \\
\sigma^2 &= 1/\tau
\end{aligned}$$

Back in the first Stat-JR tab there is a green **Run** button above the output pane. If we click this button then after a short while the model will run. There is a counter in the bar at the top of the tab which indicates when Stat-JR is working (coloured blue) or ready (coloured green) and how long the execution took. The first time a model is run the code will need compiling which will take a while. When the execution has finished we will have more objects to choose from in the pull-down list including the results (**ModelResults**) which we show popped out below:

Results

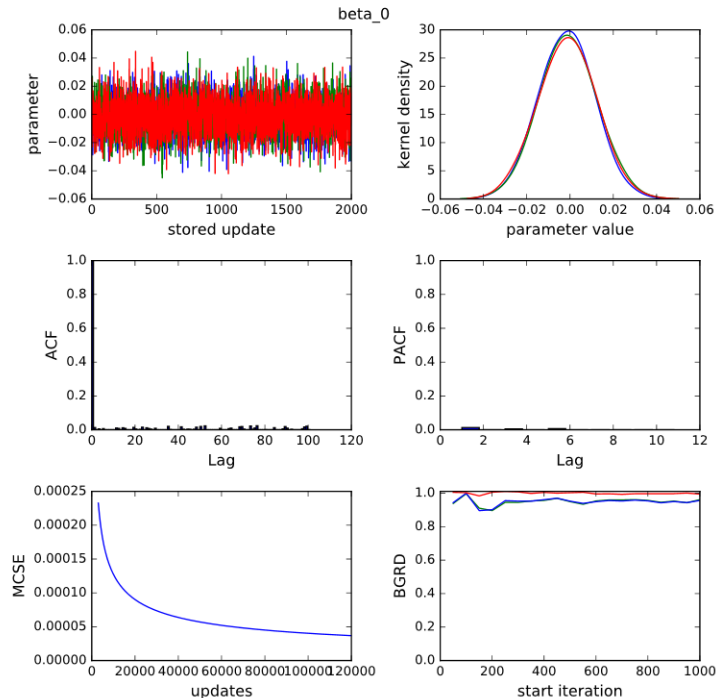
Parameters:

parameter	mean	sd	ESS	variable
tau	1.541609950742	0.0340065114631	5799	
beta_0	-0.00127835184871	0.0125770014327	5960	cons
beta_1	0.594959154334	0.012745358164	6129	standlrt
sigma2	0.648987956705	0.0143068971085	5784	
sigma	0.805548947358	0.00887975878981	5789	
deviance	9763.48848831784	2.433023996009	6061	

Model:

Statistic	Value
Dbar	9763.48848831784
D(thetabar)	9760.509788970701
pD	2.978699347139
DIC	9766.467187664979

This screen contains summary statistics for five parameters (in fact sigma, sigma2 and tau are all functions of each other). We can also look at diagnostic plots for the parameters e.g. **beta_0.svg**:



The purpose of this document is not to go into details about what these figures mean – interested readers can look at the accompanying *Beginner's guide* for such information. Instead we want to teach you here how to write a similar template yourself.

3.2 Opening the bonnet and looking at the code

The operations that we have here performed in fitting our first model are shared between the user-written template *Regression1* and other code that is generic to all templates and which we will discuss in more detail later.

So our next stage is to look at the source Python file for *Regression1*. All templates are stored in the *templates* subdirectory under the base directory and have the extension *.py* and so if we open *Regression1.py* (in Wordpad/Notepad and not Python) we will see the following:

```
# Copyright (c) 2017, University of Bristol and University of
Southampton.

from EStat.Templating import Template

class Regression1(Template):
    'A model template for fitting 1 level Normal multiple regression
    model in eStat only.'

    __version__ = '1.0.0'

    tags = [ 'Model', '1-Level', 'Normal' ]
    engines = ['eStat']

    inputs = '''
y = DataVector('Response: ', help= 'a.k.a. <em>Y</em>, Outcome
variable, Dependent variable, etc.')
x = DataMatrix('Explanatory variables: ', allow_cat = True, help=
"<p style='text-align:left'>A.k.a. X, Predictor variables,
Independent variables, etc.</p><p style='text-
align:left'><strong>Note:</strong> if you wish to include an
<strong>intercept</strong> then you need to add it (e.g. a constant
of ones) as one of the explanatory variables.</p><p style='text-
align:left'>Once you've selected a variable, you have the
opportunity to indicate whether it's categorical or not; if
categorical, dummy variables will be added to the model on your
behalf.</p>")
beta = ParamVector(parents=[x], as_scalar=True)
tau = ParamScalar()
sigma = ParamScalar(modelled = False)
sigma2 = ParamScalar(modelled = False)
deviance = ParamScalar(modelled = False)
'''

    model = '''
model{
  for (i in 1:length(${y})) {
    ${y}[i] ~ dnorm(mu[i], tau)
    mu[i] <- ${mmult(x, 'beta', 'i')}
  }

  # Priors
  % for i in range(0, x.ncols()):
  beta_${i} ~ dflat()
  % endfor
}
```

```

    tau ~ dgamma(0.001000, 0.001000)
    sigma2 <- 1 / tau
    sigma <- 1 / sqrt(tau)
}
'''

    latex = r'''
\begin{aligned}
&\mbox{\${y}}_i \sim \mbox{N}(\mu_i, \sigma^2) \\
&\mu_i = \\
&\quad \${mmulttex(x, r'\beta', 'i')}) \\
&\%for i in range(0, len(x)):
&\beta_{i} \propto 1 \\
&\%endfor
&\tau \sim \Gamma(0.001, 0.001) \\
&\sigma^2 = 1 / \tau
\end{aligned}
'''

```

We will now describe in some detail what this code does. The first line (after the initial copyright statement) here is simply importing information needed by the template and is generic to many templates. We then have a class statement which defines a class *Regression1* which is a subclass of a generic *Template* class. There is then a sentence known as a descriptor that describes what the template does. For those unfamiliar with the terminology we are using think of a class as being a definition of a type of object, for example we might have a class of rectangles where each rectangle might be described by two attributes, length and width. Then an instance of the class which we might call Dave will have these values instantiated e.g. Dave's length is 3 and width is 1.

We might think of the subclass of rectangles the squares which again have the two attributes length and width. We could state that class Square (Rectangle): in which case we know that as squares are a subclass of rectangles they have a length and width but we would now redefine the attribute width within the squares definition to equal length.

This terminology is what is used in what is called object orientated programming.

In the definition here five attributes (tags, engines, inputs, model, and latex) are then defined as being parts of a *Regression1* class although there will be other attributes that are generic to the template class and are defined elsewhere.

Briefly:

- The `__version__` attribute identifies which version of this file this is. It is useful for debugging as when a bug is fixed and a new version created we update the version number.
- The `tags` attribute identifies the template as belonging to the tag groups 'Model', '1-Level', and 'Normal' and this is used in the web interface to decide which templates to show in specific template lists.
- The `engines` attribute identifies which estimation and or graphical engines can be used with this template (in this case just the built-in 'eStat' estimation engine) which is used by Stat-JR to decide which estimation options to offer. This attribute is how, along with additional attributes, we allow Stat-JR to interoperate with other software.

- The *inputs* attribute is a text string (hence the starting and ending `'''`) which consists of a list of the inputs in this template.
- The *model* attribute is a text string that will produce the model code we saw in the web interface for this template.
- The *latex* attribute is a text string that will produce a piece of LaTeX code which is converted into the nice mathematics we saw in the web interface. We will next look at the last three attributes in more detail.

3.2.1 Inputs

When this template has been selected in the web interface it will firstly have its inputs interrogated and start creating an instance of a model object. Stat-JR has a list of object types that can be thought of as the building blocks of a model object. Statements like

```
y = DataVector('Response: ', help= 'a.k.a. <em>Y</em>, Outcome variable, Dependent variable, etc.')
```

can be thought of as defining the components that make up a model object, so here we are building a model object that contains a data vector called *y*. The text in the brackets is used by the web interface as a piece of text to place on the screen alongside the appropriate input device (in the case of a data vector a single select list) and the second *help* string is help text that appears if you hover over the input in the browser (we've greyed this out just to make the remaining code more salient).

Stat-JR's in-house eStat engine (and some of the other estimation engines with which Stat-JR interoperates, such as JAGS (Plummer, 2003), OpenBUGS (Lunn, Spiegelhalter, Thomas, & Best, 2009), R_nimble (de Valpine, Paciorek, Turek, Anderson-Bergman, & Temple Lang, 2016) and WinBUGS (Lunn, Thomas, Best, & Spiegelhalter, 2000)) distinguish between Data objects which require user inputs and Parameters (Param) which just need to be declared. This template therefore has 7 components (2 pieces of data and 5 parameters) that make up the model. The DataMatrix declaration for *x* will correspond to the multiple-select list that we saw when running the template. Here we see that this declaration takes a couple of arguments:

```
x = DataMatrix('Explanatory variables: ', allow_cat = True, help=
"<p style='text-align:left'>A.k.a. X, Predictor variables,
Independent variables, etc.</p><p style='text-align:left'><strong>Note:</strong> if you wish to include an
<strong>intercept</strong> then you need to add it (e.g. a constant
of ones) as one of the explanatory variables.</p><p style='text-align:left'>Once you've selected a variable, you have the
opportunity to indicate whether it's categorical or not; if
categorical, dummy variables will be added to the model on your
behalf.</p>")
```

In this version of Stat-JR we have implemented code to deal with categorical predictor variables and so the *allow_cat* argument tells Stat-JR that elements of *x* might be treated as categorical variables. The *help* argument contains a rather long text string that will appear on the screen if we hover over *x* with the mouse.

3.2.2 Model

The *model* attribute gives a definition (as a text string) of an instance of a model set up using this template. The definition is in a language that very much resembles the language used by the WinBUGS (Lunn et al., 2000) package to specify models (with some minor differences) and will be used in Stat-JR to create code to run the model using the eStat engine. The definition can be shown on the screen in the objects pane under the label *model.txt* so you can for example see the definition for the model we fitted to the *tutorial* dataset earlier by selecting this object from the pull down list. As the text is specific to the inputs given, the definition is a text string containing some quantities that depend on inputs. These are integrated into the text string via the $\$$ symbol for substitutions, through conditional and looping computation achieved via $\%$ commands and through the calling of external functions. The model code for this template uses all three devices, and so we will here go through stage by stage the instance of model shown in the earlier screen shots. We start with the raw code:

```
model = '''
model{
  for (i in 1:length(${y})) {
    ${y}[i] ~ dnorm(mu[i], tau)
    mu[i] <- ${mmult(x, 'beta', 'i')}
  }

  # Priors
  % for i in range(0, x.ncols()):
  beta_${i} ~ dflat()
  % endfor
  tau ~ dgamma(0.001000, 0.001000)
  sigma2 <- 1 / tau
  sigma <- 1 / sqrt(tau)
}
'''
```

Now we can substitute normexam for $\${y}$ as this is the column we chose for y thus:

```
model = '''
model{
  for (i in 1:length(normexam)) {
    normexam[i] ~ dnorm(mu[i], tau)
    mu[i] <- ${mmult(x, 'beta', 'i')}
  }

  # Priors
  % for i in range(0, x.ncols()):
  beta${i} ~ dflat()
  % endfor
  tau ~ dgamma(0.001000, 0.001000)
  sigma2 <- 1 / tau
  sigma <- 1 / sqrt(tau)
}
'''
```

Next we can evaluate the *for* loop with, in our example x having 2 columns:

```
model = '''
model{
  for (i in 1:length(normexam)) {
    normexam[i] ~ dnorm(mu[i], tau)
  }
}
```

```

      mu[i] <- ${mmult(x, 'beta', 'i')}
    }

    # Priors
    beta0 ~ dflat()
    beta1 ~ dflat()
    tau ~ dgamma(0.001000, 0.001000)
    sigma2 <- 1 / tau
    sigma <- 1 / sqrt(tau)
  }
  ...

```

Finally the function *mmult* is a function written separately and is used to create the products of the *x* variables and their associated *betas* with appropriate indexing. When run we get:

```

model = ''
model{
  for (i in 1:length(normexam)) {
    normexam[i] ~ dnorm(mu[i], tau)
    mu[i] <- cons[i]*beta0 + standlrt[i]*beta1
  }

  # Priors
  beta0 ~ dflat()
  beta1 ~ dflat()
  tau ~ dgamma(0.001000, 0.001000)
  sigma2 <- 1 / tau
  sigma <- 1 / sqrt(tau)
}
...

```

This is identical to the code we see under **model.txt** in the TREE interface and is one way of displaying the model we wish to fit. Another way is to write the model in mathematical form using the LaTeX language and this can also be shown in the web output in the pull down list under **equation.tex** as we saw earlier. Basically we are using a program called *MathJax* (Cervone, Sorge, Lawson-Perfect, & Krautzberger, 2017) which will display LaTeX code in a nice format embedded within a webpage. The attribute that is used for creating this code is `latex`.

3.2.3 Latex

If you select *equation.tex* in the pull down list click for the bottom pane then the equations will appear in LaTeX format. If you then right click in the pane and select *Show Maths as TeX commands* option you will get a window popping up that shows the LaTeX source:

```

\begin{aligned}
&\mbox{normexam}_i \sim \mbox{N}(\mu_i, \sigma^2) \\
\mu_i &= \\
&\beta_0 \mbox{cons}_i + \beta_1 \mbox{standlrt}_i \\
\beta_0 &\propto 1 \\
\beta_1 &\propto 1 \\
\tau &\sim \Gamma(0.001, 0.001) \\
\sigma^2 &= 1 / \tau \\
\end{aligned}

```

This code is created via the *latex* function and we will now look at how we get from *latex* to this source for our example. The generic code is as follows:

```

latex = r'''
\begin{aligned}
&\mbox{\${y}}_i \sim \mbox{N}(\mu_i, \sigma^2) \\
\mu_i &= \\
&\${mmulttex(x, r'\beta', 'i')}) \\
%for i in range(0, len(x)):
&\beta_{\${i}} \propto 1 \\
%endfor
\tau &\sim \Gamma(0.001, 0.001) \\
\sigma^2 &= 1 / \tau \\
\end{aligned}
'''

```

We have three steps as with the *model* function, firstly we will substitute *normexam* for $\${y}$

```

latex = r'''
\begin{aligned}
&\mbox{normexam}_i \sim \mbox{N}(\mu_i, \sigma^2) \\
\mu_i &= \\
&\${mmulttex(x, r'\beta', 'i')}) \\
%for i in range(0, len(x)):
&\beta_{\${i}} \propto 1 \\
%endfor
\tau &\sim \Gamma(0.001, 0.001) \\
\sigma^2 &= 1 / \tau \\
\end{aligned}
'''

```

Next we can evaluate the for loop with, in our example x having 2 columns:

```

latex = r'''
\begin{aligned}
&\mbox{normexam}_i \sim \mbox{N}(\mu_i, \sigma^2) \\
\mu_i &= \\
&\${mmulttex(x, r'\beta', 'i')}) \\
\beta_0 &\propto 1 \\
\beta_1 &\propto 1 \\
\tau &\sim \Gamma(0.001, 0.001) \\
\sigma^2 &= 1 / \tau
\end{aligned}

```

```
\end{aligned}
'''
```

and finally we have the step to expand a function – this time called `mmulttex` :

```
latex = r'''
\begin{aligned}
&\mbox{normexam}_i \sim \mbox{N}(\mu_i, \sigma^2) \\
&\mu_i = \\
&\quad \beta_0 \mbox{cons}_i + \beta_1 \mbox{standlrt}_i \\
&\beta_0 \propto 1 \\
&\beta_1 \propto 1 \\
&\tau \sim \Gamma(0.001, 0.001) \\
&\sigma^2 = 1 / \tau
\end{aligned}
'''
```

3.2.4 Some points to note

You will notice that the string object created in *latex* has an `r` before the `'''` and that similarly there is an `r` inside the *mmulttex* function call before the `'`. Basically the triple quotes are used in place of quotes to allow the use of single quotes within the actual expression. The `r` is used to let the computer know that the expression in the quotes is a raw string and so for example although the `\` character is often used as a control character, in a raw string it will be treated simply as a `\` and passed through to the LaTeX reading software. This avoids the use of lots of double `\` for each `\`. One debugging tip is that lines often finish with a double slash to denote a new line in LaTeX. It is important to add a space after the double slash in the text file as otherwise it will be concatenated onto the next line.

Some of you will know LaTeX and so the code in the source window will be familiar. It is however not essential to write a *latex* function for your own templates as the code is purely decorative. We will not give a crash course on LaTeX here but essentially the *aligned* environment is used to write a set of mathematical equations with the `&` sign denoting the place where the lines are lined up horizontally and the double slashes denoting new lines. LaTeX uses the `\` preceding terms to denote special characters e.g. `\beta` gives a Greek lowercase beta. The *aligned* environment is for mathematics and so if we wish to write words in normal font we enclose them in a `\mbox`. With this basic knowledge you should be able to compare the source code and the maths it produces and thus see what each of the special characters is.

3.3 Writing your own first template

We haven't at this stage explained how the *model* function is used to create code to fit the model. This is done by the Stat-JR system's eStat engine using generic code that is common to all templates and which we will discuss a bit more later. It is enough for now to realise that to write some basic templates simply requires writing code similar to that seen here and the Stat-JR system will do the rest of the hard work for you. We will now test your understanding by getting you to construct your own first template:

3.3.1 Exercise 1

It is best when starting writing templates to start from a template that works and modify it to confirm you understand what is going on. You will therefore now take the *Regression1* template and construct a template for an even simpler model – a simple linear regression. To do this in the template directory copy the file *Regression1.py* to *LinReg.py*. It is also sensible to change the classname in the template.

For a linear regression we want a template with two inputs y and x – only this time x is a vector rather than a matrix i.e. there is only one predictor plus a constant. Try changing the text to ask specifically for a Y variable and an X variable for the inputs. You will need to change *inputs* a little. Try also then simplifying the *model* and *latex* functions – you should be able to get away without needing the *mmult*/*mmulttex* functions.

In fact $\mu[i]$ should be something like $\alpha + \beta x[i]$, though if you use α and β they will both need declaring as *ParamScalars* in the *inputs* function.

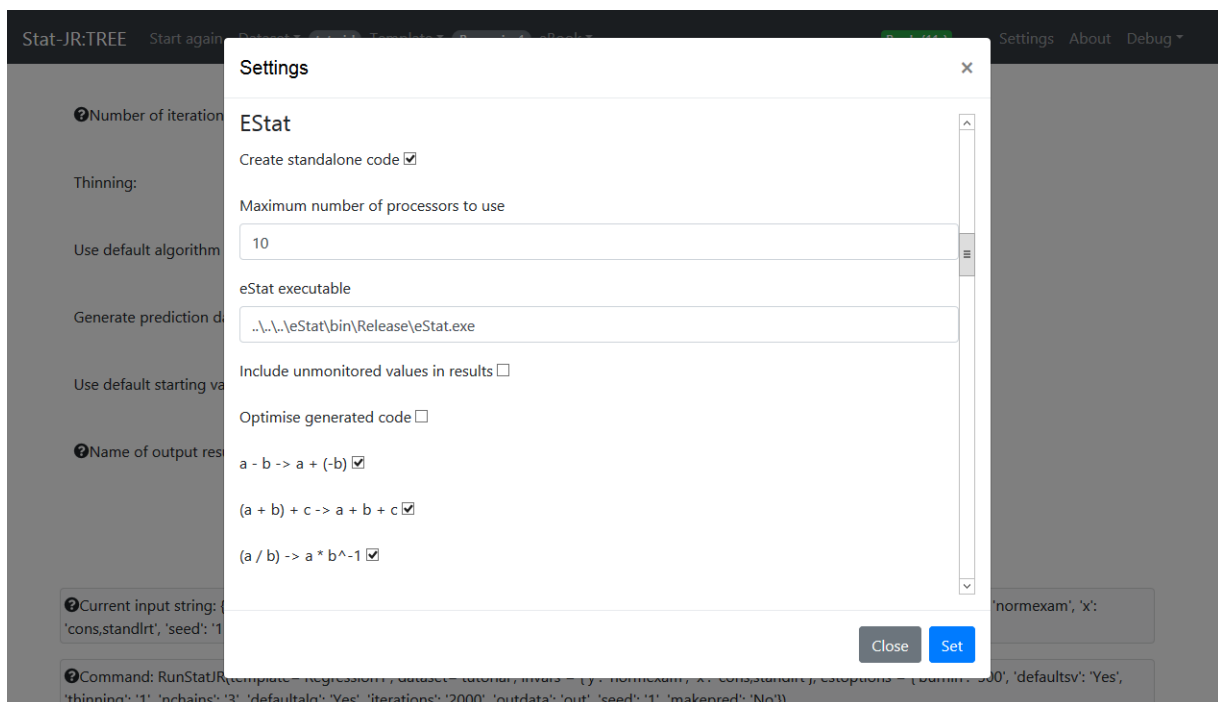
When you think you have the template correctly written save it and reload templates in Stat-JR (via the *Debug* menu) and test it out. If it is saved in the templates directory it will be automatically picked up. It should give similar results to *Regression1* for the example shown earlier.

4 Running templates with the eStat engine

4.1 Algebra and Code Generation

In section 3 we have seen the code required to create a template that fits a simple model using the built-in eStat estimation engine. We have however hidden away many of the details. In this section we will expose a few more details, including a little section on the algebra system. Let us start by returning to the same example and show a few more screens that we have not yet exposed.

We will begin however by switching a few of the settings so that we can easier see what is going on. To do this look at the black bar at the top of the screen and you will see the word **Settings**. Click on **Settings** and you will be greeted by a window that pops up (part of which is shown below) where you will need to scroll down and change the inputs to look as follows:



Here we have switched on *standalone code* and also switched off *optimisation*. The **Settings** screen contains the locations of various files used by Stat-JR, the pathnames to all third-party software one might use with Stat-JR and specific eStat settings which we have modified here. Scroll to the bottom of the screen and click on the **Set** button when you have made the changes which will take you back to the welcome screen. Now click **Begin** as before and using **Regression1** as the template and **tutorial** (Goldstein, et al., 1993) as the dataset set up the inputs as follows:

Dataset: tutorial; **Template:** Regression1; **Input string:** {'burnin': '500', 'defaultsv': 'Yes', 'outdata': 'out', 'thinning': '1', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'y': 'normexam', 'x': 'cons,standlrt', 'seed': '1', 'makepred': 'No'}

Stat-JR:TREE
Start again
Dataset
tutorial
Template
Regression1
eBook
idle
Settings
About
Debug

?
Response:

normexam
remove

?
Explanatory variables:

cons,standlrt
remove

Number of chains:

3
remove

Random Seed:

1
remove

Length of burnin:

500
remove

?
Number of iterations:

2000
remove

Thinning:

1
remove

Use default algorithm settings:

Yes
remove

Generate prediction dataset:

No
remove

Use default starting values:

Yes
remove

?
Name of output results:

out

Next

Now clicking on **Next** we can choose other options from the pull-down list so firstly choose **algorithm.tex** from the list and pop it out into a new tab.

Stat-JR:TREE

LaTeX version of algorithm
Conditional posterior for tau for Gibbs sampling

$$\tau \sim \Gamma \left(0.001 + 0.5 \times \text{length}(\text{normexam}), 0.001000 + \frac{\sum_{i=1}^{\text{length}(\text{normexam})} (\text{normexam}_i - \text{beta}_0 \times \text{cons}_i - \text{beta}_1 \times \text{standlrt}_i)^2}{2} \right)$$

Deviance Function

$$\text{deviance} = 2 \times \left(\frac{\tau \times \left(\sum_{i=1}^{\text{length}(\text{normexam})} (\text{normexam}_i - \text{beta}_0 \times \text{cons}_i - \text{beta}_1 \times \text{standlrt}_i)^2 \right)}{2} + 0.5 \times (\ln(\pi) - \ln(\tau)) \times \text{length}(\text{normexam}) + 0.346573590279973 \times \text{length}(\text{normexam}) \right)$$

Conditional posterior for beta_0 for Gibbs sampling

$$\text{beta}_0 \sim N \left(\frac{\tau \times \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i \times (\text{normexam}_i - \text{beta}_1 \times \text{standlrt}_i) \right)}{\tau \times \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i^2 \right)}, \tau \times \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i^2 \right) \right)$$

Conditional posterior for beta_1 for Gibbs sampling

$$\text{beta}_1 \sim N \left(\frac{\tau \times \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i \times (\text{normexam}_i - \text{beta}_0 \times \text{cons}_i) \right)}{\tau \times \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i^2 \right)}, \tau \times \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i^2 \right) \right)$$

Deterministic formula for parameter sigma

$$\sigma = \frac{1}{\sqrt{\tau}}$$

Deterministic formula for parameter sigma2

$$\sigma_2 = \frac{1}{\tau}$$

Basically this window shows a nicely-presented result of what is returned from the algebra system when it is given the model description constructed by the **model** method. We will look at the algebra system in a little more detail later on, but for now you will see that three of the parameters (*beta0*, *beta1* and *tau*) have posterior distributions that require sampling from a conditional distribution using a method called Gibbs sampling whilst two (*sigma* and *sigma2*) are simply calculated as deterministic functions of the other parameters. Finally a formula for the deviance function is also returned. In fact the algebra system returns a series of files (in xml format), one for each parameter and we can also view these (in nicely presented form) for example **tau.xml**

Use Gibbs sampling from conditional posterior for tau:

$$\tau \sim \Gamma\left(0.001 + 0.5 \times \text{length}(\text{normexam}), 0.001000 + \frac{\sum_{i=1}^{\text{length}(\text{normexam})} (\text{normexam}_i - \text{beta}_0 \times \text{cons}_i - \text{beta}_1 \times \text{standlrt}_i)^2}{2}\right)$$

$$\tau \sim \Gamma\left(0.001 + 0.5 \times \text{length}(\text{normexam}), 0.001000 + \frac{\sum_{i=1}^{\text{length}(\text{normexam})} (\text{normexam}_i - \text{beta}_0 \times \text{cons}_i - \text{beta}_1 \times \text{standlrt}_i)^2}{2}\right)$$

Here we get the same line repeated twice as the second line shows the posterior after optimisation (which here we have switched off). Stat-JR takes these files and converts each of them into the C++ programming language so if we look at the file **modelcode.cpp** we will see the actual C++ code constructed below (note we will not go into detail as to how this is achieved):

```
Model iteration code

Py_BEGIN_ALLOW_THREADS;
std::vector<double*> tmp_y;
tmp_y.push_back(const_cast<double*>(normexam));
RectMatrix mat_y(tmp_y, 4059);
std::vector<double*> tmp_x;
tmp_x.push_back(const_cast<double*>(cons));
tmp_x.push_back(const_cast<double*>(standlrt));
RectMatrix mat_x(tmp_x, 4059);
std::vector<double*> tmp_beta;
tmp_beta.push_back(beta);
RectMatrix mat_beta(tmp_beta, 2);
double &beta_0 = beta[0];
double &beta_1 = beta[1];
static std::unordered_map<std::string, SimpleRandomGenerator> rngstate;
if (runstate == 0) {
    rngstate.try_emplace(rngid, SimpleRandomGenerator());
}
auto &rng = rngstate[rngid];
if (runstate == 0) {
    rng.set_seed(seed);
    rng.start();
}
for (int iter = 0; iter < numiter; iter++) {
    int iterind = 0;
    if (runstate == 3) iterind = floor((start_iteration + iter) / thinning);
    // Update tau
    // This code was generated by the Stat-JR package (copyright 2012 University of Bristol and University of Southampton).

    {
        double sum0=0;
        double csum0=0;
        for(int i=0; i<4059; i++) {
            double ysum0 = pow(((normexam[i]-(beta_0*cons[i]))-(beta_1*standlrt[i])),2.0) - csum0;
            double tsum0 = sum0 + ysum0;
            csum0 = (tsum0 - sum0) - ysum0;
            sum0 = tsum0;
        }

        tau = dgamma((0.001+(0.5*4059)),(0.001000+(sum0/2)));
    }
}
```

Here after some code that is required for passing the variables back and fore from Python to C++ we see the step for tau. This is similar to that given in the algebra. One difference is that the length of normexam has its value (4059) substituted in. The code also uses a technique called Kahan summation (Kahan, 1965) and so what would have been the line

```
sum0 = pow(((normexam[i]-(beta0*cons[i]))-(beta1*standlrt[i])),2);
```

is expanded to the following:

```
double ysum0 = pow(((normexam[i]-(beta0*cons[i]))-(beta1*standlrt[i])),2) -
csum0;
double tsum0 = sum0 + ysum0;
```

```
csum0 = (tsum0 - sum0) - ysum0;
sum0 = tsum0;
```

to deal with potential rounding issues.

