

# Bayesian Modeling, Inference and Prediction

## 4: Integer-Valued Outcomes; Poisson Modeling

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**Short Course (Day 1)  
University of Reading (UK)**

27 Nov 2013

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## 4 Integer-Valued Outcomes

**Case Study:** *Hospital length of stay for birth of premature babies.* As a small part of a study I worked on at the Rand Corporation in the late 1980s, we obtained data on a random sample of  $n = 14$  women who came to a hospital in Santa Monica, CA, in 1988 to **give birth to premature babies.**

One (integer-valued) outcome of interest was  
 $y = \text{length of hospital stay (LOS)}$ .

Here's a preliminary look at the data in the excellent **freeware statistical package** R (see <http://www.r-project.org/> for more details and instructions on how to **download** the package).

```
rosalind 77> R
```

```
R : Copyright 2001, The R Development Core Team  
Version 1.2.1 (2001-01-15)
```

```
R is free software and comes with ABSOLUTELY NO WARRANTY.  
You are welcome to redistribute it under certain conditions.  
Type 'license()' or 'licence()' for distribution details.
```

```
R is a collaborative project with many contributors.  
Type 'contributors()' for more information.
```

```
Type 'demo()' for some demos, 'help()' for on-line help, or  
'help.start()' for a HTML browser interface to help.  
Type 'q()' to quit R.
```

```
[Previously