If you scroll down you will see similar code to perform the steps for the other parameters and the deviance. There are further C++ files which contain supporting routines (*supportcode.cpp* – note this used to contain random number generators but they are now included via a library instead), perform the DIC calculation (*dic.cpp*) and set up proposal distributions via adaptation when using Metropolis Hastings (Hastings, 1970) sampling but not in this example (*adapt.cpp*).

When run in the usual way, i.e. without switching settings to *run as standalone*, each of these pieces of C code is compiled separately and Python code within Stat-JR pieces everything together. If, as we have done, we choose *run as standalone* and now click on **Run** then the software does as it suggests and creates standalone C++ files. In the current version of Stat-JR we have included parallel processing and so only one standalone file is constructed, *engine.cpp*, which contains the starting values for all three chains. If we look at *engine.cpp* in a new tab we see the following:

Stat-JR:TREE

```
Standalone engine code
```

```
// This code was generated by the Stat-JR package (copyright 2012 University of Bristol and University of Southampton).  
  
#include <vector>  
#include <random>  
#include <iostream>  
#include <sstream>  
#include <fstream>  
#include <string>  
#include <limits>  
#include <chrono>  
  
#include "rng.h"  
#include "statlib.h"  
#include "thread_pool.h"
```

```
// Initialise input data  
  
const double normexam[] = {0.2613244652748108,0.13406679034233093,-1.7238824367523193,0.9675859808921814,0.5443409085273743,1.734899163246  
const double cons[] = {1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,  
const double standlrt[] = {0.6190592646598816,0.20580196380615234,-1.364575743675232,0.20580196380615234,0.3711048662662506,2.189436912536  
  
struct starting_values {  
    double beta[2];  
    double deviance;  
    double sigma;  
    double sigma2;  
    double tau;  
};
```

This code contains everything and if you scroll down to near the bottom you will find the code to update the parameters:

```

// Update tau
// This code was generated by the Stat-JR package (copyright 2012 University of Bristol and University of Southampton).

{

    double sum0=0;
    double csum0=0;
    for(int i=0; i<4059; i++) {
        double ysum0 = pow(((normexam[i]-(beta_0*cons[i]))-(beta_1*standlrt[i])),2.0) - csum0;
        double tsum0 = sum0 + ysum0;
        csum0 = (tsum0 - sum0) - ysum0;
        sum0 = tsum0;
    }

    tau = dgamma((0.001+(0.5*4059)), (0.001000+(sum0/2)));

}

// Update deviance
// This code was generated by the Stat-JR package (copyright 2012 University of Bristol and University of Southampton).

{

    double sum0=0;
    double csum0=0;
    for(int i=0; i<4059; i++) {
        double ysum0 = pow(((normexam[i]-(beta_0*cons[i]))-(beta_1*standlrt[i])),2.0) - csum0;
        double tsum0 = sum0 + ysum0;
        csum0 = (tsum0 - sum0) - ysum0;
        sum0 = tsum0;
    }

    deviance = (2*(((tau*sum0)/2)+(0.5*(log(3.14159265)-log(tau))*4059)+(0.346573590279973*4059)));

}

// Update beta_0
// This code was generated by the Stat-JR package (copyright 2012 University of Bristol and University of Southampton).

{

```

If you view the rest of this C++ code in detail you will see that there is a chunk at the top that is common to all models but the rest of the code is mostly model-specific. If you return to the **Settings** window and switch back on *optimisation* and switch off *Create standalone code* under the EStat heading and press **Set**, then repeating the model setup (you can do this via **Templates > Set Inputs**, and selecting the last model run under **History**, and then pressing **Use**) you can fit the model and view the code in *modelcode.cpp*:

```

Model iteration code

Py_BEGIN_ALLOW_THREADS;
std::vector<double*> tmp_y;
tmp_y.push_back(const_cast<double*>(>(normexam)));
RectMatrix mat_y(tmp_y, 4059);
std::vector<double*> tmp_x;
tmp_x.push_back(const_cast<double*>(>(cons)));
tmp_x.push_back(const_cast<double*>(>(standlrt)));
RectMatrix mat_x(tmp_x, 4059);
std::vector<double*> tmp_beta;
tmp_beta.push_back(beta);
RectMatrix mat_beta(tmp_beta, 2);
double &beta_0 = beta[0];
double &beta_1 = beta[1];
static std::unordered_map<std::string, SimpleRandomGenerator> rngstate;
if (runstate == 0) {
    rngstate.try_emplace(rngid, SimpleRandomGenerator());
}
auto &rng = rngstate[rngid];
if (runstate == 0) {
    rng.set_seed(seed);
    rng.start();
}
for (int iter = 0; iter < numiter; iter++) {
    int iterind = 0;
    if (runstate == 3) iterind = floor((start_iteration + iter) / thinning);
    // Update tau
    // This code was generated by the Stat-JR package (copyright 2012 University of Bristol and University of Southampton).

    {

        tau = dgamma(2029.501,(0.001+(((0.924751985818*beta_0)+((-4764.25262396)*beta_1)+(pow(beta_0,2.0)*4059.0)+((beta_0*beta_1)*14.6956619

    }

    // Update beta_0
    // This code was generated by the Stat-JR package (copyright 2012 University of Bristol and University of Southampton).

    {

```

Here the code is much harder to link to the algebra system as the data has been included into the model steps and any constants have thus been evaluated. You might like to compare the code for the tau step and see if you can spot the links, for example 2029.501 is $4059/2 + 0.001$. Our advice is that if you are interested in understanding the C++ code and the algorithm generally then it is probably easier to switch off optimisation whereas if you want the code to run faster then switch it on. We will revisit the C++ code in later sections when we introduce the use of the *preccode* method.

We will next look at how the algebra system converts the model statements into a set of steps in more detail.

4.2 The algebraic software system

The algebra system that we have developed for the Stat-JR system (with main developer Bruce Cameron) will take a BUGS-like model file and produce output xml format files for each parameter. This will consist of their full conditional posterior distribution either as a known distribution with formula or as an unknown distribution function. In version 1.0 of the software we integrated the algebra system with the main software allowing us to view some of the intermediate files that show how the algebra system works. If you have run the model that we saw above with the *Regression1* template then the intermediate algebra system steps are included as xml format files.

If we select *node_beta_0.xml* from the pull-down list and **pop it out** we get the following:

```

XML Output
  Dimension  scalar
    Child GNEs  beta_0(b)
    Parent GNEs  beta_0(a)
  Imm Parents SS  [none]
  Imm Parents DS  [none]
  Imm Parents MS  [none]
  Imm Children SS  [none]
  Imm Children DS   $\mu_*$ 
  Imm Children MS  [none]
  Parents via subs  [none]
  Parents via msubs  [none]
  Children via subs  normexam
  Children via msubs  normexam
  Coparents via subs  beta_{-1} \tau
  Coparents via msubs  beta_{-1} \tau

Statement  beta_0 ~ dflat()

With subs  beta_0 ~ dflat()

Prior  p(beta_0) = \frac{1}{\infty}
      = \frac{1}{\infty}
      \propto \frac{1}{\infty}

```

...and if we scroll to the bottom of the window we see the further algebraic processing:

```

Likelihood  \prod_{i=1}^{\text{length}(\text{normexam})} \sqrt{\frac{\tau}{2\pi}} \exp\left(-\left(\frac{\tau}{2}\right)(\text{normexam}_i - (\text{cons}_i \text{beta}_0 + \text{standlrt}_i \text{beta}_{-1}))^2\right)

Posterior  p(\text{beta}_0 | \text{normexam}, \text{beta}_{-1}, \tau) \propto p(\text{beta}_0) \prod_{i=1}^{\text{length}(\text{normexam})} p(\text{normexam}_i | \text{beta}_0, \text{beta}_{-1}, \tau)

\propto \frac{1}{\infty} \exp\left(\tau \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i (\text{normexam}_i - \text{beta}_{-1} \text{standlrt}_i) \right) \text{beta}_0 - \frac{\tau \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i^2\right) \text{beta}_0^2}{2}\right)

= \frac{\exp\left(\tau \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i (\text{normexam}_i - \text{beta}_{-1} \text{standlrt}_i) \right) \text{beta}_0 - \tau \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i^2\right) \text{beta}_0^2 / 2\right)}{\infty}

\propto \exp\left(\tau \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i (\text{normexam}_i - \text{beta}_{-1} \text{standlrt}_i) \right) \text{beta}_0 - \frac{\tau \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i^2\right) \text{beta}_0^2}{2}\right)

Log posterior  \tau \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i (\text{normexam}_i - \text{beta}_{-1} \text{standlrt}_i) \right) \text{beta}_0 - \frac{\tau \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i^2\right) \text{beta}_0^2}{2}

Distribution  dnorm

Match  A = \tau \sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i (\text{normexam}_i - \text{beta}_{-1} \text{standlrt}_i)

Match  B = -\left(\frac{\tau \sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i^2}{2}\right)

Sampling parameter  \mu = \frac{\tau \sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i (\text{normexam}_i - \text{beta}_{-1} \text{standlrt}_i)}{\tau \sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i^2}

Sampling parameter  \tau = \tau \sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i^2

Sampling distribution  \text{beta}_0 \sim \text{dnorm}\left(\frac{\tau \sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i (\text{normexam}_i - \text{beta}_{-1} \text{standlrt}_i)}{\tau \sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i^2}, \tau \sum_{i=1}^{\text{length}(\text{normexam})} \text{cons}_i^2\right)

```

The program decides which lines in the model specification involve the parameter beta_0 . It then finds the prior and likelihood parts of the model for this parameter before merging them together to

find the posterior and log posterior as a product of distributions. It then attempts to match the distribution to known statistical distributions and here spots that the posterior for *beta0* is a normal distribution. Finally it gives the conditional posterior distribution in terms of other objects in the model. We can view *beta1* via *node_beta_1.xml* and see similarly a Normal posterior:

Stat-JR:TREE

$$\begin{aligned}
\text{Likelihood} & \prod_{i=1}^{\text{length}(\text{normexam})} \sqrt{\frac{\tau}{2\pi}} \exp\left(-\left(\frac{\tau}{2}\right)(\text{normexam}_i - (\text{cons}_i \text{beta}_0 + \text{standlrt}_i \text{beta}_1))^2\right) \\
\text{Posterior} & p(\text{beta}_1 | \text{normexam}, \text{beta}_0, \tau) \propto p(\text{beta}_1)^{\prod_{i=1}^{\text{length}(\text{normexam})}} p(\text{normexam}_i | \text{beta}_0, \text{beta}_1, \tau) \\
& \propto \frac{1}{\infty} \exp\left(\tau \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i (\text{normexam}_i - \text{beta}_0 \text{cons}_i)\right) \text{beta}_1 - \frac{\tau \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i^2\right) \text{beta}_1^2}{2}\right) \\
& = \frac{\exp\left(\tau \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i (\text{normexam}_i - \text{beta}_0 \text{cons}_i)\right) \text{beta}_1 - \tau \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i^2\right) \text{beta}_1^2 / 2\right)}{\infty} \\
& \propto \exp\left(\tau \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i (\text{normexam}_i - \text{beta}_0 \text{cons}_i)\right) \text{beta}_1 - \frac{\tau \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i^2\right) \text{beta}_1^2}{2}\right) \\
\text{Log posterior} & \tau \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i (\text{normexam}_i - \text{beta}_0 \text{cons}_i)\right) \text{beta}_1 - \frac{\tau \left(\sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i^2\right) \text{beta}_1^2}{2} \\
\text{Distribution} & \text{dnorm} \\
\text{Match} & A = \tau \sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i (\text{normexam}_i - \text{beta}_0 \text{cons}_i) \\
\text{Match} & B = -\left(\frac{\tau \sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i^2}{2}\right) \\
\text{Sampling parameter} & \mu = \frac{\tau \sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i (\text{normexam}_i - \text{beta}_0 \text{cons}_i)}{\tau \sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i^2} \\
\text{Sampling parameter} & \tau = \tau \sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i^2 \\
\text{Sampling distribution} & \text{beta}_1 \sim \text{dnorm}\left(\frac{\tau \sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i (\text{normexam}_i - \text{beta}_0 \text{cons}_i)}{\tau \sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i^2}, \tau \sum_{i=1}^{\text{length}(\text{normexam})} \text{standlrt}_i^2\right)
\end{aligned}$$

Finally *tau* the precision has a Gamma posterior distribution with calculations shown in *node_tau.xml*:

$$\begin{aligned}
\text{Likelihood} & \prod_{i=1}^{\text{length}(\text{normexam})} \sqrt{\frac{\tau}{2\pi}} \exp\left(-\left(\frac{\tau}{2}\right)(\text{normexam}_i - (\text{cons}_i \text{beta}_0 + \text{standlrt}_i \text{beta}_1))^2\right) \\
\text{Posterior } p(\tau | \text{normexam}, \text{beta}_0, \text{beta}_1) & \propto p(\tau)^{\text{length}(\text{normexam})} p(\text{normexam}_i | \text{beta}_0, \text{beta}_1, \tau) \\
& \propto \frac{\exp\left(\frac{-0.001000\tau}{\tau^{0.999}}\right)}{\tau^{0.999}} \exp\left(-\left(\frac{\sum_{i=1}^{\text{length}(\text{normexam})} (\text{normexam}_i - \text{beta}_0 \text{cons}_i - \text{beta}_1 \text{standlrt}_i)^2}{2}\right)\tau\right) \tau^{0.5 \text{length}(\text{normexam})} \\
& = \frac{\exp\left(-\left(0.001000 + \left(\sum_{i=1}^{\text{length}(\text{normexam})} (\text{normexam}_i - \text{beta}_0 \text{cons}_i - \text{beta}_1 \text{standlrt}_i)^2\right)/2\right)\tau\right)}{\tau^{0.999 - 0.5 \text{length}(\text{normexam})}} \\
& \propto \frac{\exp\left(-\left(0.001000 + \left(\sum_{i=1}^{\text{length}(\text{normexam})} (\text{normexam}_i - \text{beta}_0 \text{cons}_i - \text{beta}_1 \text{standlrt}_i)^2\right)/2\right)\tau\right)}{\tau^{0.999 - 0.5 \text{length}(\text{normexam})}} \\
\text{Log posterior} & -\left(0.001000 + \frac{\sum_{i=1}^{\text{length}(\text{normexam})} (\text{normexam}_i - \text{beta}_0 \text{cons}_i - \text{beta}_1 \text{standlrt}_i)^2}{2}\right)\tau - (0.999 - 0.5 \text{length}(\text{normexam})) \ln \tau \\
\text{Distribution } \text{dgamma} & \\
\text{Match } A & = -0.001000 - \frac{\sum_{i=1}^{\text{length}(\text{normexam})} (\text{normexam}_i - \text{beta}_0 \text{cons}_i - \text{beta}_1 \text{standlrt}_i)^2}{2} \\
\text{Match } B & = -0.999 + 0.5 \text{length}(\text{normexam}) \\
\text{Sampling parameter } \mu & = 0.001000 + \frac{\sum_{i=1}^{\text{length}(\text{normexam})} (\text{normexam}_i - \text{beta}_0 \text{cons}_i - \text{beta}_1 \text{standlrt}_i)^2}{2} \\
\text{Sampling parameter } r & = 0.001 + 0.5 \text{length}(\text{normexam}) \\
\text{Sampling distribution } \tau & \sim \text{dgamma}\left(0.001 + 0.5 \text{length}(\text{normexam}), 0.001000 + \frac{\sum_{i=1}^{\text{length}(\text{normexam})} (\text{normexam}_i - \text{beta}_0 \text{cons}_i - \text{beta}_1 \text{standlrt}_i)^2}{2}\right)
\end{aligned}$$

The algebraic processing software then saves these three final distributions in XML file format (*beta_0.xml*, *beta_1.xml* and *tau.xml*) so that they can be read in later when we create code to fit the model. These files are then used to generate the C++ code to fit the model via a code generator as explained earlier.

5 Including Interoperability

We have now seen that the Stat-JR package has its own new algebra system and estimation engine, known as eStat as illustrated in the last section. Another aspect of the package is its ability to interface with other software packages and in particular (but not exclusively) their estimation engines. This feature doesn't, however, come for free and translator methods that are often template-specific need writing to achieve interoperability. The work here can be broken down into generic work that is built into the Stat-JR software and includes interfacing with the external software and managing the output received, and other work such as construction of data and script files for the external package that may be template-specific and thus written by the template-writer or generic as well.

In this section we will describe the (generic) Python code that is written to support interoperability and found in the *packages* subdirectory of Stat-JR. We will return to the regression modelling template and take a look at how we can include interoperability via an adapted template (*Regression2.py*). We will here describe work on three of the software packages that have been considered for interoperability, namely WinBUGS (Lunn, Thomas, Best, & Spiegelhalter, 2000), MLwiN (Charlton, Rasbash, Browne, Healy, & Cameron, 2017), and R (R Core Team, 2016) but first we will delve a little further into the workings of the eStat engine and look at the file *eStat.py*.

5.1 eStat.py

When running a model in Stat-JR with a specific estimation engine an object is constructed of a unique class related to that engine. These objects are what pull together inputs and data, perform the estimation and store the results. The files for the various engines are found in the *packages* subdirectory which also contains equivalent files for use with templates not related to model estimation. The object of type eSTAT is defined in the file *eStat.py* and you will see if you access this code that it is rather long and complicated. We will not try and go through everything as this would only be useful for the most expert Python coders. There are, however, some commonalities across engines and so we will give very brief indications of what certain methods do in the template. Note that only some of these are externally referenced (*Methodinput*, *init*, *run* and *runmore*) whilst others are called internally as they do parts of the work of the externally-referenced attributes:

- The *MethodInput* method is present in each engine and contains the engine's specific estimation method inputs that we saw when running the *Regression1* template earlier (Number of chains, Random Seed, etc.).
- The *init* method is what is called after the estimation method inputs have been answered by the user and the *Next* button is pressed. It calls lots of other methods to perform the various tasks here including getting the algorithm from the algebra system and constructing the code for running the model.
- The *applydata* method is used with eStat to construct starting values for parameters in the model
- The *compilemodel* method is used to call the algebra system and get back algebraic steps for each parameter.
- The *calconst* method is what is run with eStat when optimisation is switched on to pull out terms in the algebra that are purely data and evaluate them.

- The *run* method is used to run the current model with the prescribed estimation settings and is called when the **Run** button is pressed.
- The *runmore* method is used when the **More** button has been pressed for further iterations.
- The *genCPP* method is used to generate the C++ code for the standalone engine.
- The *runCPP* method is used to run the estimation algorithm when standalone C++ code is selected.
- The *saveresults* method brings together the (potentially multi-chain) output and constructs the *ModelResults* and *output* chains objects.
- The *dic* method constructs code if required to calculate the DIC diagnostic for the model.

With regard to engine classes in general we would expect to find a *MethodInput* method, an *init* method, a *run* method and often a *saveresults* method but also some engine-specific methods. The *MethodInput* method always contains any additional engine-specific inputs that are displayed on the screen. The *init* method contains the Python code to be run upon pressing the **Next** button, but prior to pressing the **Run** button, and the *run* method contains the Python code to be run after pressing the **Run** button. The *saveresults* method, where present, is usually called from the *run* method. If the estimation method allows more iterations (typically packages using MCMC estimation) then there will be a *runmore* method that is called after pressing the **More** button. We will now look at a second template that contains further interoperability.

5.2 Regression2.py

In this section we will consider a second template – *Regression2* that extends the first template by including the option to fit the same model in a variety of packages. If you look at the code in the Python file you will see that this template has identical code for the attributes defined in *Regression1* but in addition has methods to allow the user to call other programs. We will begin however by looking at the *engines* attribute:

```
engines = ['eStat', 'WinBUGS', 'OpenBUGS', 'JAGS' , 'MLwiN_MCMC',
'MLwiN_IGLS', 'R_MCMCglmm', 'R_glm', 'R_nimble', 'Stata_model',
'SPSS_model', 'PSPP_model', 'SAS_model', 'Minitab_model', 'SABRE',
'MATLAB_script', 'Octave_script', 'GenStat_model', 'gretl_model',
'Python_PyMC']
```

Here we see that this template offers very many software packages to be used. For several packages there is simply one engine whereas for MLwiN and R there are more, as these packages have both classical (ML) and Bayesian (MCMC) engines built-in. If you scroll down the file you will see additional attributes:

- *mlnscript*
- *rscript*
- *statascript*
- *spssscript*
- *psppscript*
- *sasscript*
- *minitabscript*
- *sabrescript*
- *matlabscript*
- *genstatscript*
- *gretlscript*

- `pymcscript`

Each of these methods is used to produce scripts or parts of scripts for the corresponding package, and the main point to take home here is that although some template-specific coding is required, the code required is generally short functions (and in the case of WinBUGS (Lunn, Thomas, Best, & Spiegelhalter, 2000), OpenBUGS (Lunn, Spiegelhalter, Thomas, & Best, 2009) and JAGS (Plummer, 2003) non-existent) and so the bulk of the work, at least for this template, is done by the generic code within the package files for the engines.

5.3 WinBUGS and Winbugsscript.py

We will begin by looking at the WinBUGS package (Lunn, Thomas, Best, & Spiegelhalter, 2000) as the model code we have been creating for the Stat-JR engine has many similarities with BUGS code. We will begin by running the template and viewing the output. It should be noted that in order to run the WinBUGS engine Stat-JR needs to be able to find it. Stat-JR has a file of settings, *settings.cfg* which it will have placed in a *.statjr* directory under your *Users* directory. This file contains amongst other things directory names for each package. For example on my machine I have:

```
[WinBUGS]
executable = C:\WinBUGS14\WinBUGS14.exe
```

If you wish to use this option you need to either install WinBUGS in this directory or change these paths to point to WinBUGS on your machine. This can either be done by editing the file or by going to the **Settings** screen we looked at earlier and changing the file there. If you edit the file itself you will need to restart the *TREE* program or select **Debug > Reload packages** so that it uses these settings and then select *Regression2.py* from the *template* choices and *tutorial* for the *dataset*. Next select the following inputs:

Dataset: *tutorial*; **Template:** *Regression2*; **Input string:** `{'Engine': 'WinBUGS', 'burnin': '500', 'defaultsv': 'Yes', 'outdata': 'outwinbugs', 'thinning': '1', 'nchains': '2', 'iterations': '2500', 'y': 'normexam', 'x': 'cons,standlrt', 'seed': '1'}`

Stat-JR:TREE
Start again
Dataset
tutorial
Template
Regression2
eBook
Ready (0s)
Settings
About
Debug

?
Response:

normexam
remove

?
Explanatory variables:

cons,standlrt
remove

Choose estimation engine:

WinBUGS
remove

Number of chains:

2
remove

Random Seed:

1
remove

Length of burnin:

500
remove

Number of iterations:

2500
remove

Thinning:

1
remove

Name of output results:

outwinbugs
remove

Use default starting values:

☒ Yes
☐ No

Next

Clicking on **Next** will result in Stat-JR constructing all the files it needs to fit the model in WinBUGS and these can be found under the pull-down list. There will be model code (*model.txt*) and the mathematical representation (*equation.txt*) as we saw for *Regression1* with the eStat engine apart from that this model code has been modified slightly to be in line with standard WinBUGS code, in this case *length(normexam)* has been replaced with *4059* in code. (Note that this template also supports the eStat estimation engine). We can look at the other input files required by WinBUGS for example here is the file containing initial values for chain 1:

Stat-JR:TREE
Start again
Dataset
tutorial
Template
Regression2
eBook
Ready (0s)
Settings
About
Debug

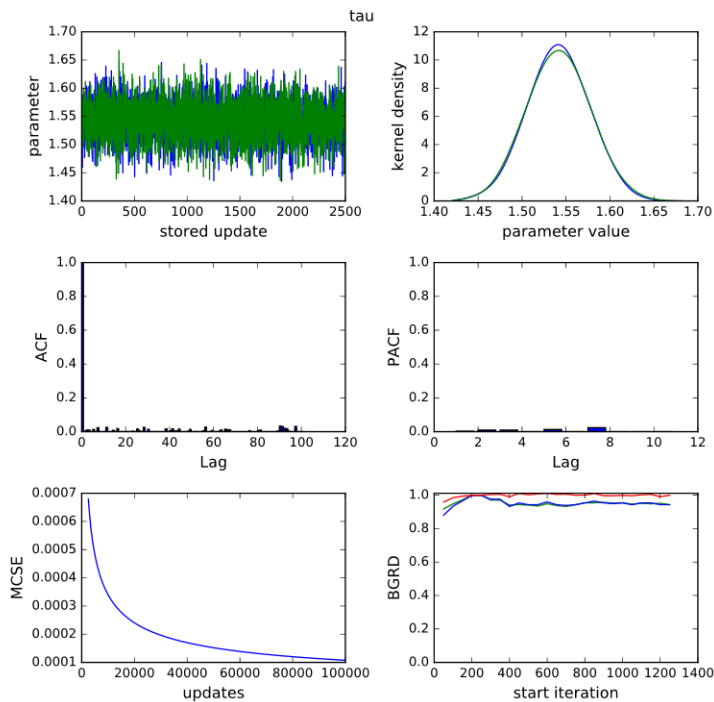
Edit

inits1.txt

Popout

```
list(
  beta_1 = 0.1,
  tau = 0.1,
  beta_0 = 0.1
)
```

There is also a data file and a script file. If we next click on **Run** you will see a WinBUGS window appear on your toolbar, and in the background, whilst WinBUGS is fitting the model. When it finishes it will disappear and the list of files in the pull-down list will lengthen; so, for example, if we select *tau.svg* and pop it out we will get the following output in the browser:



As we chose 2 chains you will also observe a green and blue output for both the chains and kernel density plots. If you look at *ModelResults* you will notice that we get results for each parameter (including the deviance and some reordering of the output). We now need to see how the connection to WinBUGS was achieved. Interestingly, for the *Regression2* template, you will not find any additional code to run WinBUGS within the template itself apart from putting WinBUGS in the engines list. This means that all the code is generic and not template-specific and will be found in the *WinBUGS.py* file within the packages directory.

As mentioned in the last section these engine files give class definitions for classes that will perform the interoperability work for specific packages, and the file *WinBUGS.py* gives the class definition for the *WinBUGSScript* class. This class has, as expected, *MethodInput*, *init* and *run* methods and, as WinBUGS supports running further MCMC iterations, there is also a *runmore* method. The *MethodInput* method is fairly self explanatory and contains the various additional estimation method inputs required by WinBUGS along with some code to allow the user to specify their own starting values if they wish. The *init* method is split into two main parts written in two methods: *PrepareWBUGSInputs* which is used to create, in turn, the three files that are needed to fit a model in WinBUGS, namely the data, initial values and model files, and also *WriteScript* which creates the script file that WinBUGS uses to perform the model-fitting and extraction of results, etc.

The *PrepareWBUGSInputs* method has code that will construct the model and data files for BUGS as well as a series of initial value files. In many simple model scenarios, including the regression model we have considered, the WinBUGS model file will, aside from simple substitutions, be identical to the input file for the eStat algebra system and so the chunk of code dealing with model construction is fairly simple and simply involves copying the *model.txt* file and making the substitutions.

If you are interested in writing templates that either only use WinBUGS or are for models where the code for WinBUGS and eStat diverges then it is possible to write methods within the template to construct the required model, data and inits files. These methods are named *bugsmodel*, *bugsdata* and *bugsinits* respectively. The *bugsmodel* method should resemble to some degree the *model* method used for eStat, whilst the *bugsdata* and *bugsinits* methods will generally consist of commands to pull out or construct the various objects that make up the data and initial values. For example in the *1LevelMVNormal* template there are lines like:

```
data['M'] = M
```

...and...

```
data['R'] = Rmat
```

...which tell Stat-JR that there are two data objects that need adding to the WinBUGS output file. Stat-JR can evaluate that M is an integer and R is a matrix from how they have been constructed in Python, and there is code within *PrepareWBugsInputs* to write these out correctly into the data file. For initial values there is a similar construction with the *data[]* construction replaced with an *inits[]* construction. Note that if you wish to write your own *bugsdata* and/or *bugsinits* methods then all data and/or parameters requiring initial values must be defined in the method.

For examples of template with their own WinBUGS functions you might look at *1LevelMVNormal* or *CapRecap*. The template *1LevelMVNormal* fits a multivariate response model and as discussed later in the manual the eStat engine has an unusual way of fitting such models and so for WinBUGS we have files for *bugsmodel* and *bugsdata* to create these files in a more standard use of the WinBUGS language. We do not have a *bugsinits* methods as the generic code works OK for creating the initial values here. The template *CapRecap* fits a capture-recapture model which involves multinomial distributions where again WinBUGS and eStat diverge. Here there is code to create all three required files, however the reason for the *bugsinits* attribute is primarily because we want to have a specific pattern of starting values.

The *WriteScript* function is totally generic as it creates the script file to be run in WinBUGS and this, at least at present, is consistent across templates.

The *run* function which is run when the **Run** button is pressed is fairly short:

```
def run(self):
    self.eng.run('script.txt')

    try:
        self.saveresults()
    except:
        logging.error('There was a problem running the model')
```

The command:

```
self.eng.run('script.txt')
```

...actually runs WinBUGS.

The last command:

```
self.saveresults()
```

...both extracts the numbers from the text files returned from WinBUGS and constructs the *ModelResults* object that can be viewed.

We have limited this section to a broad description of the purposes of specific functions used in the interoperability and how an advanced user, if required, might write their own methods for their template. Stat-JR also supports OpenBUGS (Lunn, Spiegelhalter, Thomas, & Best, 2009) and JAGS (Plummer, 2003) which are, in terms of input files, similar to WinBUGS. There are differences in their script files and so the files *OpenBUGS.py* and *JAGS.py* have similar but slightly differing code to account for this. JAGS also has a slightly different format for data and initial values files which *JAGS.py* takes care of. If you are writing your own *bugsmodel*, *bugsdata* and *bugsinit* methods then these will also be used to create the model code, data and initial values in OpenBUGS and JAGS so you will not need to repeat the work. We next look at MLwiN.

5.4 MLwiN

MLwiN (Charlton, Rasbash, Browne, Healy, & Cameron, 2017) is another package with MCMC functionality but which can also fit multilevel models using classical statistical methods. For the *Regression2* template in Stat-JR we offer the option of fitting models in MLwiN using either approach. Having seen how WinBUGS links into Stat-JR we will now show the similarities and differences in how MLwiN links in. The first observation is that MLwiN doesn't use a model description language like Stat-JR or WinBUGS. It is also more restrictive in terms of which models it can fit which means that it will not be available for all templates but many of the templates we have written thus far fit models that MLwiN can also fit. Although MLwiN has a GUI user interface which is typically how users will use it, it also has a macro language and it is this language that we have to make use of when writing interoperability code for Stat-JR. So as with WinBUGS we need to tell Stat-JR where to find MLwiN and this is found in the *settings.cfg* file, for example:

```
[MLwiN]
executable = C:\Program Files\MLwiN v3.02\mlnscript.exe
```

Let us demonstrate using MLwiN and MCMC for the *tutorial* dataset and *Regression2* template. Here select the *template* and *dataset* and next choose inputs as follows:

Dataset: *tutorial*; **Template:** *Regression2*; **Input string:** `{'Engine': 'MLwiN_MCMC', 'burnin': '500', 'outdata': 'outmlwin', 'thinning': '1', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'y': 'normexam', 'x': 'cons,standlrt', 'seed': '1'}`

Stat-JR:TREE
Start again
Dataset ▾
tutorial
Template ▾
Regression2
eBook ▾
Idle
Settings
About
Debug ▾

Response:	normexam remove
Explanatory variables:	cons,standlrt remove
Choose estimation engine:	MLwiN_MCMC remove
Number of chains:	3 remove
Random Seed:	1 remove
Length of burnin:	500 remove
Number of iterations:	2000 remove
Thinning:	1 remove
Use default algorithm settings:	Yes remove
Name of output results:	<input type="text" value="outmlwin"/>

Next

The first thing to note is that the two approaches for MLwiN have their own engine name, and we will see later that they have their own python files in the package directory. A further thing to note is that MLwiN normally only offers single chains for MCMC. However if you run it from Stat-JR you can get the illusion of multiple chains as Stat-JR will run MLwiN several times (in parallel), once for each chain. Currently each chain has the same initial values but different random number seed but in the future we hope to allow different starting values as well. Clicking on the **Next** button we see the following:

datafile.dta	normexam	cons	standlrt	_levres	_id
1	0.26132447	1	0.61905926	1.0	1
2	0.13406679	1	0.20580196	1.0	2
3	-1.7238824	1	-1.3645757	1.0	3
4	0.967586	1	0.20580196	1.0	4
5	0.5443409	1	0.37110487	1.0	5
6	1.7348992	1	2.189437	1.0	6
7	1.039608	1	-1.1166214	1.0	7
8	-0.12908468	1	-1.0339699	1.0	8
9	-0.93937767	1	-0.5380612	1.0	9
10	-1.2194855	1	-1.4472272	1.0	10
11	2.408692	1	2.4373913	1.0	11
12	0.61072856	1	2.1067855	1.0	12
13	-1.8366867	1	0.04049904	1.0	13
14	-0.12908468	1	1.1978194	1.0	14
15	2.203121	1	2.520043	1.0	15
16	1.2405332	1	1.1149681	1.0	16
17	1.7348992	1	1.0323166	1.0	17
18	1.3101424	1	0.7843622	1.0	18
19	-0.6230507	1	-1.1166214	1.0	19
20	1.039608	1	-1.1992729	1.0	20
21	-1.0290668	1	-0.37275827	1.0	21
22	-1.2194855	1	-1.3645757	1.0	22
23	0.3280722	1	-0.9513184	1.0	23
24	-0.49278083	1	-2.3563933	1.0	24
25	1.9003352	1	-0.04215242	1.0	25
26	0.8965657	1	0.37110487	1.0	26
27	0.073536366	1	1.1149681	1.0	27

View 1 - 30 of 4,059

Here we see the dataset file which contains only the columns in the data that are involved in the modelling in MLwiN. The list of objects has been populated by many MLwiN script files and we will look at one of these now, so select *initscript0.mac* and the screen will look as follows:

Edit initscript0.mac Popout

```
INIT 5 10000 1500 150 30
NOTE input data file
RSTA 'datafile.dta'
NOTE Set up the model

RESP "normexam"
IDEN 1 "_id"
ADDT "_levres"
SETV 1 "_levres"
FPAR 0 "_levres"
ADDT "cons"
ADDT "standlrt"

METH 1
BATCH 1
START
```

This is the script that is run first in MLwiN and sets up the required model and runs it (using IGLS first to generate initial values). If we look in the file *Regression2.py* we can find the attribute *mlnscript* which is as follows:

```
mlnscript = '''
RESP "${y}"
IDEN 1 "_id"
ADDT "_levres"
SETV 1 "_levres"
FPAR 0 "_levres"
% for i in range(len(x)):
ADDT "${x[i]}"
```



```
% endfor
'''
```

You should be able to see that, for our inputs, if we were to expand out this Python code we would get the second section of code that appears within *initscript0.mac*. This code essentially sets up the model in MLwiN ready to be fitted. The package file *MLwin_MCMC.py* will therefore take the code that appears in *mlnscript* in the template and place it in the *initscript* macros (note there is one *initscript* for each chain). Stat-JR will also construct 3 further macros for each chain: *burninscript*, *runscript* and *resultsscript*. As MLwiN works by building up the model (as performed in *initscript*) these further scripts perform the burnin iterations, main run iterations and results extraction respectively and are generic. They only depend on the estimation method inputs, i.e. length of burnin, number of iterations, thinning, etc., and each chain has a different random seed set.

Clicking on **Run** will fire off the three instances of MLwiN and bring back the output as follows (after changing the output list to show **ModelResults**):

Stat-JR:TREE				
Parameters:				
parameter	mean	sd	ESS	variable
deviance	9763.486009631592	2.442775481596	6225	
beta2	-0.00122328271387	0.0125588134387	6751	cons
beta3	0.59505016039	0.0125637974876	5953	standlrt
sigma1_1	0.648910145097	0.014529925453	6694	var(_levres)
Model:				
Statistic		Value		
Dbar		9763.486009631612		
D(thetabar)		9760.510895133681		
pD		2.975114497933		
DIC		9766.461124129546		

Apart from the speed of estimation (which is much quicker than Stat-JR and WinBUGS) the results are very similar. Note that we have some slightly different numbering with MLwiN. MLwiN requires being told that there is a constant variance at level 1 and to do this we create a constant column (of ones), named *_levres*, which is made random at level 1 to represent this constant variance. The fixed effects are then numbered from 2 rather than 0. We could, as an alternative run, run the model via IGLS instead of MCMC by clicking on **Choose Estimation Engine** and choosing the following and clicking **Next**:

Dataset: *tutorial*; **Template:** *Regression2*; **Input string:** `{'y': 'normexam', 'x': 'cons,standlrt', 'Engine': 'MLwiN_IGLS', 'defaultalg': 'Yes'}`

Stat-JR:TREE
Start again
Dataset
tutorial
Template
Regression2
eBook
Ready (0s)
Settings
About
Debug

?
Response:

normexam
remove

?
Explanatory variables:

cons,standlrt
remove

Choose estimation engine:

MLwiN_IGLS
remove

Use default algorithm settings:

Yes
remove

Run

Note that as the non-MCMC engines do not create a datafile of the output that question is not asked. Clicking on **Run** you get almost instantaneous answers if you choose **ModelResults**:

Stat-JR:TREE

Results

Parameters:

parameter	variable	mean	se
beta2	cons	-0.00119111914973	0.0126391831622
beta3	standlrt	0.595056780156	0.0127269561056
sigma1_1	var(_levres)	0.648418837627	0.0143933237957

Model:

Statistic	Value
converged	1.0
iterations	2.0
2*LogLikelihood	9760.509436476153

You will notice here that the results produced are simply point estimates and standard errors as the method doesn't construct chains. We also do not see the plots that we get with MCMC methods. As we mentioned earlier there are two engines and hence two files in the packages directory: *MLwiN_MCMC.py* and *MLwiN_IGLS.py*. We will discuss briefly *MLwiN_MCMC.py* which is currently, apart from *eStat.py* and an associated eStat engine (*CustomC*), the biggest file in the directory.

As usual the file defines a class, this time for an *MLwiNMCMC* object. The class has the usual *MethodInput*, *init* and *run* (and *runmore*) methods. The *init* method will construct the dataset and script files for running in MLwiN. In fact there are attributes within the code for each of the script files and you will see the code for the *init_script* abbreviated below:

```
init_script = '''
INIT 5 10000 1500 150 30
NOTE input data file
RSTA 'datafile.dta'
NOTE Set up the model

${userscript}

METH 1
BATCH 1
START
...
```

```
STOR "modelstate${chainnum}.wsz"
'''
```

Here the script written within the template gets inserted where we see `${userscript}`, and you will also see that chain number gets inserted in the last line of the macro. The *run* method simply runs MLwiN using the constructed datasets and macro files, and then calls the *saveresults* method which creates the *ModelResults* object. Again we omit details of precisely how these code sections work as they are generic code and not template-specific. The *MLwiN_IGLS.py* file has a similar form to *MLwiN_MCMC.py* except the macros are slightly shorter and the objects produced in the *saveresults* methods are different. We will leave MLwiN here and move onto another package with some functionality for the use of both MCMC and classical estimation methods: R.

5.5 R

R (R Core Team, 2016) is a general purpose statistics programme that consists of a framework of interlinking statistical commands that are known as packages. The R installation consists of a base package containing many of the standard statistical operations and to this can be added user-written packages. For our *Regression2* template we will utilise the *glm* function when performing classical inference. For MCMC methods we use the *MCMCglmm* package (Hadfield, 2010), a user-defined function that can fit many models using MCMC¹. As with the earlier programs we need to include details of the location of R in *settings.cfg* on our machine prior to running *webtest*. On my machine this is as follows:

```
[R]
executable = C:\Program Files\R\R-3.5.1\bin\x64\R.exe
```

We can again first run the *Regression2* template to see what it returns when we choose R, so select *Regression2* as the *template* and *tutorial* as the *dataset* and then input the following:

Dataset: *tutorial*; **Template:** *Regression2*; **Input string:** `{'y': 'normexam', 'x': 'cons,standlrt', 'Engine': 'R_glm'}`

Stat-JR:TREE Start again Dataset **tutorial** Template **Regression2** eBook Ready (0s) Settings About Debug

Response: normexam [remove](#)

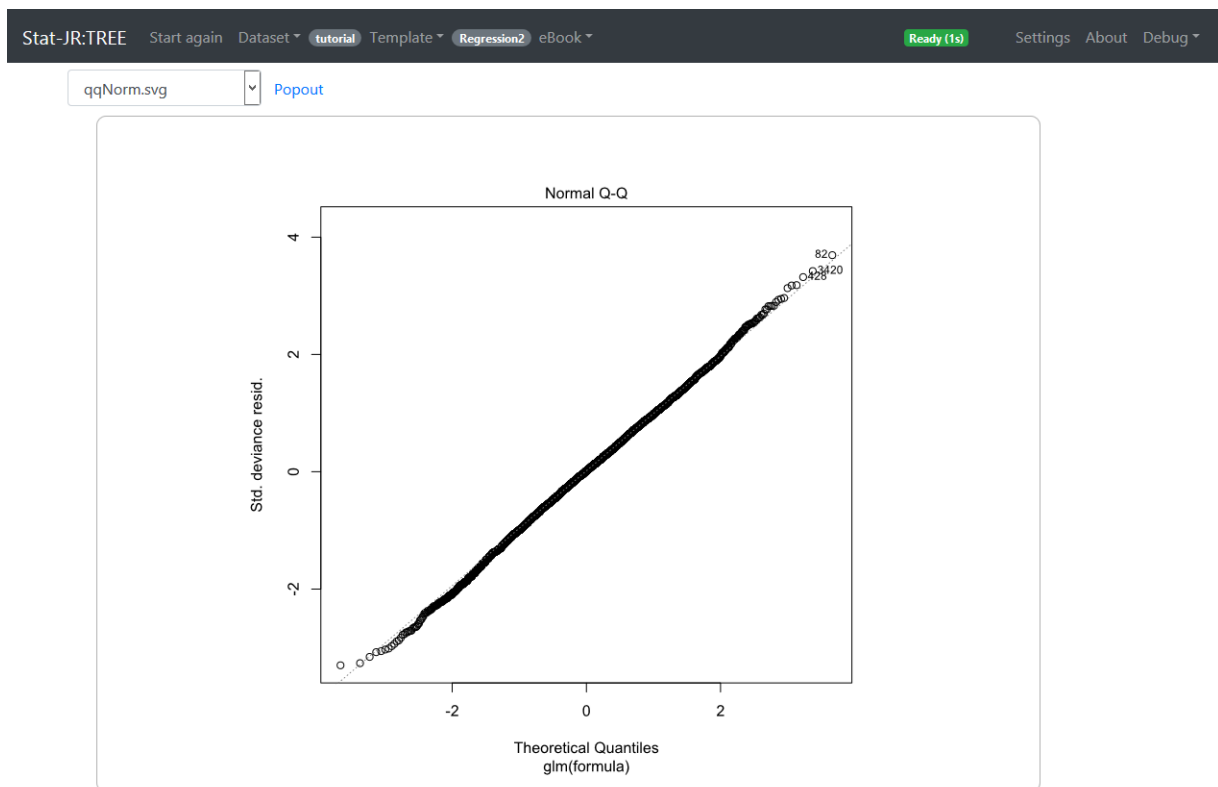
Explanatory variables: cons,standlrt [remove](#)

Choose estimation engine: R_glm [remove](#)

[Run](#)

Clicking on **Run** will fire off R and then give the following output if we choose *qqNorm.svg* from the output list:

¹ Although we have recently added support for the nimble (de Valpine, Paciorek, Turek, Anderson-Bergman, & Temple Lang, 2016) package in R too, although nimble has an additional dependency on Rtools.



Here we see a quantile-quantile plot, which is one of the outputs from R produced from the script sent to R. We can select *ModelResults* in the output list to get the following:

Stat-JR:TREE Start again Dataset **tutorial** Template **Regression2** eBook Ready (1s) Settings About Debug

ModelResults [Popout](#)

Results

Parameters:

parameter	est	se
cons	-0.00119111914973	0.0126422981796
standlrt	0.595056780156	0.0127300927553

Model:

Statistic	Value
deviance	2631.932061928951
nulldeviance	4049.433025806798
aic	9766.509376513333
converged	1
iter	2

Here you will see that as the method is maximum likelihood we get only estimates and standard errors and the AIC statistic. It is also possible to view the full log file from R and a plot of residuals against fitted values in the output pane as this is also created by the R script. If we wish to look at the script itself we can select *script.R* from the output list and pop it out as follows:

Script to run model

```

local({r <- getOption("repos"); r["CRAN"] <- "http://cran.r-project.org"; options(repos = r)})
#####
# Note that when Stat-JR interoperates with R, it sets the working
# directory to wherever the user's temporary files are stored, i.e.
# workdir = tempdir(). The data to be modelled, this script, and the
# files exported from R, are all saved there.
#####

# test to see if foreign package is already installed, if not, then install it
if (!require(foreign)) {
  install.packages("foreign")
  library(foreign)
}

# read *.dta file (Stata format) into R data frame (requires foreign):
mydata<-read.dta("datafile.dta")
# print summary of the data
summary(mydata)

#####
# Below we specify the model formula, formatted as y ~ x1 + x2 + ...
# Since Stat-JR assumes users have included the intercept in their list
# of explanatory variables, -1 removes the intercept which the glm
# function otherwise adds by default.
#####

formula <- normexam ~ cons + standlrt - 1
# fit the model using the glm function, specifying the formula, data, and distribution (with identity link) in its arguments
myModel <- glm(formula, data = mydata, family = gaussian(identity))
# print summary of the model fit
summary(myModel)

#####
# Objects of class glm have several residual plots available (can

```

Here we find some heavily commented R code. We can see the call to *glm* near the bottom of the window and this is followed by some code to generate the two plots that appear in the output list. If we wish to instead use MCMC estimation we could, for example, do so by providing the following inputs:

Dataset: *tutorial*; **Template:** *Regression2*; **Input string:** `{'Engine': 'R_MCMCglmm', 'burnin': '1000', 'outdata': 'outR', 'thinning': '1', 'iterations': '5000', 'y': 'normexam', 'x': 'cons,standlrt', 'seed': '1'}`

Stat-JR:TREE
Start again
Dataset ▾ tutorial
Template ▾ Regression2
eBook ▾
Ready (0s)
Settings
About
Debug ▾

? Response:
normexam
remove

? Explanatory variables:
cons,standlrt
remove

Choose estimation engine:
R_MCMCglmm
remove

Random Seed:
1
remove

Length of burnin:
1000
remove

Number of iterations:
5000
remove

Thinning:
1
remove

Name of output results:

Next

Clicking on **Next** and then **Run** will give the following upon running and selecting *ModelResults* from the output list:

Stat-JR:TREE

Start again

Dataset

tutorial

Template

Regression2

eBook

Ready (7s)

Settings

About

Debug

ModelResults

Popout

Results

Parameters:

parameter	mean	sd	ESS
cons	-0.00137723072367	0.0124091391668	4943
standlrt	0.595484308437	0.0128012344608	5286
sigma_2	0.649047335707	0.0145284234669	4471

Model:

Statistic	Value
DIC	9766.486799872408

It should be noted that MCMCglmm is a single chain package and so Stat-JR does not give the option for multiple chains here although in theory R could be called several times to give parallel chains as we did for MLwiN. It also only gives the actual DIC estimate and not pD. Let us now look at how interoperability is performed in the code. At present R interoperability is possibly the opposite extreme to MLwiN interoperability. In the packages directory there are files for each R package; here we are interested in *R_glm.py* and *R_MCMCglmm.py* which are quite short files defining classes for each object. Then, in the *Regression2* template file, there is a longer attribute *rscript* which is used to construct the R script for model-fitting, with Python conditional statements to split up the code for glm and for MCMCglmm.

Looking firstly at *R_glm.py*, it has a *MethodInput* method but this doesn't have any additional inputs as they are not required for this package. The *inits* method code begins as follows:

```
def init(self):
    self.WriteData()
```

Here we see a call to the *WriteData* method that constructs the data file that needs to be sent to R. Then we begin to construct the script file for R:

```
script = '''
<% from EStat.Utils import Rmmult %>\\
local({r <- getOption("repos"); r["CRAN"] <- "http://cran.r-project.org"; options(repos = r)})
# # # # #
# Note that when Stat-JR interoperates with R, it sets the working
# directory to wherever the user's temporary files are stored, i.e.
# workdir = tempdir(). The data to be modelled, this script, and the
# files exported from R, are all saved there.
# # # # #

# test to see if foreign package is already installed, if not, then install it
if (!require(foreign)) {
  install.packages("foreign")
  library(foreign)
}

# read *.dta file (Stata format) into R data frame (requires foreign):
mydata<-read.dta("datafile.dta")
```

```
# print summary of the data
summary(mydata)
'''
```

which here initially involves loading up the data and installing the R packages required if they are not already present. Next is the call to the template specific code via the *rscript* attribute as shown below:

```
script += self.template.rscript
```

Here the substitutions into the template specific code are made and it is added to the script file. Finally some more generic code to interrogate the output produced by R and create datafiles to be used as output objects in Stat-JR is written.

```

script += '''
#####
# Here an empty list called 'stats' is created, to which various
# components of the model just fitted are added. If you are fitting this
# model yourself in R, you can of course access these components directly
# yourself, rather than necessarily copying them to a list for export.
#####

# create an empty list called 'stats'
stats <- list()
# add (residual) deviance to 'stats'
stats$deviance <- myModel$deviance
# add null deviance to 'stats'
stats$nulldeviance <- myModel$null.deviance
# add Akaike information criterion to 'stats'
stats$aic <- myModel$aic
# add convergence status (logical TRUE / FALSE) to 'stats'
stats$converged <- myModel$converged
# add number of iterations taken to fit the model to 'stats'
stats$iter <- myModel$iter

#####
# A variety of parameters / model fit statistics are saved to the
# working directory as *.dta files; Stat-JR imports these and
# translates them into its own format for presentation to the user.
#####

# save 'stats' as 'stats.dta'
write.dta(data.frame(stats), file="stats.dta")
# create 'estimates.dta', consisting of the coefficient estimates on one row,
# and their standard errors on another
write.dta(data.frame(rbind(myModel$coefficients, sqrt(diag(vcov(myModel))))),
file="estimates.dta")
# save the residuals as 'residuals.dta'
write.dta(data.frame(myModel$residuals), file="residuals.dta")
'''

```

Looking at the template specific code in the template *Regression2* we see the following code at the beginning of the method:

```
rsrscript = ''
#####
# Here we specify the model formula, formatted as y ~ x1 + x2 + ...
# Since Stat-JR assumes users have included the intercept in their list
# of explanatory variables, -1 removes the intercept which the glm
# function otherwise adds by default.
#####

formula <- $ {v} ~ $ {Rmmult(x)} - 1
```

This first line here (after the comment) simply defines the formula for the model which is common to both estimation methods and then the code goes on to specific code for the glm package.

```

% if Rpackage == 'glm':
# fit the model using the glm function, specifying the formula, data, and distribution (with
identity link) in its arguments
myModel <- glm(formula, data = mydata, family = gaussian(identity))
# print summary of the model fit
summary(myModel)

#####
# Objects of class glm have several residual plots available (can
# view them all via e.g. plot(myModel)), here we export the first two.
#####

# open a scalable vector graphics device called 'ResivsFitted.svg'
svg("ResivsFitted.svg")
# request a plot of the residuals vs fitted values
plot(myModel, 1)
# close the device
dev.off()
# open a scalable vector graphics device called 'qqNorm.svg'
svg("qqNorm.svg")
# request a Q-Q plot
plot(myModel, 2)
# close the device
dev.off()
% endif

```

This second chunk is the code specific to the `glm` engine and consists of the call to that function followed by calls to a summary function and two plotting functions. There is then a large chunk of code specific for the *MCMCglmm* function which essentially runs that code and then the script is returned. So we should now see how the full script file for R is formed and what needs to be placed in the template.

The *run* method (within *R_glm.py*) that is executed when the **Run** button is pressed is, in this case, very short and basically consists of a command to run the script followed by a call to the *saveresults* method.

```

def run(self):
    self.eng.run('script.R')

    try:
        self.saveresults()
    except:
        logging.error('There was a problem running the model')

```

The *saveresults* method itself is also reasonably short and creates the *ModelResults* object. Here it involves interrogation of the two output files from R, *estimates.dta* and *stats.dta*, to extract the appropriate numbers for the *ModelResults* object.

```

def saveresults(self):
    results = ModelOutput()

    dta = self.eng.outputs['estimates.dta']
    for var in dta.variables.keys():
        results.add(var, 'est', dta.variables[var]['data'][0])
        results.add(var, 'se', dta.variables[var]['data'][1])

    statsdta = self.eng.outputs['stats.dta']
    for stat in statsdta.variables.keys():
        results.add('model', stat, statsdta.variables[stat]['data'][0])

    self.eng.outputs['ModelResults'] = results

```

It then continues to create separate *.dta* files and objects for parameters and fit.

The *R_MCMCglmm.py* file performs the equivalent operations when this engine is called from Stat-JR and the same methods are present. The code is slightly more involved and in this case the *MethodInputs* method has inputs to tell R how long to run MCMC for. There are also other differences in the functions to account for the method being MCMC and hence returning chains to be summarised. These methods are, however, similar to those for MLwiN and WinBUGS and we will not detail them here.

Finally here we should point out that there are R-specific templates that perform other functions. For example *PlotsViaR.py* allows the user to use the R *lattice* (Sarkar, 2008) graphical functions from within Stat-JR. These templates generally have a very simple structure: the *engine* attribute is set to *R_script*, the *inputs* attribute gives all the inputs required by the template and the *rscript* attribute is used to construct a script file to be used in R to perform the required operations. There is therefore a file in the *packages* directory named *R_Script.py* which handles such templates. It has a very simple structure and contains the usual methods we have become familiar with when looking at the files in this directory. It basically contains code to construct the data file for R, call the template code to construct the script and then run the script and store the output objects. We will give no further details here but finish by mentioning the other packages supported by Stat-JR.

5.6 Other packages

For our *Regression2* template you will see that we also offer interoperability with other packages: GenStat (VSN International, 2015), Gretl (Cottrell & Lucchetti, 2007), Stata (StataCorp, 2017), Matlab (The MathWorks, Inc., 2017), Minitab (Minitab, Inc., 2017), PSPP (Free Software Foundation, 2017), PyMC (Salvatier, Wiecki, & Fonnesbeck, 2016), SABRE (Barry, Francis, & Davies, 1989), SAS (SAS Institute Inc., 2011) and SPSS (IBM Corp., 2017). Each of these packages will have a Python file in the *packages* directory which deals with getting the data in the correct format for the package, calling the template-specific code for the package and interrogating the output files received back by Stat-JR from the package. Some packages will have two Python files in the *packages* directory, for example for Stata we have files *Stata_model.py* and *Stata_script.py*, and here the distinction is between calls from templates that fit models and thus need to create a *ModelResults* object and templates that use other functionality e.g. graphs from within the package.

For our *Regression2* template you will see that for most packages the code is quite short, for example for Stata, we have:

```
statascript = '''
local family gaussian
local link identity

glm ${y} \\\
% for p in x:
${p} \\\
% endfor
, family(`family') link(`link') \\\
##always remove the intercept
noconstant

## produce diagnostic plots
predict yhat, mu
predict ehat, response
```

```

predict rhat, response standardized
scatter ehat yhat
graph export "ResivsFitted.png", replace
egen rank=rank(rhat)
gen nscore=invnormal(rank/(_N+1))
scatter rhat nscore
graph export "QQ_Plot.png", replace
'''

```

Here the code not only fits a model but also produces two plots.

This ends our whirlwind description of the interoperability features in the Stat-JR program. The interoperability features are still a work in progress and although they are present in many of the templates that we will describe in later sections we will not be going into details on this aspect of these templates. The interested reader can look at these templates and see how they perform interoperability and try writing their own interoperability code for their own templates.

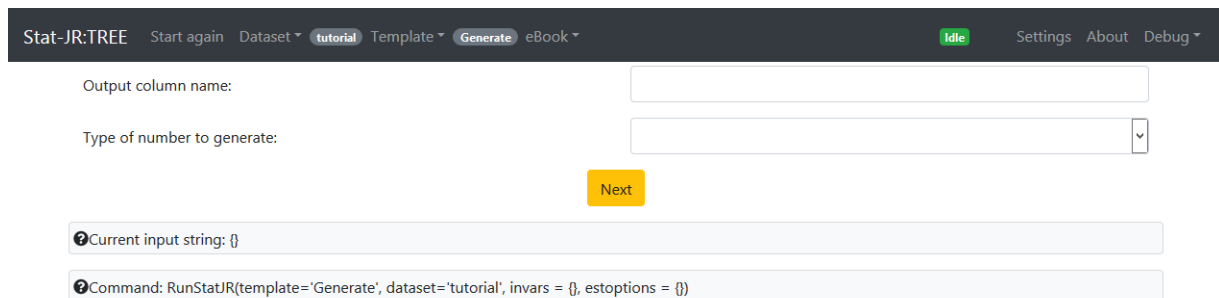
6 Input, data manipulation and output templates

The Stat-JR system does not simply consist of templates for fitting models to datasets. There are, in addition, templates that allow the user to input their own datasets, manipulate and summarise datasets and plot features of datasets. In many ways these templates are much simpler to write and understand. We will here look at a few examples of the templates along with their code and explain how they fit into the *TREE* interface.

6.1 Generate template (generate.py)

Our first template to look at is used for generating columns to add to a dataset. These columns can be constants, sequences, repeated sequences or random numbers. As this template doesn't have any exciting outputs we will not see much happen after execution. Let's look at an example of adding a vector of uniform random numbers to the *tutorial* dataset.

We firstly choose the *Generate* template from the template list on the main window and press the **Use** button. The template will look as follows:



The screenshot shows the Stat-JR: TREE interface. At the top, there is a navigation bar with 'Stat-JR: TREE', 'Start again', 'Dataset' (with a dropdown arrow), 'tutorial' (selected), 'Template' (with a dropdown arrow), 'Generate' (selected), 'eBook' (with a dropdown arrow), a green 'Idle' status indicator, and 'Settings', 'About', and 'Debug' (with a dropdown arrow) buttons. Below the navigation bar, there are two input fields: 'Output column name:' and 'Type of number to generate:'. A yellow 'Next' button is positioned below the second input field. At the bottom, there are two text boxes showing the current state: 'Current input string: {}' and 'Command: RunStatJR(template='Generate', dataset='tutorial', invars = {}, estoptions = {})'.

Now we select *random* for the output column name and choose *Uniform Random* for the type. After clicking **Next** we are asked for a name of output results, and here if we enter *tutorial* the new column will be appended onto the dataset and the tutorial dataset (in memory) will have an additional column. If we choose a new name then a new dataset containing all the columns from *tutorial* along with this new column will be formed (in memory) and *tutorial* will persist without the new column.

Pressing **Next** will finish the inputs and Pressing **Run** will run the template and the **Run** button will then disappear. If we then select *tutorial* from the pull-down list we will see:

Dataset: *tutorial*; **Template:** *Generate*; **Input string:** `{'type': 'Uniform Random', 'outdata': 'tutorial', 'outcol': 'random'}`

Stat-JR:TREE Start again Dataset **tutorial** Template **Generate** eBook Ready (0s) Settings About Debug

Output column name: random [remove](#)

Type of number to generate: Uniform Random [remove](#)

Name of output dataset: tutorial [remove](#)

[Download](#) [Make workflow](#)

Current input string: {'type': 'Uniform Random', 'outdata': 'tutorial', 'outcol': 'random'}

Command: RunStatJR(template='Generate', dataset='tutorial', invars = {'outcol': 'random', 'outdata': 'tutorial', 'type': 'Uniform Random'}, estoptions = {})

tutorial [Popout](#)

	school	student	normexcl	cons	standirt	girl	schgenr	avslrt	schav	vrband	random
1	1	1	0.261324	1	0.619056	1	1	0.166174	2	1	0.417022
2	1	2	0.134066	1	0.205801	1	1	0.166174	2	2	0.720324
3	1	3	-1.72388	1	-1.36457	0	1	0.166174	2	3	0.000114
4	1	4	0.967586	1	0.205801	1	1	0.166174	2	2	0.302332
5	1	5	0.544341	1	0.371104	1	1	0.166174	2	2	0.146755
6	1	6	1.734896	1	2.189431	0	1	0.166174	2	1	0.092336
7	1	7	1.039606	1	-1.11662	0	1	0.166174	2	3	0.186261
8	1	8	-0.12908	1	-1.03396	0	1	0.166174	2	2	0.345561

Here you can see a new column labelled *random* to the right of the dataset (you can pop this out into another tab if it is not clear).

Examining the code it is first worth noting that the template has

```
engines = ['Python_script']
```

This tells Stat-JR that this template is not a model template and therefore needs to be treated differently. The template has an *inputs* attribute as shown below:

```
inputs = ''
outcol = Text('Output column name: ')
type = Text('Type of number to generate: ', ['Uniform Random', 'Binomial
Random', 'Chi Squared Random', 'Exponential Random', 'Gamma Random',
'Normal Random', 'Poisson Random', 'Constant', 'Sequence', 'Repeated
sequence'])

if type == 'Binomial Random':
    prob = Text('Probability')
    numtrials = Integer('Number of Trials')

if type == 'Chi Squared Random':
    degreefree = Integer('Degrees of Freedom')

if type == 'Gamma Random':
    shape = Text('Shape')

if type == 'Poisson Random':
    exp = Text('Expectation')

if type == 'Constant':
    value = Text('Value')

if type == 'Sequence':
    start = Integer('Starting Value')
```

```

        step = Integer('Step')

if type == 'Repeated sequence':
    max = Integer('Maximum number')
    repeats = Integer('Repeats per block')

outdata=Text('Name of output dataset: ')
'''

```

Here we see that there are two main inputs, a name for the column to add (*outcol*) and a *type* of column to generate. Depending on the type there may be additional inputs and these are catered for through a set of “if” statements in Python. So for example if we want a constant column we will have an additional attribute, *value* which gives the value of the constant. Note that the length of the vector is controlled by the lengths of the columns already in the dataset, as a dataset is currently restricted to be a set of columns of equal length.

As this template is not a model template there is no *model* or *latex* attributes; instead the computations are performed within a method called *pythonscript* which basically performs the required calculation in Python and adds the column to the output. The method code is as follows:

```

pythonscript = '''
import numpy

import EStat
from EStat.Templating import *
from EStat.DTAFile import DTAFile

retval = DTAFile()

retval.nobs = datafile.nobs
for k in datafile.variables.keys():
    retval.addvariable(k, data = datafile.variables[k]['data'])

datalen = datafile.nobs

if type == 'Uniform Random':
    outvar = numpy.random.uniform(size = datalen)
if type == 'Binomial Random':
    outvar = numpy.random.binomial(float(numtrials), float(prob), size =
datalen)
if type == 'Chi Squared Random':
    outvar = numpy.random.chisquare(float(degreefree), size = datalen)
if type == 'Exponential Random':
    outvar = numpy.random.exponential(size = datalen)
if type == 'Gamma Random':
    outvar = numpy.random.gamma(float(shape), size = datalen)
if type == 'Normal Random':
    outvar = numpy.random.normal(size = datalen)
if type == 'Poisson Random':
    outvar = numpy.random.poisson(float(exp), size = datalen)
if type == 'Constant':
    outvar = numpy.ones(datalen) * float(value)
if type == 'Sequence':
    outvar = numpy.arange(int(start), int(start) + (datalen * int(step)),
int(step))
if type == 'Repeated sequence':

```

```

        outvar = numpy.array(list(numpy.repeat(numpy.arange(1, int(max) + 1),
int(repeats))) * numpy.ceil(datalen / (float(max) *
float(repeats))))[0:datalen]

retval.addvariable(str(outcol), data = outvar)
outputs[str(outdata)] = retval
'''

```

Although the function is long this is mainly due to the many “if” statements to cope with each type of vector to be generated. So, for example, if we wanted a vector of Uniform random numbers to be stored in random then the only lines to be executed are:

```

retval = DTAFfile()
retval.nobs = datafile.nobs
for k in datafile.variables.keys():
    retval.addvariable(k, data = datafile.variables[k]['data'])
datalen = datafile.nobs
outvar = numpy.random.uniform(size = datalen)
retval.addvariable(str(outcol), data = outvar)
outputs[str(outdata)] = retval

```

Here the code calculates the length of vector in the fifth line, uses the numpy random generator in the next line to create the column of numbers in outvar. In the remaining lines we link the column into the dataset and finally return the dataset to the output name we gave as an input.

6.1.1 Exercise 2

Try modifying this template so that it only offers the random number generators. Try expanding the inputs so for example the Normal random generator will allow a mean and a variance, the Gamma has a scale parameter and the exponential has a rate parameter.

6.2 Recode template (recode.py)

The *Generate* template allows the user to add new columns to their existing dataset. There are many templates that expand or manipulate a dataset and we will here look at a second template, the *Recode* template. The *Recode* template, as the name suggests, recodes values – in this case recoding values within a certain range to a specific new value. This can be useful for creating categorical values, although this might involve several repeated uses of the *Recode* template!

We will demonstrate this with the **tutorial** dataset and look at recoding the school gender (*schgend*) column. In the original dataset *schgend* takes values 1 for a mixed school, 2 for a boys school and 3 for a girls school. We might want to recode this to take values 1 for mixed and 2 for single sex: i.e. convert the 3s for girls’ schools to 2s. To do this first we select *Recode* from the template list and hit the **Use** button. Next we select *schgend* from the list of columns and select the other inputs as below:

Dataset: tutorial; **Template:** Recode; **Input string:** {'incol': 'schgend', 'newval': '2', 'outdata': 'tutorial', 'rangeend': '3', 'rangestart': '2'}

Stat-JR:TREE
Start again
Dataset ▾
tutorial
Template ▾
Recode
eBook ▾
Ready (0s)
Settings
About
Debug ▾

Input column name:
schgend
remove

Start of range:
2
remove

End of range:
3
remove

New value:
2
remove

Name of output dataset:
tutorial

Next

Clicking on **Next** and **Run** will run the template. Selecting **View** from the *Dataset* pull-down list at the top of the screen and then clicking on the **Summary** tab shows a dataset summary:

Stat-JR:TREE

Dataset name: tutorial
Unload
Duplicate
Download

Data
Summary
Add variable
Delete variable
Edit data label
Edit value labels

Name	Count	Missing	Min	Max	Mean	Std	Description	Value Labels
school	4059	0	1	65	31.006651884700	18.936811072595		
student	4059	0	1	198	38.699926090169	30.260690898312		
normexam	4059	0	-3.6660717	3.6660914	-0.000113907104	0.9988208092058		
cons	4059	0	1	1	1.0	0.0		
standlrt	4059	0	-2.9349535	3.0159516	0.0018102547663	0.9931017329838		
girl	4059	0	0	1	0.6001478196600	0.4898677517630		
schgend	4059	0	1	2	1.4656319290465	0.4988174372442		
avslrt	4059	0	-0.75596046	0.63765585	0.0018102472478	0.3148314944142		
schlav	4059	0	1	3	2.1271249076127	0.6529263155277		
vrband	4059	0	1	3	1.8430647942843	0.6307845929865		

Page 1 of 2
View 1 - 10 of 11

Here we see that *schgend* now goes from 1 to 2 as expected. Let us now look at the code for this template. As with *Generate* this template has an *inputs* and a *pythonscript* attribute. These are both quite short:

```
inputs = '''
incol = DataVector('Input column name: ')
rangestart = Text('Start of range: ')
rangeend = Text('End of range: ')
newval = Text('New value: ')
outdata=Text('Name of output dataset: ')
'''
```

Here the *inputs* attribute contains the five inputs that we saw when running the template. Next the *pythonscript* attribute:

```
pythonscript = '''
import numpy
import numexpr

import EStat
from EStat.Templating import *
from EStat.DTAFile import DTAFile
retval = DTAFile()
retval.nobs = datafile.nobs
for k in datafile.variables.keys():
```

```

        retval.addvariable(k, data = datafile.variables[k]['data'])

# Copy data into numpy array for processing
var = numpy.array(datafile.variables[incol]['data'])

var[(var >= float(rangestart)) & (var <= float(rangeend))] = float(newval)

retval.addvariable(incol, data = var)

outputs[str(outdata)] = retval
'''

```

After some importing lines, the *pythonscript* attribute firstly copies the original column to the object *var* and then performs the recoding by finding the values in the original column within the correct range and then replacing them with the *newval*. Note the \geq and \leq operators mean that the range is inclusive of its end points. Finally when *var* is modified it is then linked back to the input column and the dataset is returned.

6.2.1 Exercise 3

This template applies the recoding by copying the recoded column over itself. As an exercise, try modifying the template so that it will place the recoded column into a new location i.e. have another name that is where to output the column to. Note the code for **Generate** should help here.

6.3 AverageAndCorrelation template

Another template that one might consider using prior to fitting a model is the *AverageAndCorrelation* template. This template will give either some summary statistics (including the averages) for a series of columns or the correlation matrix for a set of columns.

The template has a very short *inputs* attribute:

```

inputs = '''
op = Text('Operation: ', ['averages', 'correlation'])
vars = DataMatrix('Variables: ')
'''

```

Here *op* allows the user to choose between averages and correlations whilst *vars* stores which columns to perform the operation on. This template again uses the *pythonscript* attribute but this time creates an output called *table* which will give the averages or correlations in tabular form.

The code for *pythonscript* is as follows:

```

pythonscript = '''
import numpy
import numpy.ma
import EStat
from EStat.Templating import *

tabout = TabularOutput()
if op == 'averages':
    tabout.column_headings = ['name', 'count', 'mean', 'sd']
    for i in range(0, len(vars)):
        var = datafile.variables[vars[i]]['data']
        tabout.add_row(vars[i], [len(var), var.mean(), var.std()])

if op == 'correlation':

```



```

    invars = numpy.ma.row_stack([datafile.variables[var]['data'] for var in
vars])
    corrs = numpy.corrcoef(invars)
    tabout.column_headings = ['name']
    for j in range(0, len(vars)):
        tabout.column_headings.append(vars[j])

    for i in range(0, len(vars)):
        row = []
        for j in range(0, len(vars)):
            row.append(corrs[i, j])
        tabout.add_row(vars[i], row)

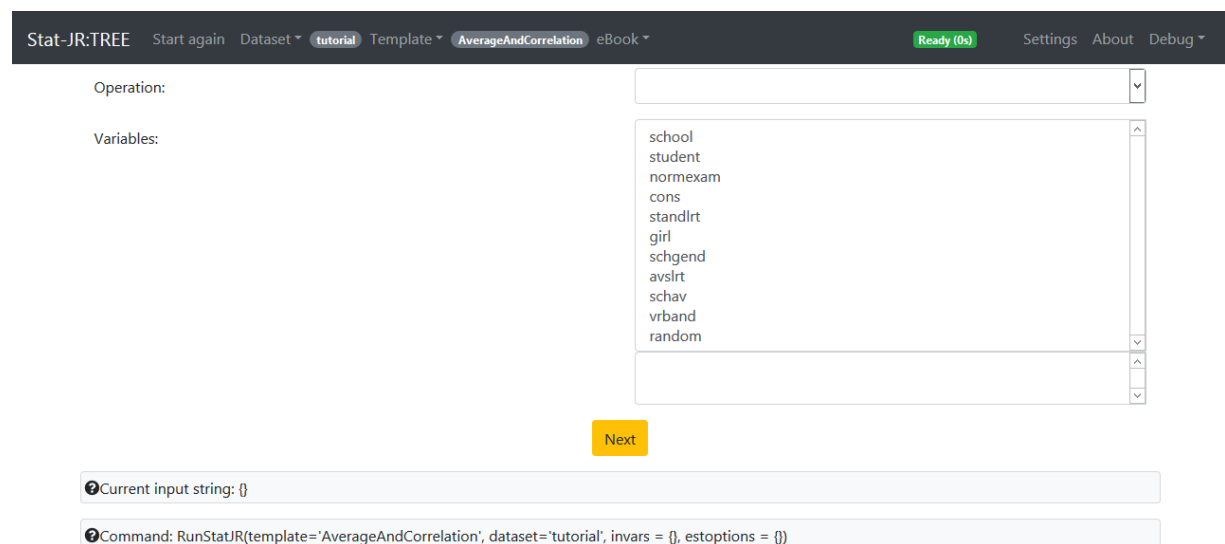
outputs['table'] = tabout
'''

```

You will see here separate chunks of code for averages and correlations. The average code basically initialises a table output with column heading and then loops through the columns in *vars* setting each in turn as a numpy masked array (the format in which all columns are currently stored in Stat-JR) stored in *var*. An array of text strings are then constructed and added to the tabular output, *tabout*, and here we are utilising the *len* function to get the number of data items and the built in numpy functions *mean* and *std* to get the mean and standard deviation respectively.

The correlation code is slightly longer, we here firstly need to construct the data as a matrix *invars* from which we can construct the correlations (*corrs*) by a call to the *numpy.corrcoef* function. Then we again format the output nicely into *tabout*.

The line `outputs['table'] = tabout` creates the table object which is then included in the output object list. If we consider using this template with the *tutorial* dataset we first need to select it from the template list and select **Use** to get the default screen:



We can now try this with some of the variables and in turn averages and correlation. Here is an example of averages – note we select *table* from the objects list:

Dataset: *tutorial*; **Template:** *AverageAndCorrelation*; **Input string:** `{'vars': 'avslrt,standlrt,girl,normexam', 'op': 'averages'}`

Stat-JR:TREE Start again Dataset **tutorial** Template **AverageAndCorrelation** eBook Ready (0s) Settings About Debug

Operation: averages [remove](#)

Variables: avslrt,standlrt,girl,normexam [remove](#)

[Download](#) [Make workflow](#)

Current input string: {'vars': 'avslrt,standlrt,girl,normexam', 'op': 'averages'}

Command: RunStatJR(template='AverageAndCorrelation', dataset='tutorial', invars = {'vars': 'avslrt,standlrt,girl,normexam', 'op': 'averages'}, estoptions = {})

table [Popout](#)

	name	count	mean	sd
	avslrt	4059	0.00181024724787	0.314831494414
	standlrt	4059	0.00181025476637	0.993101732984
	girl	4059	0.60014781966	0.489867751763
	normexam	4059	-0.000113907104703	0.998820809206

...and the correlations for the same four variables:

Dataset: *tutorial*; **Template:** *AverageAndCorrelation*; **Input string:** {'vars': 'avslrt,standlrt,girl,normexam', 'op': 'correlation'}

Stat-JR:TREE Start again Dataset **tutorial** Template **AverageAndCorrelation** eBook Ready (0s) Settings About Debug

Operation: correlation [remove](#)

Variables: avslrt,standlrt,girl,normexam [remove](#)

[Download](#) [Make workflow](#)

Current input string: {'vars': 'avslrt,standlrt,girl,normexam', 'op': 'correlation'}

Command: RunStatJR(template='AverageAndCorrelation', dataset='tutorial', invars = {'vars': 'avslrt,standlrt,girl,normexam', 'op': 'correlation'}, estoptions = {})

table [Popout](#)

	name	avslrt	standlrt	girl	normexam
	avslrt	1.0	0.317018374232	0.0407055371049	0.287936526679
	standlrt	0.317018374232	1.0	0.053210872887	0.591649587344
	girl	0.0407055371049	0.053210872887	1.0	0.114602445574
	normexam	0.287936526679	0.591649587344	0.114602445574	0.0

6.3.1 Exercise 4

Why not try and add the option to this template to give the standard error of the mean and also to allow the template to output both averages and correlations together for the same variables. Remember to rename the template first!

6.4 XYPlot template

Our final template in our whistle-stop tour of non-model templates is a graphing template. Python has excellent graphing facilities and so we have created a few very basic graphing templates that demonstrate some of these facilities. The *xyplot* template basically allows the user to plot one or more Y variables against an X variable on the same plot.

The template has an *inputs* attribute as shown below:

```
inputs = '''
yaxis = DataMatrix('Y values: ')
xaxis = DataVector('X values: ')
'''
```

Here we have two inputs, the various Y variables and the corresponding X variable to plot against. For a graph template we once again use the *pythonscript* attribute but this time the method constructs an object called *graphxy* which is in fact a .svg image file and is constructed by a function called ImageOutput.

The *pythonscript* code is as follows:

```
pythonscript = '''
from io import BytesIO

from matplotlib.figure import Figure
import matplotlib.lines as lines
from matplotlib.backends.backend_agg import FigureCanvasAgg

import EStat
from EStat.Templating import *

fig = Figure(figsize = (8, 6))
ax = fig.add_subplot(100 + 10 + 1, xlabel = str(xaxis))
for n in yaxis:
    #Here put a space in before label so works if variable name begins with
    underscore...
    #ax.plot(datafile.variables[xaxis]['data'],
    datafile.variables[n]['data'], 'x', label = n)
    ax.plot(datafile.variables[xaxis]['data'],
    datafile.variables[n]['data'], 'x', label = ' ' + n)
    #ax.legend()

#Shrink current axis by 20 percent:
box = ax.get_position()
ax.set_position([box.x0, box.y0, box.width * 0.75, box.height])

#put legend to right of current axis
#numpoints reduces number of markers in legend to 1 from default of 2
leg = ax.legend(loc = 'center left', prop = {'size':10}, bbox_to_anchor =
(1, 0.5), numpoints = 1)
#request semi-transparent legend (in case of any overlap with plotting
area):
leg.get_frame().set_alpha(0.5)

canvas = FigureCanvasAgg(fig)
buf = BytesIO()
canvas.print_figure(buf, dpi=80, format='svg')

buf.seek(0)
```

```

outputs['graphxy.svg'] = ImageOutput(buf.getvalue())
buf.close()
'''

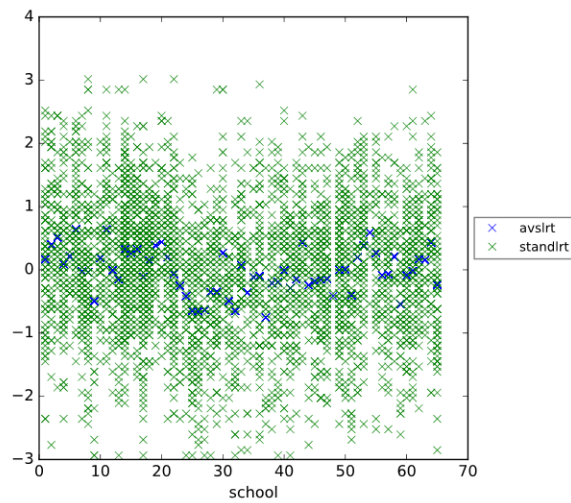
```

Here we have to firstly import lots of Python libraries in order to call the graphics functions. The function we are using is the *Figure* function from the *matplotlib* package. We then make a blank plot sticking on the axes labels before looping over the y variables and plotting their points. The 'x' is the symbol to be plotted for each plot. The last six lines are used to store the plotted figure as a .svg file. To see this template in action we will pick it from the *template* pull down list (along with the *tutorial* dataset) and we will be greeted by the following in the browser:

Perhaps the simplest plot here would be to plot *normexam* against *standlrt* which you can try yourself. Here we illustrate instead the use of more than one y variable by making the following selections:

Dataset: *tutorial*; **Template:** *XYPlot*; **Input string:** `{'xaxis': 'school', 'yaxis': 'avslrt,standlrt'}`

Clicking on the **Run** button and choosing to popout *graphxy.svg* gives the following graph:



Here we see plotted the actual intake scores for each pupil against school number in green and the school average in blue.

6.4.1 Exercise 5

Simplify this template to only allow a single y variable. Try adding a main title to the graph and varying the symbol and colours – maybe make this an option for the user to choose. Remember to rename the template before you start!

7 Single level models of all flavours – A logistic regression example

We have so far met two model templates: *Regression1*, which could be used to fit normal response multiple regression models in the Stat-JR built-in MCMC engine eStat, and *Regression2*, which allowed the same models to be fitted in other statistics packages. We will now look at a generalisation of these templates, *1LevelMod* that allows other response types including Binomial and Poisson responses. This template will illustrate the use of conditional statements within the *inputs* and *model* functions.

We will begin by looking at the template in action in *Stat-JR*. The template should be able to fit all the models that *Regression1* fits and so you could test the earlier regressions but here we will look at a logistic regression. So from the main menu headings we need to set the *template* to be *1LevelMod* and the *dataset* to be *bang*, our example binary response dataset taken from the 1988 Bangladeshi Fertility Survey and analysed in (Browne, MCMC Estimation in MLwiN, v2.36, 2016). Clicking on **Use** gives the following output in the browser:

The screenshot shows the Stat-JR:TREE web interface. At the top, a dark navigation bar contains the text 'Stat-JR:TREE' followed by links 'Start again', 'Dataset' (with a dropdown arrow), 'Template' (with a dropdown arrow), and 'eBook' (with a dropdown arrow). To the right of these links are 'Idle' (in a green box), 'Settings', 'About', and 'Debug' (with a dropdown arrow). Below the navigation bar, the main content area has a light gray background. It features two dropdown menus: the first is labeled 'Response:' and the second is labeled 'Specify distribution:'. Below these menus is a yellow 'Next' button. At the bottom of the interface, there are two light gray text boxes. The first box contains the text 'Current input string: {}'. The second box contains the text 'Command: RunStatJR(template='1LevelMod', dataset='bang', invars = {}, estoptions = {})'.

We will now set up the various inputs and the screen will look as follows:

Dataset: bang; **Template:** 1LevelMod; **Input string:** {'Engine': 'eStat', 'burnin': '500', 'D': 'Binomial', 'outdata': 'out', 'n': 'cons', 'nchains': '3', 'thinning': '1', 'link': 'logit', 'defaultalg': 'Yes', 'iterations': '2000', 'y': 'use', 'x': 'cons,age', 'makepred': 'No', 'seed': '1', 'defaultsv': 'Yes'}

1 Response:	use	remove
Specify distribution:	Binomial	remove
2 Denominator:	cons	remove
Specify link function:	logit	remove
3 Explanatory variables:	cons,age	remove
Choose estimation engine:	eStat	remove
Number of chains:	3	remove
Random Seed:	1	remove
Length of burnin:	500	remove
4 Number of iterations:	2000	remove
Thinning:	1	remove
Use default algorithm settings:	Yes	remove
Generate prediction dataset:	No	remove
Use default starting values:	Yes	remove
5 Name of output results:	<input type="text" value="out"/>	

[Next](#)

We are here fitting a logistic regression to the response variable which is whether the women in Bangladesh in the dataset use contraception or not. We are regressing this against age and using the Stat-JR built-in MCMC engine with some default settings for estimation.

If we click on **Next**, **equation.tex** will display the model:

[Edit](#) [Popout](#)

$$\begin{aligned}
 \text{use}_i &\sim \text{Binomial}(\text{cons}_i, \pi_i) \\
 \text{logit}(\pi_i) &= \beta_0 \text{cons}_i + \beta_1 \text{age}_i \\
 \beta_0 &\propto 1 \\
 \beta_1 &\propto 1
 \end{aligned}$$

We will next click on **Run** to run the model and then get the following results by selecting **ModelResults** from the objects list:

Stat-JR:TREE
Start again
Dataset
bang
Template
1LevelMod
eBook
Ready (31s)
Settings
About
Debug

ModelResults
Popout

Results

Parameters:

parameter	mean	sd	ESS	variable
beta_0	-0.410701702733	0.0384173614069	1390	cons
beta_1	0.0120500531917	0.00427390926192	1428	age
deviance	3846.609021168352	2.0631647580842	1305	

Model:

Statistic	Value
Dbar	3846.609021168352
D(thetabar)	3844.579024871756
pD	2.0299962965955
DIC	3848.639017464947

Here we see that the age coefficient is positive and significant meaning that older women are more likely to use contraceptives. We now want to look at the template to see what the code looks like. We will only concern ourselves with the Stat-JR built-in engine here and so will not look at how the template works with interoperability as this will be an extension of the code for *Regression2* in Section 0.

7.1 Inputs

The code for *inputs* is as follows:

```
inputs = ''
y = DataVector('Response: ', help= 'a.k.a. <em>Y</em>, Outcome variable,
Dependent variable, etc.')
D = Text('Specify distribution: ', ['Normal', 'Binomial', 'Poisson', '-ve
Binomial'])
if D == 'Binomial':
    n = DataVector('Denominator: ', help='e.g. if modelling a binary 0/1
response, select a constant of ones.')
    link = Text('Specify link function: ', ['logit', 'probit', 'cloglog'])
if D == 'Poisson':
    link = Text(value = 'ln')
    offset = Boolean('Is there an offset: ', help="An offset allows you to
model rates, instead of raw counts.")
    if offset:
        n = DataVector('Offset: ')
if D == '-ve Binomial':
    offset = Boolean('Is there an offset: ')
    if offset:
        n = DataVector('Offset: ')

x = DataMatrix('Explanatory variables: ', allow_cat = True, help= "<p
style='text-align:left'>A.k.a. X, Predictor variables, Independent
variables, etc.</p><p style='text-align:left'><strong>Note:</strong> if you
wish to include an <strong>intercept</strong> then you need to add it (e.g.
a constant of ones) as one of the explanatory variables.</p><p style='text-
align:left'>Once you've selected a variable, you have the opportunity to
```


indicate whether it's categorical or not; if categorical, dummy variables will be added to the model on your behalf.</p>")

```
if D == 'Normal':
    tau = ParamScalar()
    sigma = ParamScalar(modelled = False)
    sigma2 = ParamScalar(modelled = False)
if D == '-ve Binomial':
    alpha = ParamScalar()
    rho = ParamVector(parents = [y])
beta = ParamVector(parents = [x], as_scalar = True)
deviance = ParamScalar(modelled = False)
'''
```

Compared to *Regression1* you will see that we have introduced an input *D* for distribution and that we introduce conditional statements (“if” statements). The distribution *D* is defined as a *Text* input and you will see that there are a limited number of choices given as a second argument to the statement. The *TREE* program will treat this as a pull-down list input with the limited number of choices populating the list.

As we saw in our example when fitting a Binomial model we introduce additional inputs *n* – the denominator column and *link* a *Text* based input to indicate the link function. We also see that for non-normal models there is no level 1 variance and so the quantities *tau*, *sigma* and *sigma2* are not included.

7.2 Engines

This template allows many estimation engines as shown below:

```
engines = ['eStat', 'WinBUGS', 'OpenBUGS', 'JAGS', 'MLwiN_MCMC',
'MLwiN_IGLS', 'R_glm', 'R_MCMCglmm', 'R_MCMCpack', 'R_nimble',
'Stata_model', 'SPSS_model', 'SAS_model', 'R_INLA', 'R_RStan']
```

when we originally wrote Stat-JR each template had its own inputs for these engines defined in a *Methodinput* function but now these are generic inputs and so simply by including an engine here, Stat-JR knows which inputs to use.

7.3 Model

The *model* attribute now also contains conditional statements as shown below:

```
model = '''
model{
  for (i in 1:length(${y})) {
    ${y}[i] ~ \\\
    % if D == 'Normal':
dnorm(mu[i], tau)
    mu[i] <- \\\
    % endif
    % if D == 'Binomial':
dbin(p[i], ${n}[i])
    ${link}(p[i]) <- \\\
    % endif
    % if D == 'Poisson':
dpois(p[i])
    ${link}(p[i]) <- \\\
    % if offset:
${n}[i] + \\\
```

```

        % endif
        % endif
        % if D == '-ve Binomial':
dpois(p[i])
        p[i] <- rho[i] * exp(\
        % if offset:
${n}[i] + \
        % endif
        % endif
        % if D == '-ve Binomial':
${mmult}(x, 'beta', 'i'))
        rho[i] ~ dgamma(alpha, alpha)
        % else:
${mmult}(x, 'beta', 'i'))
        % endif
    }

    # Priors
    % for i in range(0, x.ncols()):
    beta_${i} ~ dflat()
    % endfor
    % if D == 'Normal':
    tau ~ dgamma(0.001000, 0.001000)
    sigma <- 1 / sqrt(tau)
    sigma2 <- 1 / tau
    % endif
    % if D == '-ve Binomial':
    alpha ~ dlnorm(0, 0.001)
    % endif
}

'''

```

Basically in the *model* code, conditional statements are started by a %if and the code to be conditionally executed is ended by a %endif. The conditional statements can be hierarchical for example the line

```
% if offset:
```

is within another %if statement and now the %endif will correspond to the latest %if. In our example we have D == 'Binomial' and so the code simplifies to:

```

model = '''
model{
    for (i in 1:length(${y})) {
        ${y}[i] ~ \
    dbin(p[i], ${n}[i])
        ${link}(p[i]) <- \
    ${mmult}(x, 'beta', 'i'))
    }
    # Priors
    % for i in range(0, x.ncols()):
    beta_${i} ~ dflat()
    % endfor
}

'''

```

and as we demonstrated for *Regression1* we can fill in the \$ calls and unwind the %for loop and the \$mmult function to get the code we can view in the *model.txt* output object.

7.4 LaTeX

Finally the *latex* method now also contains conditional statements.

```
latex = r'''
\begin{aligned}
%if D == 'Normal':
  \mbox{\${y}}_i & \sim \mbox{N}(\mu_i, \sigma^2) \\
\mu_i & = \\
%endif
%if D == 'Binomial':
  \mbox{\${y}}_i & \sim \mbox{Binomial}(\mbox{\${n}}_i, \pi_i) \\
\mbox{\${link}}(\pi_i) & = \\
%endif
%if D == 'Poisson':
  \mbox{\${y}}_i & \sim \mbox{Poisson}(\pi_i) \\
\mbox{\${link}}(\pi_i) & = \\
%if offset:
  \mbox{\${n}}_i & + \\
%endif
%endif
  \${mmulttex(x, r'\beta', 'i'))} \\
%if str(Engine) in ['eStat', 'WinBUGS', 'OpenBUGS', 'JAGS', 'R_nimble',
'MLwiN_MCMC', 'R_MCMCglmm' ]:
%for i in range(0, len(x)):
\beta_{\${i}} & \propto 1 \\
%endfor
%if D == 'Normal':
\tau & \sim \Gamma(0.001, 0.001) \\
\sigma^2 & = 1 / \tau \\
%endif
%endif
\end{aligned}
'''
```

and as with the *model* function we achieve conditional operations via the %if and %endif pairs. Again for our example we can strip out the conditionals to get:

```
latex = r'''
\begin{aligned}
\mbox{\${y}}_i & \sim \mbox{Binomial}(\mbox{\${n}}_i, \pi_i) \\
\mbox{\${link}}(\pi_i) & = \\
  \${mmulttex(x, r'\beta', 'i'))} \\
%for i in range(0, len(x)):
\beta_{\${i}} & \propto 1 \\
%endfor
\end{aligned}
'''
```

If you look at the code you will see other functions for the various other software packages but we will not discuss these here.

7.4.1 Exercise 6

Convert the more general *1LevelMod* template into a specific logistic regression template. To do this copy *1LevelMod.py* to *1LevelLogit.py* and simply remove the conditional statements and additional

options so that the template only allows the user to fit logistic regression models. You can check the template works by attempting the example given in the section with your new template.

8 Including categorical predictors

Originally in Stat-JR all predictor variables were assumed to be continuous and so if a predictor was categorical, for example school gender in the tutorial dataset, we would need some method to transform the original form to a series of dummy variables. To this end several templates were created that performed this transformation as part of the template in an attribute called *preparedata*. We will look at an example of this in a minute with the *1LevelCatRef* template which allows the user to specify variables as categorical and to specify which category is the reference. In later versions of Stat-JR functionality was built in to allow the user to specify that an input might be categorical and so, for example, in the *inputs* in *1LevelMod* you will see the line:

```
x = DataMatrix('Explanatory variables: ', allow_cat = True, help= "<p style='text-align:left'>A.k.a. X, Predictor variables, Independent variables, etc.</p><p style='text-align:left'><strong>Note:</strong> if you wish to include an <strong>intercept</strong> then you need to add it (e.g. a constant of ones) as one of the explanatory variables.</p><p style='text-align:left'>Once you've selected a variable, you have the opportunity to indicate whether it's categorical or not; if categorical, dummy variables will be added to the model on your behalf.</p>")
```

which tells Stat-JR to ask for each element of *x* whether it is categorical or not; then, within each package file, there is code to construct the dummy variables. This method is restricted in that it always chooses the first category to be the reference. We will here look at an alternative template that has built in functionality for constructing these categorical variables within the template. This template is called *1LevelCatRef* and we will first look at its *inputs* attribute to see how it gets the user to input the model structure before demonstrating its use on the *tutorial* dataset.

The *inputs* code is as follows:

```
inputs = '''
y = DataVector('Response: ', help= 'a.k.a. <em>Y</em>, Outcome variable, Dependent variable, etc.')
D = Text('Specify distribution: ', ['Normal', 'Binomial', 'Poisson'])
if D == 'Binomial':
    n = DataVector('Denominator: ', help='e.g. if modelling a binary 0/1 response, select a constant of ones.')
    link = Text('Specify link function: ', ['logit', 'probit', 'cloglog'])
if D == 'Poisson':
    link = Text(value = 'ln')
    offset = Boolean('Is there an offset: ', help="An offset allows you to model rates, instead of raw counts.")
    if offset:
        n = DataVector('Offset: ')
x = DataMatrix('Explanatory variables: ', help= "<p style='text-align:left'>A.k.a. X, Predictor variables, Independent variables, etc.</p><p style='text-align:left'><strong>Note:</strong> if you wish to include an <strong>intercept</strong> then you need to add it (e.g. a constant of ones) as one of the explanatory variables.</p><p style='text-align:left'>Once you've selected a variable, you have the opportunity to indicate whether it's categorical or not, and then which value you wish to make the reference category.</p>")
for var in x:
    context[var + '_cat'] = Boolean('Is ' + var + ' categorical? ', default=False)
```

```

        if context[var + '_cat']:
            context[var + '_ref'] = Integer('Reference Category: ',
help="A.k.a. the base category (coded zero in all associated dummy
variables); i.e. the category against which other categories are
contrasted.")

origx = Text(value = [])
if D == 'Normal':
    tau = ParamScalar()
    sigma = ParamScalar(modelled = False)
    sigma2 = ParamScalar(modelled = False)
    beta = ParamVector(parents = [x], as_scalar=True)
    deviance = ParamScalar(modelled = False)
'''

```

This code section is much the same as that in *1LevelMod* (aside from not doing negative binomial) up to the point that *x* is input. We next see a “for” loop that includes the use of the *context* statement which is used to construct attribute names that are a combination of text and variable names. If, for example, *x* contains the three variable list ['cons', 'standlrt', 'schgend'] then the context statements will create 3 variables 'cons_cat', 'standlrt_cat' and 'schgend_cat' which will store the text strings 'yes' or 'no' depending on whether the variables are categorical or not. If 'yes' then a further context statement is used to construct a variable to house the reference category for that variable. The line

```
origx = Text(value = [])
```

will be used to store the original *x* variables prior to manipulating the categorical variables. By setting its value in the assignment we will not get an input widget appearing in the browser.

Let us demonstrate fitting this model: choose *1LevelCatRef* from the template list and *tutorial* as the dataset. Note if you have previously used the **recode** template on this dataset, on the main menu click on **Debug > Reload datasets** to get back the original *tutorial* dataset. Firstly we will choose the inputs as follows:

Dataset: *tutorial*; **Template:** *1LevelCatRef*; **Input string:** `{'defaultsv': 'Yes', 'schgend_ref': '1', 'D': 'Normal', 'schgend_cat': 'Yes', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'outdata': 'tutout', 'seed': '1', 'standlrt_cat': 'No', 'Engine': 'eStat', 'burnin': '500', 'thinning': '1', 'y': 'normexam', 'x': 'cons,standlrt,schgend', 'cons_cat': 'No', 'makepred': 'No'}`

Response:	normexam remove
Specify distribution:	Normal remove
Explanatory variables:	cons,standlrt,schgend remove
Is cons categorical?	No remove
Is standlrt categorical?	No remove
Is schgend categorical?	Yes remove
Reference Category:	1 remove
Choose estimation engine:	eStat remove
Number of chains:	3 remove
Random Seed:	1 remove
Length of burnin:	500 remove
Number of iterations:	2000 remove
Thinning:	1 remove
Use default algorithm settings:	Yes remove
Generate prediction dataset:	No remove
Use default starting values:	Yes remove
Name of output results:	<input type="text" value="tutout"/>

[Next](#)

Next we click on the **Next** button and we will be able to look at the equation for the model:

equation.tex [Popout](#)

$$\text{normexam}_i \sim N(\mu_i, \sigma^2)$$

$$\mu_i = \beta_0 \text{cons}_i + \beta_1 \text{standlrt}_i + \beta_2 \text{schgend}_2_i + \beta_3 \text{schgend}_3_i$$

$$\beta_0 \leq 1$$

$$\beta_1 \leq 1$$

$$\beta_2 \leq 1$$

$$\beta_3 \leq 1$$

$$\tau \sim \Gamma(0.001, 0.001)$$

$$\sigma^2 = 1/\tau$$

Here we see that in the maths that the expression for the linear predictor has two terms to represent two of the possible categories for school gender (*schgend_2* and *schgend_3*). The important attribute here is *preparedata*. The *preparedata* attribute allows for template specific data manipulations to be executed prior to the model run. In this case the code is as overleaf:

```
preparedata = ''
mydata = data['datafile']
for var in x:
```

```

origx.name.append(var) # Save user's original selection

del x[:]
x.orignames = []
for var in origx.name:
    if context[var + '_cat']:
        uniqvals = list(set(mydata.variables[var]['data'].compressed()))
        uniqvals.sort()
        uniqvals.remove(int(context[var + '_ref']))
        for i in uniqvals:
            if int(i)<0:
                lab = 'neg'+str(abs(int(i)))
            else :
                lab = str(int(i))
            mydata.addvariable(var + '_' + lab, data =
(mydata.variables[var]['data'][:] == i).astype(float))
            x.name.append(var + '_' + lab)
            x.orignames.append(var)
    else:
        # TODO: fix this
        x.name.append(var)
        x.orignames.append(var)
beta.ncols = len(x)
'''

```

This code firstly retains the named predictor variables in *origx* by copying the contents of *x* to *origx* and then deleting them from *x*. Then the code loops over the variables via the second *for* statement and conditionally (the “*if*” statement) on a particular variable being categorical does some processing.

The lines

```

uniqvals = list(set(mydata.variables[var]['data'].compressed()))
uniqvals.sort()
uniqvals.remove(int(context[var + '_ref']))

```

firstly find all unique values in the categorical predictor which are then stored in *uniqvals*. We then sort these into ascending order before removing the user defined reference category as it will play the role as the base category in the model. We then have a second loop over this list of *uniqvals* where we create the dummy variables. The lines

```

mydata.addvariable(var + '_' + lab, data =
(mydata.variables[var]['data'][:] == i).astype(float))
x.name.append(var + '_' + lab)

```

firstly construct an array which takes value 1 if the original variable has value *i* or 0 otherwise. This newly constructed predictor variable is then appended to the new variable list. If the variable is not categorical it is simply added to this new variable list itself. We finally adjust the length of *beta* to account for the expansion of the categorical variables and return the new dataset.

This *preparedata* method is run before the *model* and *latex* attributes and so these are similar to those we saw in *1LevelMod*. To continue running the example we can press the **Run** button and then select the *ModelResults* object from the list to get the following results:

Stat-JR:TREE
Start again
Dataset
tutorial
Template
1LevelCatRef
eBook
Ready (7s)
Settings
About
Debug

ModelResults
Popout

Results

Parameters:

parameter	mean	sd	ESS	variable
tau	1.569262200894	0.0345825873237	6854	
beta_0	-0.0957604037338	0.0169644449491	2175	cons
beta_1	0.59418498653	0.0127518971538	5820	standlrt
beta_2	0.11667656935	0.0395283789139	3614	schgend
beta_3	0.235413834131	0.0268427475791	2375	schgend
sigma2	0.637551909719	0.0140628885717	6869	
sigma	0.798419950681	0.00880295820815	6865	
deviance	9692.102086663124	3.0665911479559	4947	

Model:

Statistic	Value
Dbar	9692.102086663126
D(thetabar)	9687.129926364645
pD	4.972160298481
DIC	9697.0742469616071

This completes this section and is the last single level model we will meet for a while. Another extension would be to allow the inclusion of interactions into the model. This has been done in the template *1LevelInteractions* (which is available from the template repository but not part of the core release). Here the modifications are done in the *inputs* and *model/latex* methods as no new predictor variables are created. Instead the model code includes multiplications between the variables. We will leave you to try out this template as an exercise.

9 Multilevel models

Our next step is to move onto templates for models for more complex data structures. In this section we look at multilevel modelling templates – templates that allow random effects to account for clustering in the data. We will look at two templates of increasing complexity, firstly a template for fitting models that have 2 levels i.e. 1 higher level of clustering and then secondly a more general template that will fit models with any number of levels clustering whether nested or crossed. Note here that these templates allow only random intercepts in the models we are fitting.

9.1 2LevelMod template

We will begin our investigation of *2LevelMod* by looking at its *inputs* attribute. Note that here and later we have stripped out the help text from some of the inputs for readability:

```
inputs = ''
y = DataVector('Response: ')
L2ID = IDVector('Level 2 ID: ')
D = Text('specify distribution: ', ['Normal', 'Poisson', 'Binomial'])
if D == 'Binomial':
    n = DataVector('Denominator: ')
    link = Text('Specify link function: ', ['logit', 'probit', 'cloglog'])
if D == 'Poisson':
    link = Text(value = 'ln')
    offset = Boolean('Is there an offset: ')
    if offset:
        n = DataVector('Offset: ')
if D == '-ve Binomial':
    offset = Boolean('Is there an offset: ')
    if offset:
        n = DataVector('Offset: ')

x = DataMatrix('Explanatory variables: ', allow_cat = True)
storeresid = Boolean('Store level 2 residuals?')

if D == 'Normal':
    tau = ParamScalar()
    sigma2 = ParamScalar(modelled = False)

if D == '-ve Binomial':
    alpha = ParamScalar()
    rho = ParamVector(parents = [y])

beta = ParamVector(parents=[x], as_scalar=True)

if storeresid:
    u = ParamVector(parents=[L2ID], as_scalar=False)
else:
    u = ParamVector(parents=[L2ID], as_scalar=False, monitor=False)
tau_u = ParamScalar()
sigma2_u = ParamScalar(modelled = False)
deviance = ParamScalar(modelled = False)
''
```

If you compare this with the *inputs* function for *1LevelMod* you will see we have added 2 additional inputs: *L2ID* to allow the user to input the column containing the level 2 identifiers and *storeresid*, a Boolean indicator of whether to store the level 2 residuals or not. We also have three additional

parameters u , τ_u and σ^2_u (to represent the level 2 residuals, their precision and variance respectively) that have been included. We can try out an example of these inputs by selecting the template *2LevelMod* and the dataset *tutorial* and applying the following inputs:

Dataset: *tutorial*; **Template:** *2LevelMod*; **Input string:** `{'Engine': 'eStat', 'L2ID': 'school', 'burnin': '500', 'D': 'Normal', 'outdata': 'tutout', 'storeressid': 'No', 'thinning': '1', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'y': 'normexam', 'x': 'cons,standlrt', 'makepred': 'No', 'seed': '1', 'defaultsv': 'Yes'}`

Stat-JR:TREE
Start again
Dataset ▾ **tutorial**
Template ▾ **2LevelMod**
eBook ▾
Idle Settings About Debug ▾

① Response:	normexam remove
② Level 2 ID:	school remove
Specify distribution:	Normal remove
③ Explanatory variables:	cons,standlrt remove
Store level 2 residuals?	No remove
Choose estimation engine:	eStat remove
Number of chains:	3 remove
Random Seed:	1 remove
Length of burnin:	500 remove
④ Number of iterations:	2000 remove
Thinning:	1 remove
Use default algorithm settings:	Yes remove
Generate prediction dataset:	No remove
Use default starting values:	Yes remove
⑤ Name of output results:	<input type="text" value="tutout"/>

Next

Clicking on **Next** we will see **equation.tex** in the bottom pane:

Stat-JR:TREE
Start again
Dataset ▾ **tutorial**
Template ▾ **2LevelMod**
eBook ▾
Ready (5s) Settings About Debug ▾

Edit ▾ [Popout](#)

$$\begin{aligned} \text{normexam}_i &\sim N(\mu_i, \sigma^2) \\ \mu_i &= \beta_0 \text{cons}_i + \beta_1 \text{standlrt}_i + u_{\text{school}[i]} \\ u_{\text{school}[i]} &\sim N(0, \sigma_u^2) \\ \beta_0 &\propto 1 \\ \beta_1 &\propto 1 \\ \tau &\sim \Gamma(0.001, 0.001) \\ \sigma^2 &= 1/\tau \\ \tau_u &\sim \Gamma(0.001, 0.001) \\ \sigma_u^2 &= 1/\tau_u \end{aligned}$$

Here we see a mathematical representation of the model created in *latex*. Let's look next at *model*:

```
model = ''
model {
  for (i in 1:length(${y})) {
    ${y}[i] ~ \
    % if D == 'Normal':
dnorm(mu[i], tau)
    mu[i] <- \
```

```

        % endif
        % if D == 'Binomial':
dbin(p[i], ${n}[i])
        ${link}(p[i]) <- \\
        % endif
        % if D == 'Poisson':
dpois(p[i])
        ${link}(p[i]) <- \\
        % if offset:
${n}[i] + \\
        % endif
        % endif
        % if D == '-ve Binomial':
dpois(p[i])
        p[i] <- rho[i] * exp(\\
        % if offset:
${n}[i] + \\
        % endif
        % endif
        % if D == '-ve Binomial':
${mmult(x, 'beta', 'i')} + u[${L2ID}[i]])
        rho[i] ~ dgamma(alpha, alpha)
        % else:
${mmult(x, 'beta', 'i')} + u[${L2ID}[i]]
        % endif
    }

    for (j in 1:length(u)) {
        u[j] ~ dnorm(0, tau_u)
    }

    # Priors
    % for i in range(0, x.ncols()):
    beta_${i} ~ dflat()
    % endfor

    % if D == 'Normal':
    tau ~ dgamma(0.001000, 0.001000)
    sigma2 <- 1 / tau
    % endif

    tau_u ~ dgamma(0.001000, 0.001000)
    sigma2_u <- 1 / tau_u
    % if D == '-ve Binomial':
    alpha ~ dlnorm(0, 0.001)
    % endif
}
'''

```

The code has become quite long mainly due to the conditional statements for the different distribution types. We see that the term `u[${L2ID}[i]]` has been appended to the linear predictor where L2ID is inserted for a particular model. The chunk of code

```

    for (j in 1:length(u)) {
        u[j] ~ dnorm(0, tau_u)
    }

```

then gives the random effect distribution and finally the chunk

```

tau_u ~ dgamma(0.001000, 0.001000)

```

```
sigma2_u <- 1 / tau_u
```

gives a prior distribution for the variance of the random effects. The *latex* function is adapted in very similar ways and so for brevity we omit this code here. We will finish off this template by running it and looking at *ModelResults* (in a new tab). If we do this we only get results for the variables that have had their chains stored:

Stat-JR:TREE
Start again
Dataset
tutorial
Template
2LevelMod
eBook
Ready (8s)
Settings
About
Debug

ModelResults
Popout

Results

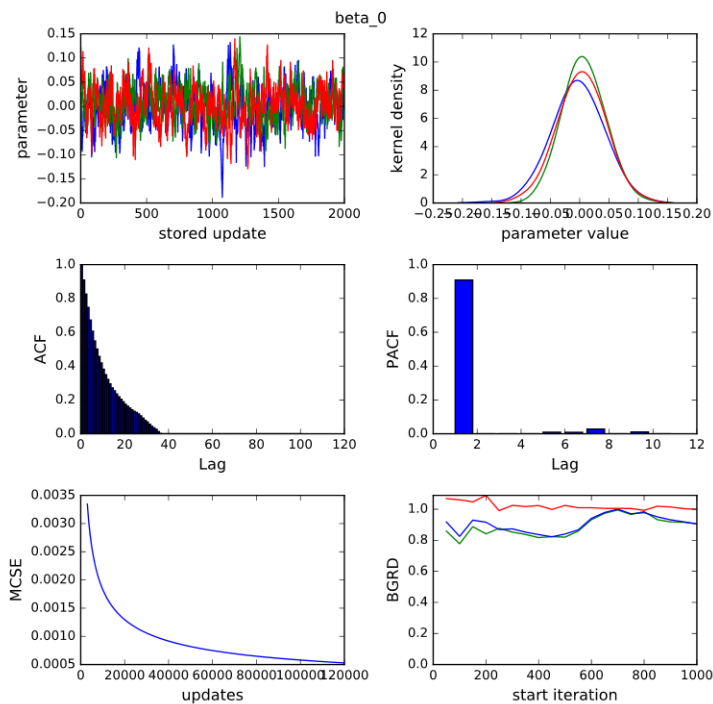
Parameters:

parameter	mean	sd	ESS	variable
sigma2_u	0.097038288567	0.0202790981815	3109	
tau	1.767200644422	0.0396319573944	6240	
deviance	9208.784400791064	11.943453653672	5549	
beta_0	0.00254149956589	0.0399530738962	319	cons
beta_1	0.563428180775	0.0124864567817	4829	standlrt
tau_u	10.74722600344	2.207139596557	3105	
sigma2	0.566151195557	0.0126922164147	6211	

Model:

Statistic	Value
Dbar	9208.784400791064
D(thetabar)	9148.958639137034
pD	59.82576165403
DIC	9268.610162445095

Basically although we didn't store chains for each of the 65 random effects u we can store summary statistics for them but by default we do not display them unless we change the output options on the *settings* screen. As usual we also can get the MCMC plots e.g. for *beta_0.svg*:



9.1.1 Exercise 7

Try adapting this template so that it allows the user to incorporate interactions.

9.2 NLevelMod template

The *NlevelMod* template, as the name suggests, extends the *2LevelMod* template to an unlimited number (input by the user) of levels of clustering. Note that these clusters can be either nested or cross-classified. We will once again start by looking at the *inputs* attribute to see how it differs from *2LevelMod* (again we've removed the help text):

```
inputs = ''
NumLevs = Integer('Number of classifications: ')
for i in range(0, int(NumLevs)):
    selstr = 'Classification ' + str(i + 1) + ': '
    context['C' + str(i + 1)] = IDVector(selstr)

y = DataVector('Response: ')
D = Text('Specify distribution: ', ['Normal', 'Binomial', 'Poisson'])
if D == 'Binomial':
    n = DataVector('Denominator: ')
    link = Text('Specify link function: ', ['logit', 'probit', 'cloglog'])
if D == 'Poisson':
    link = Text(value = 'ln')
    offset = Boolean('Is there an offset: ')
    if offset:
        n = DataVector('Offset: ')
if D == '-ve Binomial':
    offset = Boolean('Is there an offset: ')
    if offset:
        n = DataVector('Offset: ')
x = DataMatrix('Explanatory variables: ', allow_cat = True)
storeresid = Boolean('Store residuals?')
```

```

if D == '-ve Binomial':
    alpha = ParamScalar()
    rho = ParamVector(parents = [y])

beta = ParamVector(parents=[x], as_scalar=True)
if D == 'Normal':
    tau = ParamScalar()
    sigma2 = ParamScalar(modelled = False)

for i in range(0, int(NumLevs)):
    if storeresid:
        context['u' + str(i + 1)] = ParamVector(parents=[context['C' +
str(i + 1)]], as_scalar=False)
    else:
        context['u' + str(i + 1)] = ParamVector(parents=[context['C' +
str(i + 1)]], as_scalar=False, monitor=False)
        context['tau_u' + str(i + 1)] = ParamScalar()
        context['sigma2_u' + str(i + 1)] = ParamScalar(modelled = False)

deviance = ParamScalar(modelled = False)
'''

```

Here we have needed to replace the code for inputting the level 2 identifier with code to input the number of classifications (levels of clustering) and then we have looped over the number of classifications constructing both the names of the columns that contain the classification vectors (which will be labelled *C1*, *C2* ...) and, towards the bottom of the code, the new parameters associated with each classification (*u1*, *tau_u1* and *sigma2_u1* etc). To achieve these inputs we have used the *context* command to construct attribute names by concatenating strings and also a simple string concatenation to create *selstr* which contains the question associated with inputting each classification name. The rest of the code is similar to before. It should be noted that a 2 level model in this template has 1 classification as we are not considering level 1 here.

We can consider using this template on a cross-classified example with two higher classifications. This example is a dataset from Fife in Scotland (Paterson, 1991) where we are looking at the impact of both primary school and secondary school on the attainment of children at age 16. To do this select the template *NLevelMod* from the *template* list and the dataset *xc* from the *dataset* list. Select the inputs as shown:

Dataset: *xc*; **Template:** *NLevelMod*; **Input string:** {'D': 'Normal', 'storeresid': 'No', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'C2': 'sid', 'outdata': 'out', 'NumLevs': '2', 'seed': '1', 'defaultsv': 'Yes', 'Engine': 'eStat', 'burnin': '500', 'thinning': '1', 'y': 'attain', 'x': 'cons,vrq', 'C1': 'pid', 'makepred': 'No'}

Stat-JR:TREE
Start again
Dataset
Template
NLevelMod
eBook
Idle
Settings
About
Debug

Number of classifications:
2
remove

Classification 1:
pid
remove

Classification 2:
sid
remove

Response:
attain
remove

Specify distribution:
Normal
remove

Explanatory variables:
cons,vrq
remove

Store residuals?
No
remove

Choose estimation engine:
eStat
remove

Number of chains:
3
remove

Random Seed:
1
remove

Length of burnin:
500
remove

Number of iterations:
2000
remove

Thinning:
1
remove

Use default algorithm settings:
Yes
remove

Generate prediction dataset:
No
remove

Use default starting values:
Yes
remove

Name of output results:
out

Next

Clicking on the **Next** button will display the mathematical formulation of the model (**equation.tex**) in the pull-down list:

Stat-JR:TREE
Start again
Dataset
Template
NLevelMod
eBook
Ready (5s)
Settings
About
Debug

Edit

equation.tex

Popout

$$\begin{aligned} \text{attain}_i &\sim N(\mu_i, \sigma^2) \\ \mu_i &= \beta_0 \text{cons}_i + \beta_1 \text{vrq}_i + u_{\text{pid}[i]}^{(2)} + u_{\text{sid}[i]}^{(3)} \\ u_{\text{pid}[i]}^{(2)} &\sim N(0, \sigma_{u1}^2) \\ u_{\text{sid}[i]}^{(3)} &\sim N(0, \sigma_{u2}^2) \\ \beta_0 &\propto 1 \\ \beta_1 &\propto 1 \\ \tau &\sim \Gamma(0.001, 0.001) \\ \sigma^2 &= 1/\tau \\ \tau_{u1} &\sim \Gamma(0.001, 0.001) \\ \sigma_{u1}^2 &= 1/\tau_{u1} \\ \tau_{u2} &\sim \Gamma(0.001, 0.001) \\ \sigma_{u2}^2 &= 1/\tau_{u2} \end{aligned}$$

If we select **model.txt** from the list we can see the model code. It is similar to that we had for the 2-level model and *2LevelMod*.

Edit model.txt  Popout

```
model {
  for (i in 1:length(attain)) {
    attain[i] ~ dnorm(mu[i], tau)
    mu[i] <- cons[i] * beta_0 + vrq[i] * beta_1 + u1[pid[i]] + u2[sid[i]]
  }

  for (i1 in 1:length(u1)) {
    u1[i1] ~ dnorm(0, tau_u1)
  }
  for (i2 in 1:length(u2)) {
    u2[i2] ~ dnorm(0, tau_u2)
  }

  # Priors
  beta_0 ~ dflat()
  beta_1 ~ dflat()
  tau ~ dgamma(0.001000, 0.001000)
  sigma2 <- 1 / tau
  tau_u1 ~ dgamma(0.001000, 0.001000)
  sigma2_u1 <- 1 / tau_u1
  tau_u2 ~ dgamma(0.001000, 0.001000)
  sigma2_u2 <- 1 / tau_u2
}
```

The model code is created by the *model* attribute and here we see the code:

```
model = ''
<% numlevs = int(NumLevs) %>

model {
  for (i in 1:length(${y})) {
    ${y}[i] ~ \\\
    % if D == 'Normal':
    dnorm(mu[i], tau)
    mu[i] <- \\\
    % endif
    % if D == 'Binomial':
    dbin(p[i], ${n}[i])
    ${link}(p[i]) <- \\\
    % endif
    % if D == 'Poisson':
    dpois(p[i])
    ${link}(p[i]) <-
    % if offset:
    ${n}[i] + \\\
    % endif
    % endif
    % if D == '-ve Binomial':
    dpois(p[i])
    p[i] <- rho[i] * exp(\\
    % if offset:
    ${n}[i] + \\\
    % endif
    % endif
    ${mmult(x, 'beta', 'i')} \\\
    % for i in range(0, numlevs):
    + u${i + 1}[${context['C' + str(i + 1)}][i]] \\\
    % endfor
    % if D == '-ve Binomial':
```

```

)
    rho[i] ~ dgamma(alpha, alpha)
    % endif

}
% for i in range(0, numlevs):
for (i${i + 1} in 1:length(u${i + 1})) {
    u${i + 1}[i${i + 1}] ~ dnorm(0, tau_u${i + 1})
}
% endfor

# Priors
% for i in range(0, x.ncols()):
beta_${i} ~ dflat()
% endfor
% if D == 'Normal':
tau ~ dgamma(0.001000, 0.001000)
sigma2 <- 1 / tau
% endif
% for i in range(0, numlevs):
tau_u${i + 1} ~ dgamma(0.001000, 0.001000)
sigma2_u${i + 1} <- 1 / tau_u${i + 1}
% endfor
% if D == '-ve Binomial':
alpha ~ dlnorm(0, 0.001)
% endif
}
'''

```

Here we introduce the use of local variable *numlevs*. Basically the *model* attribute is a text string with substitutions. Then if we wish to include a Python statement, whilst inside the text string, we place it within a `<%` and a `%>`. In this case we set a value to *numlevs* and then use it as a looping upper bound later in the code. You will see that the rest of the code contains many of the features we have discussed in earlier examples. You do however have to be careful as the code is such a mixture of WinBUGS like model code and Python code. For example if we consider the chunk:

```

% for i in range(0, numlevs):
    for (i${i + 1} in 1:length(u${i + 1})) {
        u${i + 1}[i${i + 1}] ~ dnorm(0, tau_u${i + 1})
    }
% endfor

```

with our cross-classified model. Here we are using *i* in both the model code we are constructing and as a python variable. So *numlevels* in our example is 2 and so the outside `%for` (Python) can be expanded out and the *i* substitutions made and we get:

```

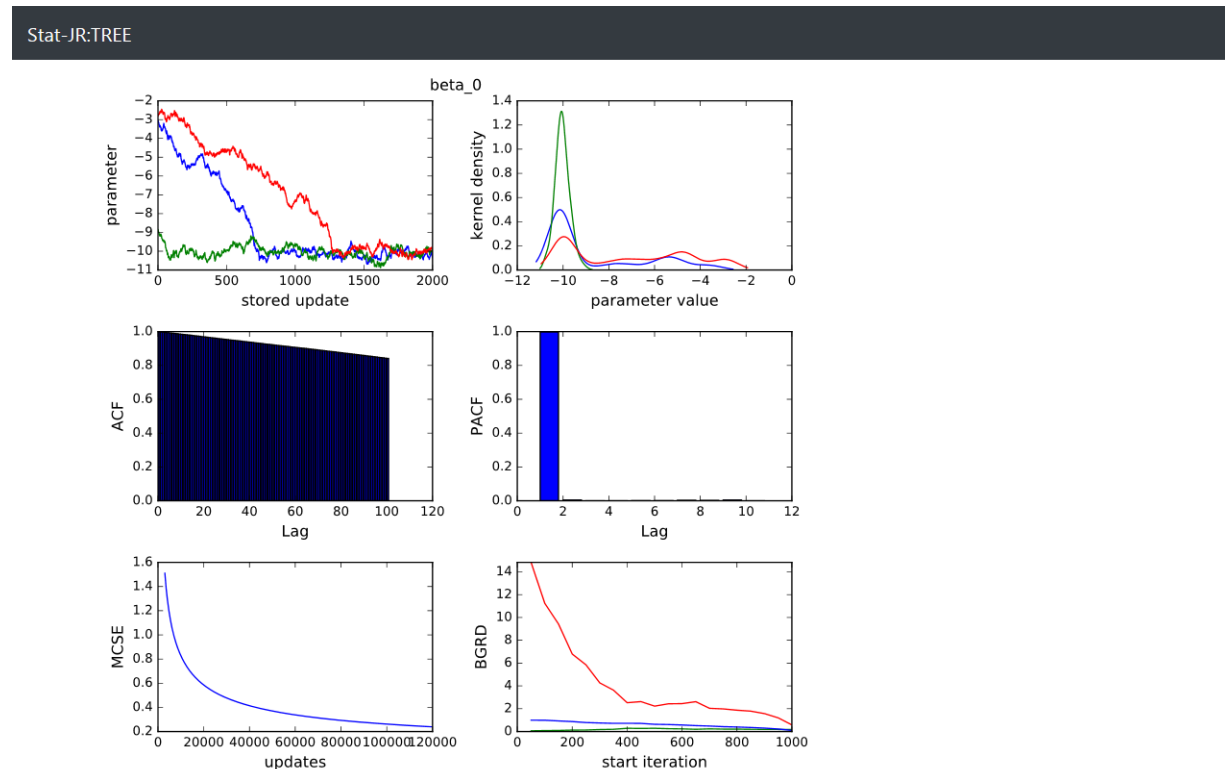
for (i1 in 1:length(u1)) {
    u1[i1] ~ dnorm(0, tau_u1)
}
for (i2 in 1:length(u2)) {
    u2[i2] ~ dnorm(0, tau_u2)
}

```

as we see in the browser. Once again the *latex* function which creates the LaTeX output will have similar substitutions via Python but we will not describe this in detail here.

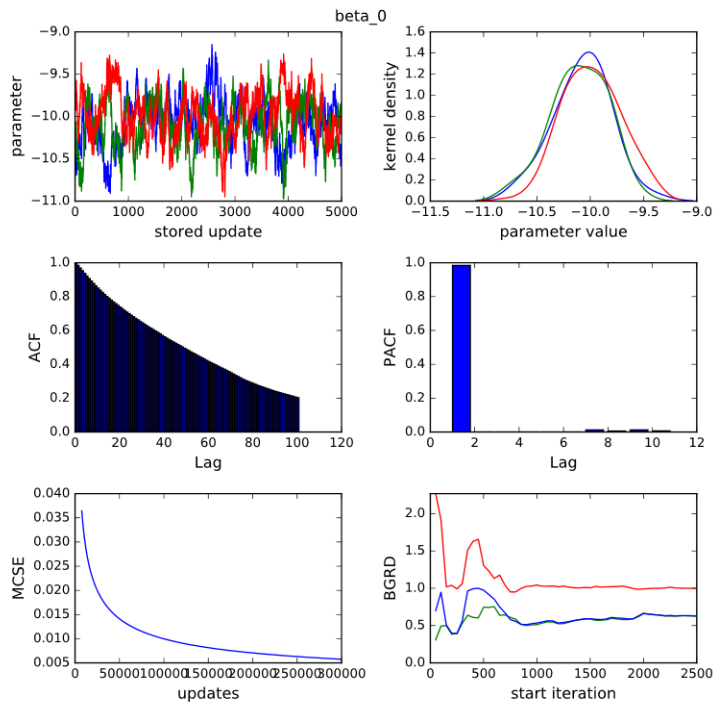
Clicking on **Run** will run the model and the output contains information for all the parameters but not the residuals as we didn't ask to store them and the usual MCMC plots are available. Interestingly the ESS values for beta_0 and beta_1 are poor and if we look at the object **beta_0.svg**

We see the following:



Clearly in this case the 500 burnin was not long enough and convergence has not been achieved. If we modify the burnin to 2000 and main run to 5000 we get the following:

Dataset: xc; **Template:** NLevelMod; **Input string:** {'D': 'Normal', 'storerresid': 'No', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '5000', 'C2': 'sid', 'outdata': 'out', 'NumLevs': '2', 'seed': '1', 'defaultsv': 'Yes', 'Engine': 'eStat', 'burnin': '2000', 'thinning': '1', 'y': 'attain', 'x': 'cons,vrq', 'C1': 'pid', 'makepred': 'No'}



There are several other N level modelling templates included with the software that you can also look at. We will describe one further such template (*NLevelRS*) which allows random slopes in section 11. This template will need to utilise the *preccode* feature and so we will first explain this with a simpler 1 level example.

9.2.1 Exercise 8

Try adapting this template to allow interactions between predictors calling your new templates *nlevelint*.

10 Using the Precode method

One of the aims of the Stat-JR system is to allow other estimation engines aside from our built-in MCMC engine to be used with templates. We saw in section 0 details of how the system can interact with third-party software. In this section (and in fact the following three sections) we will see how through the inclusion of additional C++ code the user can increase the set of models and methods that can be fitted using the built-in eStat engine. At present the methods we describe are partly to advance the modelling but also partly to cover current limitations in the algebra system which may eventually be rectified. As the names suggest the *precode* function will involve writing C++ code and so some knowledge of the C/C++ languages would be useful. The examples given here will however allow the user with some modification to use similar chunks of code for their examples. We begin in this chapter with a simple example of a 1 level probit regression model.

10.1 The 1LevelProbitRegression template

We have seen already that the *1LevelMod* template can be used to fit binary response models and we have demonstrated a logistic regression model for the *bang* dataset. A probit regression is similar to a logistic regression but uses a different link function. One interesting feature of a probit regression is that the link function is the inverse normal distribution cdf. This means that we can interpret the model using latent variables in an interesting way.

Imagine that you had a variable which was a continuous measurement but that we can only observe a binary indicator as to whether the variable was above or below a threshold, for example in education we might have a mark in an exam but the student is only told whether they pass or fail. If we model the pass/fail indicators using a probit regression then this is equivalent to assuming the unobserved (latent) continuous measure follows a normal distribution (with threshold 0 and variance 1).

We can use this fact in our modelling when we use MCMC by generating the latent continuous variables as part of the algorithm. Then having generated the latent variables we have a normal response model for these variables which is easy to fit. The *1LevelProbitRegression* template therefore fits a probit regression using this technique and we will add the step to update the continuous response variables via the *precode* methods.

We will start as usual by looking at the *inputs* attribute which is quite short (again, omitting the help text):

```
inputs = '''
v = DataVector('Response: ')
y = ParamVector(parents=[v], as_scalar=False, customstep=True,
monitor=False)
x = DataMatrix('Explanatory variables: ', allow_cat = True)
beta = ParamVector(parents=[x], as_scalar=True)
deviance = ParamScalar(customstep=True)
'''
```

Here you will see that the column containing the 0/1 response is actually stored as *v* in this template as we will use *y* to be the underlying continuous response. As *y* is latent it is defined as a *Paramvector* rather than data, and the parents term links the lengths of the two vectors together

which basically ensures that the continuous response vector y is the same length as the observed binary response vector v . The argument *customstep*=*True* tells Stat-JR that this parameter will have it's own C code step and the *monitor*=*False* argument tells Stat-JR not to store a chain for each element of y . As always it helps to demonstrate the template with an example so we will fit a probit regression model (equivalent to the logistic regression in section 7) to the Bangladeshi dataset. Select *1LevelProbitRegression* from the *template* list and *bang* from the *dataset* list and then fill in the template as shown below:

Dataset: *bang*; **Template:** *1LevelProbitRegression*; **Input string:** `{'burnin': '500', 'defaultsv': 'Yes', 'thinning': '1', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'v': 'use', 'outdata': 'out', 'x': 'cons,age', 'seed': '1', 'makepred': 'No'}`

Stat-JR: TREE Start again Dataset **bang** Template **1LevelProbitRegression** eBook **Idle** Settings About Debug

Response: use [remove](#)

Explanatory variables: cons,age [remove](#)

Number of chains: 3 [remove](#)

Random Seed: 1 [remove](#)

Length of burnin: 500 [remove](#)

Number of iterations: 2000 [remove](#)

Thinning: 1 [remove](#)

Use default algorithm settings: Yes [remove](#)

Generate prediction dataset: No [remove](#)

Use default starting values: Yes [remove](#)

Name of output results:

[Next](#)

Clicking on the **Next** button, *equation.tex* will appear in the output pane and we see the model described mathematically:

Stat-JR: TREE Start again Dataset **bang** Template **1LevelProbitRegression** eBook **Ready (4s)** Settings About Debug

[Edit](#) equation.tex [Popout](#)

$$\begin{aligned} & use_i^* \sim N(\mu_i, 1) \\ & \text{where } use_i^* > 0 \text{ if } use_i = 1 \\ & \text{and } use_i^* < 0 \text{ if } use_i = 0 \\ & \mu_i = \beta_0 cons_i + \beta_1 age_i \\ & \beta_0 \propto 1 \\ & \beta_1 \propto 1 \end{aligned}$$

Here you see how use^* is the latent continuous variable written as y in the model code. If we look at *model.txt* (below) we see that the model code is really just fitting a normal model as if we already know the values of y .



The screenshot shows the Stat-JR:TREE application interface. At the top, there is a dark header bar with the text 'Stat-JR:TREE' and several navigation links: 'Start again', 'Dataset' (with a dropdown arrow), 'bang' (highlighted in a blue pill), 'Template' (with a dropdown arrow), '1LevelProbitRegression' (highlighted in a blue pill), and 'eBook' (with a dropdown arrow). On the right side of the header, there is a green 'Ready (4s)' status indicator, and links for 'Settings', 'About', and 'Debug' (with a dropdown arrow). Below the header, there is a toolbar with a blue 'Edit' button, a dropdown menu showing 'model.txt', and a blue 'Popout' button. The main area is a large white box containing the following R model code:

```
model{
  for (i in 1:length(use)) {
    y[i] ~ dnorm(mu[i],1.0)
    mu[i] <- cons[i] * beta_0 + age[i] * beta_1
    # Priors
    beta_0 ~ dflat()
    beta_1 ~ dflat()
  }
}
```

If we look at the *model* attribute we can see that clearly.

```
model = '''
model{
  for (i in 1:length(${v})) {
    y[i] ~ dnorm(mu[i],1.0)
    mu[i] <- ${mmult(x, 'beta', 'i')}
    # Priors
    % for i in range(0, x.ncols()):
    beta_${i} ~ dflat()
    % endfor
  }
}
'''
```

Here the code is fairly straight-forward so the interesting thing is how we actually include a step for y to make this the correct model. You will recall that y will need a custom step and will not be monitored. To see this in practice we will continue our example and press the **Run** button. When finished if you select **ModelResults** then the results will look as follows:

Stat-JR:TREE
Start again
Dataset
bang
Template
1LevelProbitRegression
eBook
Ready (22s)
Settings
About
Debug

ModelResults
Popout

Results

Parameters:

parameter	mean	sd	ESS	variable
beta_0	-0.258985721812	0.0239119026417	2770	cons
beta_1	0.00759034568215	0.00262156649463	2663	age
deviance	3846.425343849193	1.962766724882	4866	

Model:

Statistic	Value
Dbar	3846.425343849193
D(thetabar)	3844.431572015837
pD	1.993771833356
DIC	3848.419115682549

We see that the model has run and got reasonable ESS values and has returned a DIC value. To see how this happened we need to look at the **preccode** and **deviancecode** attributes

10.2 preccode and deviancecode attributes

We have seen that the code works but we need now to look and see how the step for updating the latent y variable is incorporated into the code. This is done via the *preccode* attribute which for this template looks as follows:

```

preccode = '''
<%!
def mmult(names, var, index):
    out = ""
    count = 0
    for name in names:
        if count > 0:
            out += ' + '
        out += 'double(' + name + '[' + index + ']) * ' + var + '_' +
str(count)
        count += 1
    return out
%>

double mean;
for(int i=0;i<length(y);i++)
{
    mean = ${mmult(x, 'beta', 'i')};
    if(${v}[i] <= 0)
        y[i] = dtnormal(mean,1,2,0,0);
    else
        y[i] = dtnormal(mean,1,1,0,0);
}
'''

```

This function could have been even shorter except we need to include in here a definition for the `mmult` function that is used to construct the linear predictor, this time as C++ code.

The actual C++ code is the chunk

```
double mean;
for(int i=0;i<length(y);i++)
{
    mean = ${mmult(x, 'beta', 'i')};
    if(${v}[i] <= 0)
        y[i] = dtnormal(mean,1,2,0,0);
    else
        y[i] = dtnormal(mean,1,1,0,0);
}
```

Here we see that the code involves looping over all data points via a “for” loop and for each point evaluating the mean value which is the linear predictor calculated via the substitution. Then depending on the value of the binary response a call is made to the truncated normal random number generator via the dtnormal function. Here dtnormal takes 5 arguments, the mean, the sd, the type of truncation with 1 left truncation, 2 right truncation and 3 both, and finally the left and right truncation values.

To see this in action choose **modelcode.cpp** from the list and choose to pop it out:

Stat-JR:TREE

Model iteration code

```
RunningStatVector y_results(2867, y_n, y_M, y_S);
Py_BEGIN_ALLOW_THREADS;
std::vector<double*> tmp_v;
tmp_v.push_back(const_cast<double*>(use));
RectMatrix mat_v(tmp_v, 2867);
std::vector<double*> tmp_x;
tmp_x.push_back(const_cast<double*>(cons));
tmp_x.push_back(const_cast<double*>(age));
RectMatrix mat_x(tmp_x, 2867);
std::vector<double*> tmp_beta;
tmp_beta.push_back(beta);
RectMatrix mat_beta(tmp_beta, 2);
double &beta_0 = beta[0];
double &beta_1 = beta[1];
std::vector<double*> tmp_y;
tmp_y.push_back(y);
RectMatrix mat_y(tmp_y, 2867);
static std::unordered_map<std::string, SimpleRandomGenerator> rngstate;
if (runstate == 0) {
    rngstate.try_emplace(rngid, SimpleRandomGenerator());
}
auto &rng = rngstate[rngid];
if (runstate == 0) {
    rng.set_seed(seed);
    rng.start();
}
for (int iter = 0; iter < numiter; iter++) {
    int iterind = 0;
    if (runstate == 3) iterind = floor((start_iteration + iter) / thinning);

    double mean;
    for(int i=0;i<2867;i++)
    {
        mean = double(cons[i]) * beta_0 + double(age[i]) * beta_1;
        if(use[i] <= 0)
            y[i] = dtnormal(mean,1,2,0,0);
        else
            y[i] = dtnormal(mean,1,1,0,0);
    }

    // Update beta_0
    // This code was generated by the Stat-JR package (copyright 2012 University of Bristol and University of Southampton).
```

Here we see that after some initial setup lines, the **preccode** chunk, as the name suggests appears before the steps for other parameters (in this case beta_0). This is important as the y variable needs initialising before the other parameters are updated and updating it first ensures y is positive when use is 1 and negative when use is 0.

We have added in a step via precode to enable the MCMC algorithm to work correctly. Of course the model that the algebra system has been sent is the simpler normal model and so the deviance for this model would be returned by it and thus as this is used to construct the DIC diagnostic then we would get a model fit diagnostic for the wrong model. To rectify this the attribute *deviancecode* can be used to overwrite the definition of the deviance. This attribute contains a piece of C++ code for the deviance step. This code is then included in both the iteration loop and the DIC code and thus the DIC diagnostic is calculated correctly. The code can be seen within the template but will not be repeated here.

11 Multilevel models with Random slopes and the inclusion of Wishart priors

One limitation of the algebra system in its current form is that it treats all parameters as scalars. This means for example that for the *Regression1* template, the set of beta parameters are all updated individually through univariate normal steps. We will investigate the implications of this in section 12. In section 9 we introduced our first multilevel models all of which only had random intercepts. To extend such models to include random slopes requires (assuming slopes and intercepts are correlated) the use of a multivariate normal distribution for the random effects.

Multivariate normal distributions by their nature have vector and not scalar parameters and so our model code diverges from standard WinBUGS model code here (and hence this is an example template where template specific methods are required for WinBUGS). Our improvised model code depends on the number of response variables i.e. we have bivariate, trivariate etc normal distributions. We will see how these work in practice via the template *NLevelRS*. It should be noted that we also have templates that completely circumvent the algebra system and simply write custom C code. These templates have the postfix 'cc' at their end for example *1LevelModcc*.

11.1 An example with random slopes

Firstly select *NLevelRS* from the *template* list and *tutorial* from the *data* list. Then choose the inputs as follows:

Dataset: *tutorial*; **Template:** *NLevelRS*; **Input string:** `{'Engine': 'eStat', 'x1': 'cons,standlrt', 'burnin': '500', 'D': 'Normal', 'outdata': 'outrs', 'storeresid': 'No', 'makepred': 'No', 'thinning': '1', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'y': 'normexam', 'x': 'cons,standlrt', 'C1': 'school', 'NumLevs': '1', 'seed': '1', 'priors0': 'Uniform', 'defaultsv': 'Yes'}`

Setting	Value	Action
Number of Classifications:	1	remove
Classification 1:	school	remove
Response:	normexam	remove
Specify distribution:	Normal	remove
Explanatory variables:	cons,standlrt	remove
Explanatory variables random at school classification:	cons,standlrt	remove
Store residuals?	No	remove
Priors (NB Uniform not supported by WinBUGS / OpenBUGS):	Uniform	remove
Choose estimation engine:	eStat	remove
Number of chains:	3	remove
Random Seed:	1	remove
Length of burnin:	500	remove
Number of iterations:	2000	remove
Thinning:	1	remove
Use default algorithm settings:	Yes	remove
Generate prediction dataset:	No	remove
Use default starting values:	Yes	remove
Name of output results:	<input type="text" value="outdata"/>	

[Next](#)

You will see that there are lots of inputs here and correspondingly the *inputs* function for this template is therefore quite long as we see below (omitting the help text):

```
inputs = ''
NumLevs = Integer('Number of Classifications: ')

for i in range(0, int(NumLevs)):
    selstr = 'Classification ' + str(i + 1) + ': '
    context['C' + str(i + 1)] = IDVector(selstr)
y = DataVector('Response: ')
D = Text('Specify distribution: ', ['Normal', 'Binomial', 'Poisson'])
if D == 'Binomial':
    n = DataVector('Denominator: ')
    link = Text('Specify link function: ', ['logit', 'probit', 'cloglog'])
if D == 'Poisson':
    link = Text(value = 'ln')
    offset = Boolean('Is there an offset: ')
    if offset:
        n = DataVector('Offset: ')
if D == '-ve Binomial':
    offset = Boolean('Is there an offset: ')
    if offset:
        n = DataVector('Offset: ')
if D == 'Normal':
```

```

    tau = ParamScalar()
    sigma = ParamScalar(modelled = False)
x = DataMatrix('Explanatory variables: ', allow_cat = True)

for i in range(0, int(NumLevs)):
    context['x'+str(i+1)] = DataMatrix('Explanatory variables random at ' +
context['C' + str(i + 1)] + ' classification: ', allow_cat = True)

storeresid = Boolean('Store residuals?')

if D == '-ve Binomial':
    alpha = ParamScalar()
    rho = ParamVector(parents = [y])

beta = ParamVector(parents=[x], as_scalar=True)

for i in range(0, int(NumLevs)):
    for var in range(0, len(context['x'+str(i+1)])):
        if storeresid:
            context['u' + str(var) + '_' + str(i)] =
ParamVector(parents=[context['C' + str(i + 1)]], as_scalar=False)
        else:
            context['u' + str(var) + '_' + str(i)] =
ParamVector(parents=[context['C' + str(i + 1)]], as_scalar=False,
monitor=False)
            num = len(context['x'+str(i+1)])
            if num == 1:
                context['tau_u0_'+str(i+1)] = ParamScalar()
                context['sigma_u0_'+str(i+1)] = ParamScalar(modelled = False)
            else:
                context['omega_u'+str(i+1)] = ParamMatrix(modelled = False,
customstep=True)
                context['omega_u'+str(i+1)].size = num
                context['d_u'+str(i+1)] = ParamMatrix(customstep=True)
                context['d_u'+str(i+1)].size = num
                context['priors' + str(i)] = Text('Priors (NB Uniform not supported
by WinBUGS / OpenBUGS): ', ['Uniform', 'Wishart'])
                if context['priors' + str(i)] == 'Wishart':
                    context['R' + str(i)] = List('R matrix: ')
                    context['v' + str(i)] = Integer('Degrees of Freedom:')

deviance = ParamScalar(modelled = False)
'''

```

The template is initially like the *NLevelMod* template but then has an additional section that is used to input the variables that have random effects associated with them (at each level), and then any priors at those levels are input. You will see that we use the *context* functionality to construct variable names a lot and that there are different parameters for classifications where there is a single random parameter and where there are more than one. In brief parameters beginning *tau_u0* and *sigma_u0* are the precision and variance of the random effects if there is a single set of random effects; those beginning *omega_u* and *d_u* are the variance matrix and precision matrix if we have multiple sets of random effects at a classification. Finally in this case there are two possible priors and for the (informative) Wishart priors an estimate (beginning with R) and degrees of freedom (beginning with v) parameter are required.

Having completed our inputs we now need to click on **Next** to see what the model looks like (as shown by *equation.tex*):

Stat-JR:TREE Start again Dataset **tutorial** Template **NLevelRS** eBook Ready (5s) Settings About Debug

Edit equation.tex Popout

$$\begin{aligned}
 \text{normexam}_i &\sim N(\mu_i, \sigma^2) \\
 \mu_i &= \beta_0 \text{cons}_i + \beta_1 \text{standlrt}_i + u_{0,\text{school}[i]}^{(2)} \text{cons}_i + u_{1,\text{school}[i]}^{(2)} \text{standlrt}_i \\
 \begin{pmatrix} u_{0,\text{school}(i)}^{(2)} \\ u_{1,\text{school}(i)}^{(2)} \end{pmatrix} &\sim N \left(\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \Omega_u^{(2)} \right) \\
 \Omega_u^{(2)} &\propto 1 \\
 \beta_0 &\propto 1 \\
 \beta_1 &\propto 1 \\
 \tau &\sim \Gamma(0.001, 0.001) \\
 \sigma^2 &= 1/\tau
 \end{aligned}$$

Here we see the LaTeX code including the multivariate normal distribution for the random intercepts and slopes. To see the model specification we choose *model.txt* from the list:

Stat-JR:TREE Start again Dataset **tutorial** Template **NLevelRS** eBook Ready (5s) Settings About Debug

Edit model.txt Popout

```

model {
  for (i in 1:length(normexam)) {
    normexam[i] ~ dnorm(mu[i], tau)
    mu[i] <- cons[i] * beta_0 + standlrt[i] * beta_1 + u0_0[school[i]] * cons[i]
    + u1_0[school[i]] * standlrt[i]
  }

  for(i1 in 1:length(u0_0)) {
    dum_0[i1] ~ ddummy(dummy_0[i1])
    dummy_0[i1] ~ dnormal2a(u0_0[i1], u1_0[i1], 0, 0, d_u1[0], d_u1[1], d_u1[2])
    u0_0[i1] ~ dflat()
    u1_0[i1] ~ dflat()
  }

  # Priors

  beta_0 ~ dflat()
  beta_1 ~ dflat()

  tau ~ dgamma(0.001000, 0.001000)
  sigma <- 1 / sqrt(tau)
}

```

The multivariate normal distribution is written in the model code as follows:

```

for(i1 in 1:length(u0_0)) {
  dum_0[i1] ~ ddummy(dummy_0[i1])
  dummy_0[i1] ~ dnormal2a(u0_0[i1], u1_0[i1], 0, 0, d_u1[0],
d_u1[1], d_u1[2])
  u0_0[i1] ~ dflat()
  u1_0[i1] ~ dflat()
}

```

Basically the *dnormal2a* distribution has as its first two arguments the two responses. Next we get the 2 means and then the 3 parameters that make up the precision matrix. As the algebra system expects all parameters to appear on the left-hand side we complete our workaround for a multivariate Normal distribution by including the two *dflat* statements which do not change the posterior but mean that the *u0_0[i1]* and *u1_0[i1]* are regarded in the algebra system as parameters. Note that the *dummy_0* parameters are simply placeholders as each distribution needs a scalar left-hand side. The definition of *dnormal2a* does not depend on the left hand side term. The *dummy_0* parameters also appears on the right hand side in the *ddummy* statement and this is to trick the algebra system into thinking that *dummy_0* is truly a parameter so that the *dnormal2a* statement is not considered part of the likelihood for calculating DIC etc.

The code for creating the model code is in *model* but doesn't contain anything very new that needs reporting here. The *latex* code might interest those trying to learn LaTeX as it contains a chunk to produce the multivariate Normal line as follows:

```
\left(
\begin{array}{l}
% for i in range(0, len(context['x'+str(lev+1)])):
u^{\left(\left\{lev + 2\right\}\right)}_{\left\{i\right\},\left\{context\left['C' + str(lev + 1)\right]\right\}\left(i\right)}
% if i != len(context['x'+str(lev+1)]) -1:
\\
% endif
% endfor
\end{array}
\right) & \sim \mbox{N}
\left[ \left(
\begin{array}{l}
% for i in range(0, len(context['x'+str(lev+1)])):
0
% if i != len(context['x'+str(lev+1)]) -1:
\\
% endif
% endfor
\end{array}
\right), \Omega^{\left(\left\{lev + 2\right\}\right)}_{\left(u\right)} \right] \\
```

Here we use Python %ifs and %fors to allow conditional code and the array environment and \left and \right (for big brackets) in LaTeX to deal with vectors and matrices. The actual code that is produced can be looked at by right clicking on the LaTeX and selecting show source and selecting the appropriate lines. It looks as follows:

```
\left(
\begin{array}{l}
u^{\left(2\right)}_{\left\{0,school\left(i\right)\right\}}
\\
u^{\left(2\right)}_{\left\{1,school\left(i\right)\right\}}
\end{array}
\right) & \sim \mbox{N}
\left[ \left(
\begin{array}{l}
0
\\
0
\end{array}
\right)
```


\right), \Omega^{\{2\}}_{\{u\}} \right] \\

Looking at the model code we have not included a prior for d_{u1} and so here we again resort to writing our own *precode* chunk.

11.2 Precode for NLevelRS

We will here look at the *precode* in chunks. The *precode* is being used to add a step for updating the precision matrix d_{u1} and the corresponding variance matrix ω_{u1} . Looking at the start of the code overleaf:

```
precode = '''
{
<% numlevs = int(NumLevs) %>\\
    bool fail = false;
% for i in range(0, numlevs):
<% n = len(context['x'+str(i + 1)]) %>\\
% if n > 1 :

    std::vector<double*> tmp_u${i};
% for j in range(0, n):
    tmp_u${i}.push_back(u${j}_${i});
% endfor
    RectMatrix mat_u${i}(tmp_u${i}, length(u0_${i}));

    SymMatrix sb${i + 1} = mat_u${i}.T() * mat_u${i};
```

This first section stores the number of levels (*numlevs*) for looping purposes and also within the loop the number of random effects are constructed (as *n*) because for classifications with only 1 set of random effects nothing needs doing as the algebra system has evaluated the posterior required. We take the *u*'s and store them in a matrix so that we can do matrix arithmetic. We next construct a matrix variable *sb1* which initially stores the crossproduct matrix of the residuals before moving to the next chunk of code:

```
% if context['priors' + str(i)] == 'Uniform':
    int vw${i+1} = length(u0_${i})-${n + 1};
    if (runstate == 0) {
% for j in range(0, n):
        sb${i + 1}(${j}, ${j}) += 0.0001;
% endfor
    }
% endif
% if context['priors' + str(i)] == 'Wishart':
    int vw${i+1} = length(u0_${i}) + ${context['v' + str(i)]};
% endif

% if context['priors' + str(i)] == 'Wishart':
<%
import numpy
Rmat = numpy.empty([n, n])
count = 0
for j in range(0, n):
    for k in range(0, j + 1):
        Rmat[j, k] = float(context['R' + str(i)].name[count])
        Rmat[k, j] = Rmat[j, k]
        count += 1
```

```
%>

<% count = 0 %>
% for j in range(0, n):
% for k in range(j, n):
    sb${i+1}(${j}, ${k}) += ${str(Rmat[j, k] * float(context['v' +
str(i)]))});
% endfor
% endfor
% endif
```

In this chunk of code we have different blocks of code depending on prior distribution types. For the uniform prior we simply construct the degrees of freedom parameter (*vw1*), which equals the number of higher level units minus the number of sets of random effects + 1. We also have some code for the first iteration (*runstate* = 0) to avoid numerical problems as the residual starting values may all be the same. For the Wishart prior we have to add the prior parameters to the *sb1* and *vw1* parameters. Next we have:

```
    matrix_sym_invinplace(sb${i+1});
    mat_d_u${i + 1} = dwishart(vw${i+1}, sb${i+1}, fail);
    mat_omega_u${i + 1} = matrix_sym_inverse(mat_d_u${i + 1}, fail);
%endif
%endfor
}
'''
```

In this last chunk of code we invert the *sb1* parameter before drawing the new precision matrix which we store in *mat_d_u1* and the inverse matrix to the vector *mat_omega_u1*. To see the code that the *preccode* method generates for our example we can select **modelcode.cpp** and scroll down a few lines as shown below:

Stat-JR:TREE
Start again
Dataset
tutorial
Template
NLevelRS
eBook
Ready (5%)
Settings
About
Debug

```

{
    bool fail = false;

    std::vector<double*> tmp_u0;
    tmp_u0.push_back(u0_0);
    tmp_u0.push_back(u1_0);
    RectMatrix mat_u0(tmp_u0, 65);

    SymMatrix sb1 = mat_u0.T() * mat_u0;

    // Note currently using a uniform prior for variance matrix

    int vw1 = 65-3;
    if (runstate == 0) {
        sb1(0, 0) += 0.0001;
        sb1(1, 1) += 0.0001;
    }

    matrix_sym_invinplace(sb1);
    mat_d_u1 = dwishart(vw1, sb1, fail);
    mat_omega_u1 = matrix_sym_inverse(mat_d_u1, fail);
}

// Update tau

```

As the name *preccode* suggests the code appears before the other steps in the algorithm. We can finally run the template by clicking on the **Run** button and selecting **ModelResults** from the list. The results appear as follows:

12 Improving mixing (1LevelBlock and 1LevelOrthogParam)

In this section we will return once again to our first template *Regression1* but use it on a different dataset, *rats*. This dataset consists of the weights of 30 laboratory rats at weekly intervals from 8 days old and here we will consider a regression looking at the impact on their final weight at 36 days of their initial weight at 8 days old.

12.1 Rats example

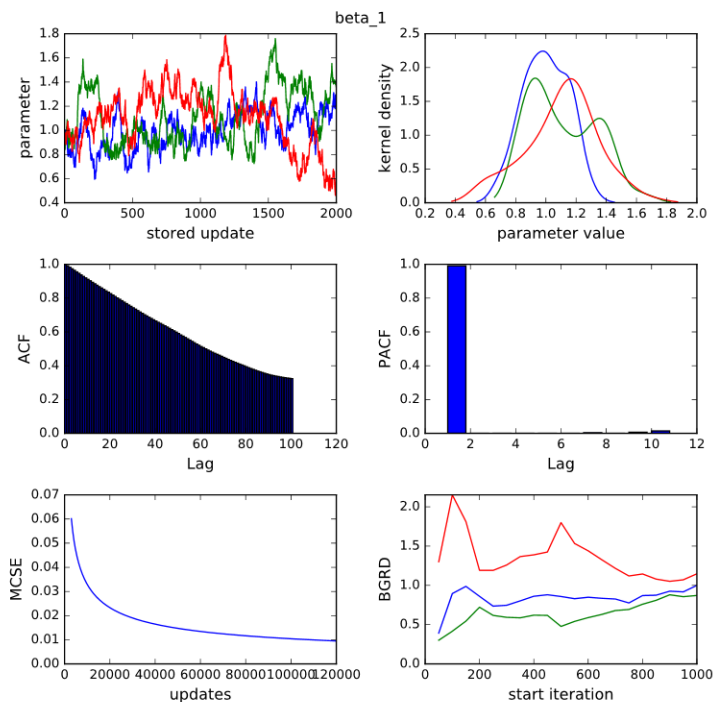
We will set up a simple regression for this rather small dataset as follows:

Dataset: *rats*; **Template:** *Regression1*; **Input string:** `{'burnin': '500', 'defaultsv': 'Yes', 'outdata': 'ratsout', 'thinning': '1', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'y': 'y36', 'x': 'cons,y8', 'seed': '1', 'makepred': 'No'}`

Response:	y36 remove
Explanatory variables:	cons,y8 remove
Number of chains:	3 remove
Random Seed:	1 remove
Length of burnin:	500 remove
Number of iterations:	2000 remove
Thinning:	1 remove
Use default algorithm settings:	Yes remove
Generate prediction dataset:	No remove
Use default starting values:	Yes remove
Name of output results:	<input type="text" value="ratsout"/>

[Next](#)

We will then run the model by clicking the **Next** and **Run** buttons. If we look at the output and change the pull down list to *beta_1.svg* and pop it out so that we have the MCMC plot for *beta1* visible we will see the following:



In *ModelResults* we see that both the regression coefficients have very small effective sample sizes (32 and 32 respectively) and the chains we observe in the graphs above are not mixing well. Aside from being a small dataset a difference between the *rats* and the *tutorial* dataset is that the data have not been centred. This means that the joint posterior distribution of β_0 and β_1 has a very large correlation between the pair of parameters and so if we update them separately we will have problems. We will look at two templates that will rectify this problem.

12.2 The 1LevelBlock template

Most MCMC algorithms implemented in software packages will update the parameters β_0 and β_1 together in one multivariate normal block. As we have seen, the current algebra system in Stat-JR does not produce multivariate posterior distributions. We can, however, work out the correct posterior distribution by hand and plug this into the code via the *precode* options we have seen earlier. This is performed by the *1LevelBlock* template. If you look at the template code you will see it has an initial input in the *inputs* attributes as to whether or not to block the fixed effects and conditional on this we let Stat-JR know whether β is to be updated via a custom step.

```
mv = Boolean('Use MVNormal update for beta?: ')
if mv:
    beta = ParamVector(parents=[x], as_scalar=True, customstep=True)
else:
    beta = ParamVector(parents=[x], as_scalar=True)
```

This code is informing the code generator that customsteps are to be used for the beta parameters when the block updating option (*mv*) is selected and that it should ignore whatever has been returned from the algebra system for these steps. The *precode* method then contains the code to

update the beta vector which has mean (in matrix form) $(X^T X)^{-1} X^T y$ and variance $(X^T X)^{-1}$ times the residual variance. The code which uses matrix classes is as follows:

```
preccode = '''
% if mv:
    {
        bool fail = false;
        static RectMatrix xtxchol(${len(x)}, ${len(x)});
        static RectMatrix mean(${len(x)}, 1);

        // Setting up constant terms for beta step
        if (runstate == 0) {
            xtxchol = matrix_cholesky(mat_x.T() * mat_x, false,
fail);

            RectMatrix xty = mat_x.T() * mat_y;
            mean = matrix_cholsolve(xtxchol, xty);
        }

        // Multivariate step for beta
        DiagMatrix taudiag = identity(${len(x)}) / tau;
        SymMatrix variance = matrix_cholsolve(xtxchol, taudiag);
        mat_beta = dmultnormal(mean, variance, fail);
    }
% endif
'''
```

If we want to test this template we can choose it (along with *rats*) from the template list and set up the inputs as follows:

Dataset: *rats*; **Template:** *1LevelBlock*; **Input string:** *{'Engine': 'eStat', 'burnin': '500', 'defaultsv': 'Yes', 'outdata': 'outblock', 'thinning': '1', 'mv': 'Yes', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'y': 'y36', 'x': 'cons,y8', 'seed': '1', 'makepred': 'No'}*

Stat-JR:TREE
Start again
Dataset
rats
Template
1LevelBlock
eBook
Ready (7%)
Settings
About
Debug

?
Response:

y36
remove

?
Explanatory variables:

cons,y8
remove

Use MVNormal update for beta?:

Yes
remove

Choose estimation engine:

eStat
remove

Number of chains:

3
remove

Random Seed:

1
remove

Length of burnin:

500
remove

?
Number of iterations:

2000
remove

Thinning:

1
remove

Use default algorithm settings:

Yes
remove

Generate prediction dataset:

No
remove

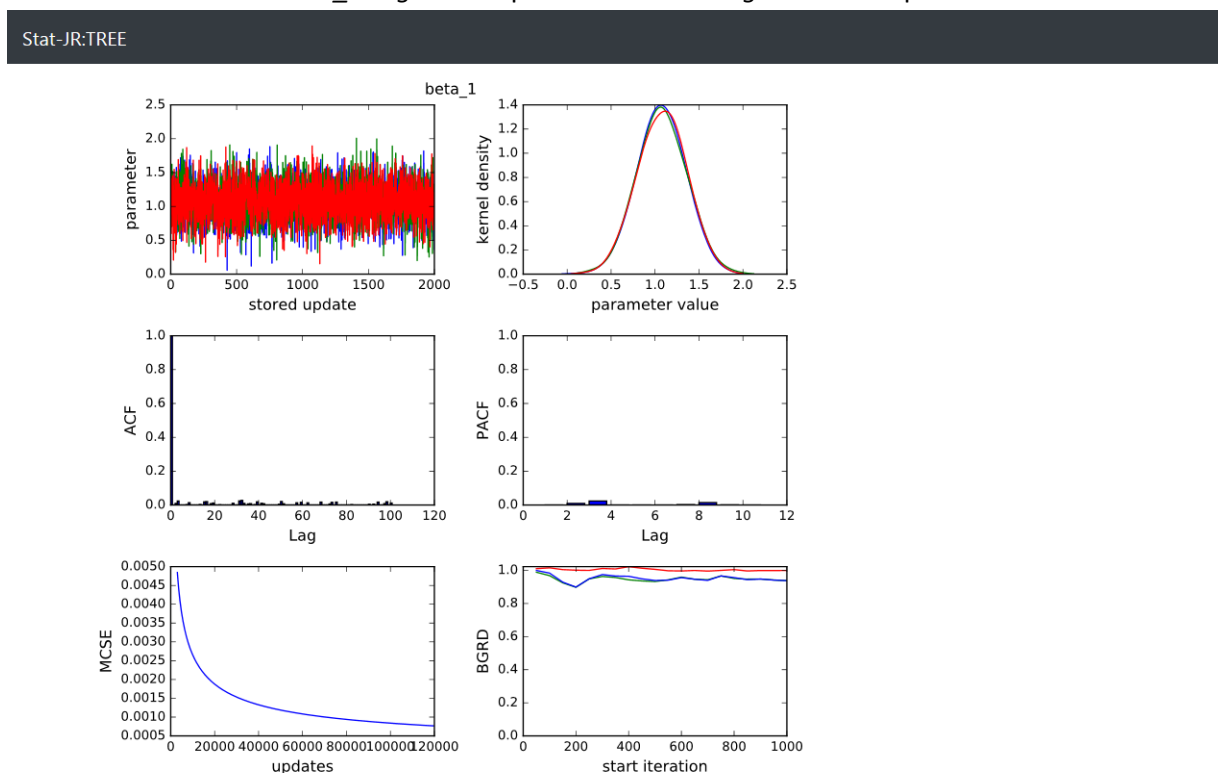
Use default starting values:

Yes
remove

?
Name of output results:

Next

Running the template by pressing the **Next** and **Run** buttons results in the following output. Note here we have selected *beta_1.svg* for comparison with the *Regression1* output.



We can see that the method has given much better mixing for *beta1*. Looking at the *ModelResults* the effective sample size values have increased from 32/32 to 5745/5780 for *beta_0* and *beta_1* respectively! We have in other templates (*2LevelBlock* and *NLevelBlock*) implemented similar block updating of fixed effects for multilevel models. We will next look at an alternative method that has the advantages of not needing to use *preccode* and also of being useful for non-normal response models.

12.3 The 1LevelOrthogParam template

The alternative approach to blocking variables that are correlated is to reparameterise the parameters to a configuration that are less correlated. We will achieve this by using an orthogonal parameterisation for the fixed effects rather than the standard parameterisation.

The template we will use is called *1LevelOrthogParam* and the inputs are very similar to the *1LevelMod* template (as this approach also works for non-normal responses). The template does have 2 additional inputs in *inputs* which are used to find out whether or not to use a transformed parameterisation and if so whether to use an orthogonal or orthonormal parameterisation.

This can be seen in the following lines (omitting the help text):

```
useorthog = Boolean('Do you want to use orthogonal parameterisation?: ')
if useorthog:
    orthtype = Text('Type:', ['Orthogonal', 'Orthonormal'])
```

and the following lines are conditional on using the orthogonal parameterisation:

```
if useorthog:
    betaort = ParamVector(parents=[x], as_scalar=True)
    orthogmat = List(value = [])
    #orthogmat = ParamVector()
    #orthogmat.ncols = -(len(x) * len(x))
    beta = ParamVector(parents=[x], as_scalar=True, modelled = False)
else:
    beta = ParamVector(parents=[x], as_scalar=True)
```

Here we add an additional vector of responses, *betaort* if the orthogonal parameterisation is to be used and the standard *beta* vector is now not modelled but becomes deterministically calculated. Let us try out the template on the *rats* example so choose *1LevelOrthogParam* from the template list and input the following:

Dataset: *rats*; **Template:** *1LevelOrthogParam*; **Input string:** {'Engine': 'eStat', 'burnin': '500', 'D': 'Normal', 'outdata': 'outort', 'thinning': '1', 'orthtype': 'Orthogonal', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'y': 'y36', 'x': 'cons,y8', 'makepred': 'No', 'seed': '1', 'useorthog': 'Yes', 'defaultsv':

'Yes'}

Stat-JR:TREE
Start again
Dataset ▾ rats
Template ▾ 1LevelOrthoParam
eBook ▾
Ready (9%)
Settings
About
Debug ▾

1
Response:
y36
remove

Specify distribution:
Normal
remove

2
Explanatory variables:
cons,y8
remove

3
Do you want to use orthogonal parameterisation?:
Yes
remove

4
Type:
Orthogonal
remove

Choose estimation engine:
eStat
remove

Number of chains:
3
remove

Random Seed:
1
remove

Length of burnin:
500
remove

5
Number of iterations:
2000
remove

Thinning:
1
remove

Use default algorithm settings:
Yes
remove

Generate prediction dataset:
No
remove

Use default starting values:
Yes
remove

6
Name of output results:

Next

Clicking on the **Next** button will give the following output for the model:

Stat-JR:TREE
Start again
Dataset ▾ rats
Template ▾ 1LevelOrthoParam
eBook ▾
Ready (1s)
Settings
About
Debug ▾

Edit
equation.tex
Popout

$$\begin{aligned}
y_{36_i} &\sim N(\mu_i, \sigma^2) \\
\mu_i &= \beta_0^* \text{orthcons}_i + \beta_1^* \text{orthy8}_i \\
\beta_0^* &\propto 1 \\
\beta_1^* &\propto 1 \\
\beta_0 &= 1.0\beta_0^* - 152.16666666666666\beta_1^* \\
\beta_1 &= 0.0\beta_0^* + 1.0\beta_1^* \\
\tau &\sim \Gamma(0.001, 0.001) \\
\sigma^2 &= 1/\tau
\end{aligned}$$

The method of using an orthogonal parameterisation is mentioned in (Browne, Steele, Golalizadeh, & Green, 2009) for non-normal examples and has also been implemented in MLwiN. For details on how we construct orthogonal vectors we refer the reader to (Browne, Steele, Golalizadeh, & Green, 2009) but note that a function to do the procedure named *orthog* that is stored elsewhere is used in this template. Here you will see that we fit a model with the parameters *betaort* placed in the linear predictor along with data vectors *orthcons* and *orthy8*. These data vectors are constructed in the *preparedata* attribute that we detail here:

```
preparedata = '''
```

```

from EStat.stats.utils.orthog import orthog
import numpy
mydata = data['datafile']

if useorthog:
    orth = numpy.zeros([len(mydata.variables[x[0]]['data']), len(x)])

    for i in range(0, len(x)):
        orth[:, i] = mydata.variables[x[i]]['data']

    if orthtype == 'Orthogonal':
        (tmp, om) = orthog(orth)

        orthogmat[:] = [str(i) for i in om.flat]

        for n in range(0, len(x)):
            mydata.addvariable('orth' + x[n], data = numpy.array(tmp[:,
n])).flatten())

    if orthtype == 'Orthonormal':
        (tmp, om) = numpy.linalg.qr(numpy.mat(orth))

        orthogmat[:] = [str(i) for i in om.I.flat]

        for n in range(0, len(x)):
            mydata.addvariable('orth' + x[n], data = numpy.array(tmp[:,
n])).flatten())

    x[:] = ['orth' + n for n in x]
'''

```

We begin by constructing a blank list 'orthogmat' and an empty matrix *orth*. We then implement the orthogonalising algorithm by filling *orth* with the original *x* variable vectors and then calling the *orthog* function. This results in *tmp* which is the matrix of orthogonal versions of the predictors and *om* which is the matrix that performs the orthogonalisation. We store this as a vector in the object 'orthogmat'. A slightly different routine is given if the user chooses Orthonormal instead here. The columns of this *tmp* matrix are then placed in objects that have the string 'orth' appended to the front of the original *x* variables names. Finally the original *x* variable names are replaced with these new orthogonal variable names before the data is returned. The *model* attribute then constructs the model code:

```

model = '''
model{
  for (i in 1:length(${y})) {
    ${y}[i] ~ \\
    % if D == 'Normal':
dnorm(mu[i], tau)
    mu[i] <- \\
    % endif
    % if D == 'Binomial':
dbin(p[i], ${n}[i])
    ${link}(p[i]) <- \\
    % endif
    % if D == 'Poisson':
dpois(p[i])
    ${link}(p[i]) <- \\
    % if offset:
${n}[i] + \\

```

```

        % endif
    % endif
    %if useorthog:
    ${mmult(x, 'betaort', 'i')}
    % else:
    ${mmult(x, 'beta', 'i')}
    % endif
    }

    # Priors
    % for i in range(0, beta.ncols):
    %if useorthog:
    betaort_${i} ~ dflat()
    % else:
    beta_${i} ~ dflat()
    % endif
    % endfor

    % if useorthog:
    <% count = 0%>
    % for i in range(0, beta.ncols):
    beta_${i} <- \\
    % for j in range(0, beta.ncols):
    ${orthogmat[count]} * betaort_${j}\\
    % if j == (beta.ncols - 1):

    % else:
    % if float(orthogmat[count+1]) >= float(0.0) :
    + \\
    % endif
    % endif
    <% count += 1 %>\\
    % endfor
    % endfor
    % endif

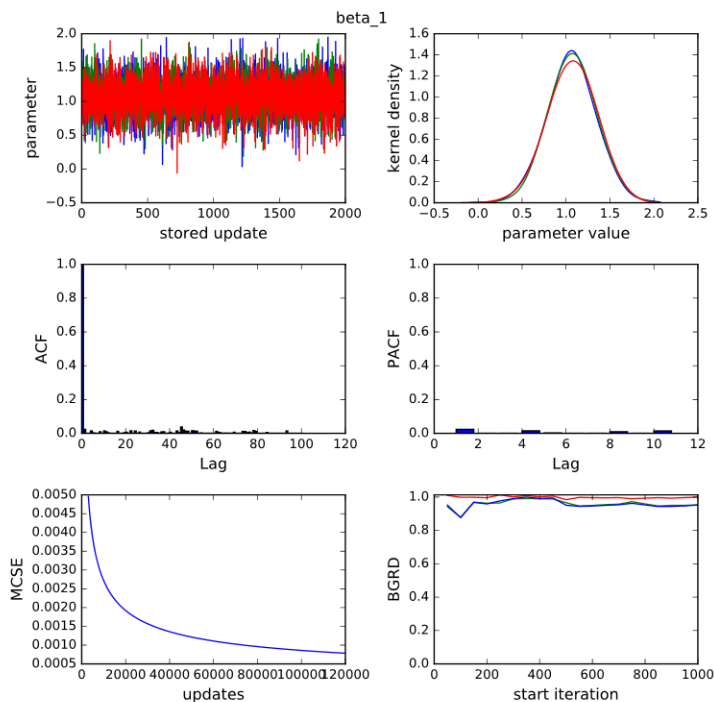
    % if D == 'Normal':
    tau ~ dgamma(0.001000, 0.001000)
    sigma <- 1 / sqrt(tau)
    sigma2 <- 1 / tau
    % endif
}

'''

```

Here we see that a different *mmult* function is performed for the orthogonal parameterisation and priors are given for *betaort* rather than *beta* in this case. Finally code is given to allow us to recover *beta* from *betaort* deterministically. We construct the product of the *orthogmat* terms and the *betaorts* placing + signs between the terms unless the *orthogmat* term is negative.

We can run the model by clicking on the **Run** button and we will see the following results for *beta_1* if we select *beta_1.svg* in the list:



We again see good mixing of the chains and very similar estimates to the blocking approach (Effective sample sizes for beta0 and beta1 are 5686 and 5725 respectively). The other advantage of this orthogonal approach is in it's generalisability to non-normal response models. In these cases Metropolis Hastings algorithms are used and so a blocking approach is not so straight forward.

12.3.1 Exercise 10

Convert this template so that it is analogous to the *Regression1* template but uses the orthogonal parametrisation. Call this new template *orthogregression*.

12.4 Multivariate Normal response models

Having established a method of including multivariate distributions for use with random slopes in the *precode* we can reuse the same method to allow us to fit multivariate Normal response models. We will here consider the template for fitting 1 level multivariate response models, *1LevelMVNormal.py*. This template can be used to fit models with missing data for some responses which is achieved by a method similar to that used for the probit regression and so the *precode* will generate (at least) two steps, one for the variance matrix of the responses and an initial step to set up the missing responses. Looking at the *inputs* attribute we see the following (omitting the help text):

```
inputs = '''
y = DataMatrix('Responses: ')
for i in range(0, len(y)):
    context['x'+str(i+1)] = DataMatrix('Explanatory variables for response
' + y[i] + ': ', allow_cat = True)

mv = Boolean('Use MVNormal update for beta?: ')

lenbeta = 0
```

```

for i in range(0, len(y)):
    lenbeta += len(context['x'+str(i+1)])
    context['miss'+y[i]] = ParamVector(monitor=False)
n = len(y)
if n == 1:
    tau = ParamScalar()
    sigma = ParamScalar(modelled = False)
else:
    omega_e = ParamMatrix(modelled = False, customstep=True)
    omega_e.size = n
    d_e = ParamMatrix(customstep=True)
    d_e.size = n
    priors = Text('Priors: ', ['Uniform', 'Wishart'], help="<p>Note:
Uniform <em>not</em> supported by WinBUGS / OpenBUGS</p>")
    if priors == 'Wishart':
        R = List('R matrix: ')
        v = Integer('Degrees of Freedom:')
if mv:
    beta = ParamVector(customstep=True)
else:
    beta = ParamVector()
beta.ncols = lenbeta
deviance = ParamScalar(modelled=False)
'''

```

Here you will notice that we construct parameter vectors that are a combination of the string ‘miss’ and the *y* variable names input using a *context* statement and these will be used in the model. Note that in line with the *1LevelBlock* template we have also given the option to update *beta* as a block but for now we will ignore this here. Let us run the template with the *gcsemv1* (Rasbash, Steele, Browne, & Goldstein, 2012) dataset that contains two responses for secondary school pupils taking General Certificate of Secondary Education (GCSE) exams in 1989, a written and a coursework test score. We will set up the inputs as follows:

Dataset: *gcsemv1*; **Template:** *1LevelMVNormal*; **Input string:** `{'imputeiters': '1000,2000', 'defaultsv': 'Yes', 'outdata': 'outmv', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'x2': 'cons,female', 'x1': 'cons,female', 'seed': '1', 'Engine': 'eStat', 'burnin': '500', 'priors': 'Uniform', 'thinning': '1', 'mv': 'Yes', 'y': 'written,csework', 'makepred': 'No'}`

Stat-JR:TREE
Start again
Dataset ▾ gcsemv1
Template ▾ 1LevelMvNormal
eBook ▾
Ready (56)
Settings
About
Debug ▾

Responses:
written,csework
remove

Explanatory variables for response written:
cons,female
remove

Explanatory variables for response csework:
cons,female
remove

Use MVNormal update for beta?:
Yes
remove

Priors:
Uniform
remove

Choose estimation engine:
eStat
remove

Number of chains:
3
remove

Random Seed:
1
remove

Length of burnin:
500
remove

Number of iterations:
2000
remove

Thinning:
1
remove

Use default algorithm settings:
Yes
remove

Generate prediction dataset:
No
remove

Use default starting values:
Yes
remove

Impute at iterations:
1000, 2000
remove

Name of output results:
outmv

Next

Here we allow the two responses to both depend on one predictor female. Note that both responses contain missing values as there are some pupils with only a written score and some with only a coursework score. The missing values are given the value $-9.999\text{e}29$ and this value will be looked for in the *preccode* function. You will also note the extra input for imputing datasets. Here we will return datasets with the current values of missing data at the prescribed iteration numbers for each chain. Clicking on the **Next** button and looking at the model output, *equation.tex* in the output pane we see:

Stat-JR:TREE
Start again
Dataset ▾ gcsemv1
Template ▾ 1LevelMvNormal
eBook ▾
Ready (16)
Settings
About
Debug ▾

Edit
equation.tex
Popout

$$\begin{pmatrix} \text{written}_i \\ \text{csework}_i \end{pmatrix} \sim N \left[\begin{pmatrix} \mu_{0i} \\ \mu_{1i} \end{pmatrix}, \Omega_\theta \right]$$

$$\mu_{0i} = \beta_0 \text{cons}_i + \beta_1 \text{female}_i$$

$$\mu_{1i} = \beta_2 \text{cons}_i + \beta_3 \text{female}_i$$

$$\Omega_\theta \propto 1$$

$$\beta_0 \propto 1$$

$$\beta_1 \propto 1$$

$$\beta_2 \propto 1$$

$$\beta_3 \propto 1$$

If we select *model.txt* we can see the model code thus:

Stat-JR:TREE
Start again
Dataset ▾
gcsemv1
Template ▾
1LevelMVMNormal
eBook ▾
Ready (1s)
Settings
About
Debug ▾

Edit
model.txt
Popout

```

model {
  for (i in 1:length(written)) {

    dummy[i] ~ dnormal2a( misswritten[i], misscsework[i], mu0[i], mu1[i], d_e[0], d_e[1], d_e[2])
    mu0[i] <- cons[i] * beta_0 + female[i] * beta_1

    mu1[i] <- cons[i] * beta_2 + female[i] * beta_3

    misswritten[i] ~ dflat()
    misscsework[i] ~ dflat()
  }

  # Priors

  beta_0 ~ dflat()
  beta_1 ~ dflat()
  beta_2 ~ dflat()
  beta_3 ~ dflat()
}

```

Here we see again the use of the *dnormal2a* function and also that we have included *dflat* statements for both the *misswritten* and *misscsework* responses to let the algebra system know that these are parameters. We will not look in detail at the *model* method as we can see the output it produces on the screen.

There is a *preparedata* attribute that is used to set the length of the missing data vector to equal the original response vector:

```

preparedata = '''
mydata = data['datafile']
for i in range(0, len(y)):
    context['miss'+y[i]].ncols = -1*len(mydata.variables[y[i]]['data'])
'''

```

We next turn our attention to the *precode* function.

12.5 The precode function for this template

We will deal with the code here in chunks. We begin with a definition of the *mmult2* function that we will use to work out the linear predictors for each response. The *mmult2* function is specifically useful for multivariate response models as it contains a count parameter which informs us which element of beta to start with in the linear predictor:

```

precode = '''
<%!
def mmult2(names, var, index,count):
    out = ""
    first = True
    for name in names:
        if first == False:
            out += ' + '
        else:
            first = False
        out += 'double(' + name + '[' + index + ']) * ' + var + '_' +
str(count)
        count += 1
'''

```

```

        return out
    %>
    {
    <% n = len(y) %>\\

```

Next we have the code chunk for generating the step for the level 1 variance matrix. This is almost identical to the random slopes code except we need the crossproduct of the level 1 residuals e (instead of the higher level random effects u) and this needs constructing which is done in the initial code using the *mmult2* function:

```

        SymMatrix sb(${n});
        for(int i = 0; i < length(miss${y[0]}); i++) {
    <% lenbeta = 0 %>\\
    % for i in range(0, n):
        double e${i} = double(miss${y[i]}[i]) -
        (${mmult2(context['x' + str(i+1)], 'beta', 'i', lenbeta)});
    <% lenbeta += len(context['x' + str(i + 1)]) %>\\
    % endfor
    % for i in range(0, n):
    % for j in range(i, n):
        sb(${i}, ${j}) += e${i} * e${j};
    % endfor
    % endfor
    }

```

Once constructed the remainder of the code follows the same pattern as random slopes and so for brevity we omit this code here, it can be viewed in *1Level/MVNormal.py*.

The one thing we have not mentioned is how the missing data is updated and here this is currently done in a slightly undesirable way, and relies on the parameter name beginning with the character string *miss*. To see how this is done we once again have to delve deeper into the code. In the subdirectory of Stat-JR with path *src/lib/EStat/templates* you will find some of the files that are used in the code generation. The file *gibbsstep.cpp* contains the template that is used by Stat-JR to convert the step from the algebra system into C code and in here we can modify what precisely is written in the C code. You will notice a few statements that involve the “miss” prefix at the start and end of the code:

```

% if "miss" in theta:
<% temp = theta.replace('miss', '',1) %>
if (${temp} <= -9.999e29) {
% endif

```

and

```

% if "miss" in theta:
}
% endif

```

This code recognises the prefix “miss” in a variable name and places the condition statements around the update step for that parameter. There are also some more complicated reliance on various prefixes involving “mis” but these are primarily for the mixed response modelling which we do not discuss here. Basically for the case “miss” we have:

```

% if fn == "dnorm" and "mis" in theta:

```



```
% if ... (different other cases)
% elif "miss" in theta:
    ${theta} = ${expr};
% endif
% endif
```

which simply translates to equating the variable name of interest (*theta*) to the expression the algebra system gives for its posterior (*expr*). This reliance on the parameter name is undesirable and we will hopefully come up with a better method for making such algorithmic changes in later releases.

It would be good at this point to look at the code generated for this example. To do this choose *modelcode.cpp* from the object list and scroll down. Here we see the step for the variance matrix *omega_e* near the top of the code:

```
{
    // Note currently using a uniform prior for variance matrix
    SymMatrix sb(2);
    for(int i = 0; i < 1905; i++) {
        double e0 = double(misswritten[i]) - (double(cons[i]) *
beta_0 + double(female[i]) * beta_1);
        double e1 = double(misscsework[i]) - (double(cons[i]) *
beta_2 + double(female[i]) * beta_3);
        sb(0, 0) += e0 * e0;
        sb(0, 1) += e0 * e1;
        sb(1, 1) += e1 * e1;
    }
    if (runstate == 0) {
        sb(0, 0) += 0.0001;
        sb(1, 1) += 0.0001;
    }
    matrix_sym_invinplace(sb);
    int vw = 1905 - 3;
    bool fail = false;
    mat_d_e = dwishart(vw, sb, fail);
    mat_omega_e = matrix_sym_inverse(mat_d_e, fail);
}
```

and later on the steps for the missing data:

```
// Update misswritten
    for(unsigned int i=0; i<1905; i++){
// This code was generated by the Stat-JR package (copyright 2012
// University of Bristol and University of Southampton).
    {
        if (written[i] <= -9.999e29) {
            misswritten[i] =
dnorm(((cons[i]*beta_0)+(beta_1*female[i])+((d_e[1]*misscsework[i]*pow(d_e[
0], (-1.0)))*(-1.0)))+(d_e[1]*beta_2*pow(d_e[0], (-
1.0))*cons[i])+(d_e[1]*beta_3*female[i]*pow(d_e[0], (-1.0))))),d_e[0]);
        }
    }
}
// Update misscsework
    for(unsigned int i=0; i<1905; i++){
```

```
// This code was generated by the Stat-JR package (copyright 2012
University of Bristol and University of Southampton).
{
if (csework[i] <= -9.999e29) {
    misscsework[i] = dnorm((((d_e[1]*pow(d_e[2], (-
1.0))*misswritten[i))*(-1.0))+(d_e[1]*pow(d_e[2], (-
1.0))*beta_0*cons[i])+(d_e[1]*pow(d_e[2], (-
1.0))*beta_1*female[i])+(beta_2*cons[i])+(beta_3*female[i])),d_e[2]);
}
}
}
```

We can run the template by clicking on the **Run** button and choosing the **ModelResults** in the list we see:

Results Parameters:

parameter	mean	sd	ESS
deviance	30681.69985820675	29.734176776263	4366
beta_0	48.795008073984	0.493724189901	5384
beta_1	-3.431364887468	0.648549598813	5283
beta_2	69.820524428293	0.59656271344	5246
beta_3	5.910043847774	0.771859763322	5657
omega_e_0	177.0910237586032	6.012972299174	4809
omega_e_1	108.196610096192	5.901770071378	5179
omega_e_2	258.420338290875	8.834234822372	5089
d_e_0	0.00760169785297	0.000263327167839	4416
d_e_1	-0.00318301611484	0.000179923287534	4163
d_e_2	0.00520943129392	0.000182635751795	4172

Model:

Statistic	Value
Dbar	30681.69985820675
D(thetabar)	30292.250242305403
pD	389.449615901347
DIC	31071.149474108097

Note here we do not see the missing values as by default non-monitored nodes are not displayed in **ModelResults**. To view the missing values you would need to return to the **Settings** screen (from the main screen) and click on the tick box, under the **EStat** heading (*not* the CustomC heading), that allows you to **Include unmonitored values in results** and click on **Set** before setting up the model again. At present due to the number of nodes this takes a very long time in the browser so we do not advise you to try (although the .dta version of the output is faster) however if you do then eventually the screen will look as follows:

ModelResults Popout

Results

Parameters:

parameter	mean	sd	ESS
deviance	30681.69985820675	29.734176776263	4366
beta_0	48.795008073984	0.493724189901	5384
beta_1	-3.431364887468	0.648549598813	5283
beta_2	69.820524428293	0.59656271344	5246
beta_3	5.910043847774	0.771859763322	5657
omega_e_0	177.0910237586032	6.012972299174	4809
omega_e_1	108.196610096192	5.901770071378	5179
omega_e_2	258.420338290875	8.834234822372	5089
d_e_0	0.00760169785297	0.000263327167839	4416
d_e_1	-0.00318301611484	0.000179923287534	4163
d_e_2	0.00520943129392	0.000182635751795	4172
misswritten_0	23.75	0.0	
misswritten_1	43.597368430095	11.436358676938	
misswritten_2	39.375	0.0	
misswritten_3	36.875	0.0	
misswritten_4	16.875	0.0	
misswritten_5	36.25	0.0	
misswritten_6	49.375	0.0	
misswritten_7	25.0	0.0	
misswritten_8	33.105183660376	11.728282671877	

Here you will see that for the missing data variables the ones that correspond to actual data have standard deviation zero in the output as they shouldn't change from iteration to iteration so for example the first and third written scores were observed. We can also look at the values of these missing data at prescribed iterations/chains and so selecting `impute_datafile_chain0_iter1000` gives the following:

Stat-JR:TREE
Start again
Dataset
gcsemv1
Template
1LevelMVNormal
eBook
Ready (9s)
Settings
About
Debug

impute_datafile_chain0_iter1000
Popout

	school	student	female	agemths	written	csework	cons
1	20920	16	0	219	23.75	33.178677	1
2	20920	25	1	217	53.88549	71.296	1
3	20920	27	1	216	39.375	76.852	1
4	20920	31	1	201	36.875	87.963	1
5	20920	42	0	219	16.875	44.444	1
6	20920	62	1	202	36.25	85.321686	1
7	20920	101	1	197	49.375	89.815	1
8	20920	113	0	200	25.0	17.593	1
9	20920	146	0	203	28.576193	32.407	1
10	22520	1	1	218	48.75	84.259	1
11	22520	7	0	201	46.875	66.667	1
12	22520	9	1	198	28.125	47.222	1
13	22520	15	1	216	43.75	80.556	1
14	22520	16	0	218	29.375	57.407	1
15	22520	18	1	199	25.0	42.593	1
16	22520	21	0	202	30.625	36.111	1
17	22520	24	1	217	44.375	58.333	1
18	22520	25	0	199	30.625	37.963	1
19	22520	27	1	218	26.25	74.074	1
20	22520	29	0	197	30.625	41.667	1
21	22520	34	1	199	39.375	76.852	1
22	22520	37	1	216	41.25	34.259	1
23	22520	41	1	198	44.375	86.111	1
24	22520	42	0	196	36.25	56.481	1
25	22520	43	1	196	45.625	42.593	1
26	22520	45	1	219	41.25	63.889	1
27	22520	47	1	197	28.125	20.37	1

View 1 - 30 of 1,905

Here the second written test score has value 53.89, and the ninth written score is 28.58, while their means (in the earlier output) are 43.60 and 33.11 respectively across all iterations and chains. We have extended these multivariate normal modelling templates to more levels and to include random slopes. They also form the basis for the mixed response templates which allow other response types via the use of latent variables, mimicing and extending the functionality that exists in the REALCOM software program (Goldstein, Rasbash, Steele, & Charlton, 2007), and a number of these are called by Stat-JR multiple imputation templates such as 2LevelImpute. You will see that these templates are pretty big and involve coding in several languages (Python, WinBUGS model code, LaTeX and C++). It is hoped that with advances in the algebra system that the reliance on the *preccode* functions will reduce but if you want to look at the other multivariate templates you will see many similarities in the code in these functions. This is one of the plus points of the ability to view the code in the templates within the Stat-JR system.

We will finish this documentation by considering one more example of getting more from the MCMC estimation engine.

13 Out of sample predictions

Most of the statistical modelling templates we have thus far created are primarily being used for statistical inference. We might however be interested in using the model to predict future responses. The advantage of a simulation-based approach is that we can easily get confidence intervals about these predictors at the same time as we estimate the model. We do however have to be careful that we do not feedback the results of our predicting into the estimation part of the model. WinBUGS has a method to do this with its cut function and we have developed a similar method which we will demonstrate here.

13.1 The 1LevelOutSampPred template – using the zxfd trick

We will illustrate our approach on a 1 level model which we can fit using the *1LevelOutSampPred* template. We will firstly choose this template along with the *tutorial* dataset and then select the following inputs:

Dataset: *tutorial*; **Template:** *1LevelOutSampPred*; **Input string:** `{'nmiss': '10', 'burnin': '500', 'D': 'Normal', 'outdata': 'outpred', 'xm': 'cons,standlrt', 'thinning': '1', 'nchains': '3', 'defaultalg': 'Yes', 'iterations': '2000', 'y': 'normexam', 'x': 'cons,standlrt', 'makepred': 'No', 'seed': '1', 'defaultsv': 'Yes'}`

The screenshot shows the Stat-JR: TREE interface. At the top, there is a navigation bar with 'Stat-JR: TREE', 'Start again', 'Dataset - tutorial', 'Template - 1LevelOutSampPred', and 'eBook -'. On the right, there is a status bar with 'Idle', 'Settings', 'About', and 'Debug'. The main area is a configuration table with 12 rows. Each row has a label on the left and a value on the right, with a 'remove' link next to the value. The values are: normexam, Normal, cons,standlrt, cons,standlrt, 10, 3, 1, 500, 2000, 1, Yes, No, Yes. At the bottom, there is a text input field for 'Name of output results' containing 'outpred' and a yellow 'Next' button.

Response:	normexam	remove
Specify distribution:	Normal	remove
Explanatory variables:	cons,standlrt	remove
Missing explanatory variables:	cons,standlrt	remove
Number of missing:	10	remove
Number of chains:	3	remove
Random Seed:	1	remove
Length of burnin:	500	remove
Number of iterations:	2000	remove
Thinning:	1	remove
Use default algorithm settings:	Yes	remove
Generate prediction dataset:	No	remove
Use default starting values:	Yes	remove
Name of output results:	<input type="text" value="outpred"/>	

Next

To explain what is going on we are planning to fit a regression model to *normexam* with predictor *standlrt* as we have done previously using the *1LevelMod* template. We will then use the predictors given in 'missing explanatory variables' to predict the 10 individuals who in this case have the same scores as the first 10 in the model actually fit. Note if you want to predict other individuals you need to form new columns of the same length as the data although the values below the 'Number of

missing' row will be ignored. Clicking on the **Next** button and choosing *model.txt* gives the following output:

```

model{
  for (i in 1:length(normexam)) {
    normexam[i] ~ dnorm(mu[i], tau)
    mu[i] <- cons[i] * beta_0 + standlrt[i] * beta_1
  }
  for (j in 1:10) {
    mnormexam[j] ~ dnorm(mumiss[j], tau)
    mumiss[j] <- cons[j] * betazxfd_0 + standlrt[j] * betazxfd_1
    dummy[j] ~ ddummy(mnormexam[j])
  }
  # Priors
  beta_0 ~ dflat()
  beta_1 ~ dflat()
  tau ~ dgamma(0.001000, 0.001000)
  sigma <- 1 / sqrt(tau)
  sigma2 <- 1 / tau
}

```

Here you will notice that we have an additional j loop in the model code for the out-of-sample predictions which will be stored in *mnormexam*. There are two interesting parts to this code. Firstly the line

```
mumiss[j] <- cons[j] * betazxfd_0 + standlrt[j] * betazxfd_1
```

has the strange string *zxfd* placed in the middle of the two parameter names. This is our way of stopping the predictions from feeding back to the model parameter estimation (equivalent to performing the cut function in WinBUGS). Basically as the predictors in this line are not *beta0* and *beta1* then this line will not influence the posteriors for the fixed effects. The posterior for *mnormexam* will be calculated but this is only because we include the line

```
dummy[j] ~ ddummy(mnormexam[j])
```

so that *mnormexam* appears on both the left and right hand side within the model code to differentiate it from data. The algebra system will formulate the posterior which will depend on *betazxfd0* and *betazxfd1*. Of course in practice we want these replaced by the correct *beta0* and *beta1* and this is done in the bowels of the code generator with the lines:

```

elif type == 'variable':
    result=l['name'].replace('.', '_').replace('zxfd','')

```

which is in code that is not currently available to view by the user. If we run the template we get the following output for *ModelResults*:

Stat-JR:TREE
Start again
Dataset
tutorial
Template
1LevelOutSampPred
eBook
Ready (8s)
Settings
About
Debug

ModelResults
Popout

Results

Parameters:

parameter	mean	sd	ESS	variable
tau	1.541467819601	0.0341823158931	5914	
deviance	0.1	0.77555756156e-17	5997	
mnormexam_0	0.35699487103	0.802028748875	5849	
mnormexam_1	0.106670715629	0.79973678697	6045	
mnormexam_2	-0.813028277704	0.815469762172	6592	
mnormexam_3	0.116898900322	0.80098530988	5296	
mnormexam_4	0.224305830587	0.802395087757	5672	
mnormexam_5	1.302085049305	0.814557118592	5644	
mnormexam_6	-0.678199036527	0.807525224432	6220	
mnormexam_7	-0.611135137603	0.797084227086	6611	
mnormexam_8	-0.329770473016	0.818625525329	6305	
mnormexam_9	-0.875352636264	0.804207074955	6343	
beta_0	-0.00106010282763	0.0126049730013	6385	cons
beta_1	0.594987849173	0.0126520001441	5877	standlirt
sigma	0.805587678841	0.0089293989058	5907	
sigma2	0.649051242466	0.0143890566484	5905	

Model:

Statistic	Value
-----------	-------

Here you can see that the out of sample predictions, *mnormexam* have been estimated with standard errors. We do not get a DIC diagnostic here as this would include the missing data and be a little misleading. We have recently incorporated the ability to use additional datasets in a template and we may in the future update this template to allow the data to be predicted to be in a different dataset. We hope that this and other templates give you a flavour of the possibilities that are available in the Stat-JR package. The package is still evolving and so we very much welcome feedback and suggestions for improvement. We also encourage you to send us your own templates for inclusion with the software.

13.1.1 Exercise 11

Try modifying the *regression1* template to allow for out of sample predictions. Call the new template *regression1pred*.

14 References

- SAS Institute Inc. (2011). Base SAS® 9.3 Procedures Guide. Cary, NC.
- Barry, J., Francis, B., & Davies, R. (1989). SABRE: Software for the Analysis of Binary Recurrent Events. *Decarli A., Francis B.J., Gilchrist R., Seeber G.U.H. (eds) Statistical Modelling. Lecture Notes in Statistics*, 57.
- Browne, W. (2016). *MCMC Estimation in MLwiN*, v2.36. Centre for Multilevel Modelling, University of Bristol.
- Browne, W., Steele, F., Golalizadeh, M., & Green, M. (2009). The use of simple reparameterizations to improve the efficiency of Markov chain Monte Carlo estimation for multilevel models with applications to discrete time survival models. *Journal of Royal Statistical Society, Series A*(172), 579-598.
- Cervone, D., Sorge, V., Lawson-Perfect, C., & Krautzberger, P. (2017). MathJax version 2.7.2. MathJax.
- Charlton, C., Rasbash, J., Browne, W., Healy, M., & Cameron, B. (2017). MLwiN Version 3.00. Centre for Multilevel Modelling.
- Cottrell, A., & Lucchetti, R. (2007). Gretl User's Guide.
- de Valpine, P., Paciorek, C., Turek, D., Anderson-Bergman, C., & Temple Lang, D. (2016). nimble: Flexible BUGS-Compatible System for Hierarchical Statistical Modeling and Algorithm Development. R package version 0.5. <http://r-nimble.org>.
- Free Software Foundation. (2017). GNU PSPP (Version 1.0.1). Boston, MA: GNU Project.
- Goldstein, H., Rasbash, J., Steele, F., & Charlton, C. (2007). REALCOM: Methodology for realistically complex multilevel modelling. Centre for Multilevel Modelling.
- Goldstein, H., Rasbash, J., Yang, M., Pan, H., Nuttall, D., & Thomas, S. (1993). A multilevel analysis of school examination results. *Oxford Review of Education*(19), 425–433.
- Hadfield, J. (2010). MCMC Methods for Multi-Response Generalized Linear Mixed Models: The MCMCglmm R Package. *Journal of Statistical Software*(33(2)), 1-22.
- Hastings, W. (1970). Monte Carlo Sampling Methods Using Markov Chains and Their Applications. *Biometrika*, 1(57), 97–109.
- Hetland, M. (2005). *Beginning Python: From Novice to Professional*. New York: Springer-Verlag.
- IBM Corp. (2017). IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY.
- Kahan, W. (1965). Further Remarks On Reducing Truncation Errors. *Communications of the ACM*, 1(8), 40.
- Lunn, D., Spiegelhalter, D., Thomas, A., & Best, N. (2009). The BUGS project: Evolution, critique, and future directions. *Statistics in Medicine*(28), 3049-3067.

- Lunn, D., Thomas, A., Best, N., & Spiegelhalter, D. (2000). WinBUGS - a Bayesian modelling framework: concepts, structure, and extensibility. *Statistics and Computing*(10), 325--337.
- Lutz, M., & Ascher, D. (2005). *Learning Python, Second Edition*. Sebastopol, CA: O'Reilly Media.
- Minitab, Inc. . (2017). Minitab 18 Statistical Software . State College, PA.
- Paterson, L. (1991). Socio economic status and educational attainment: a multidimensional and multilevel study. *Evaluation and Research in Education*(5), 97-121.
- Plummer, M. (2003). JAGS: A Program for Analysis of Bayesian Graphical Models Using Gibbs Sampling. *Proceedings of the 3rd International Workshop on Distributed Statistical Computing (DSC 2003)*. Vienna, Austria.
- R Core Team. (2016). A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing.
- Rasbash, J., Steele, F., Browne, W., & Goldstein, H. (2012). *A User's Guide to MLwiN*. Centre for Multilevel Modelling,.
- Rossum, G. v. (n.d.). The Python Language Reference. Python Software Foundation.
- Salvatier, J., Wiecki, T., & Fonnesbeck, C. (2016). Probabilistic programming in Python using PyMC3. *PeerJ Computer Science* 2:e55.
- Sarkar, D. (2008). *Lattice: Multivariate Data Visualization with R*. New York: Springer.
- StataCorp. (2017). Stata Statistical Software: Release 15. College Station, TX: StataCorp LLC.
- Stroustrup, B. (2013). *The C++ Programming Language*. Addison-Wesley Professional.
- The MathWorks, Inc. (2017). MATLAB and Statistics Toolbox Release 2017b. Natick, Massachusetts.
- VSN International. (2015). Genstat for Windows 18th Edition. Hemel Hempstead: VSN International.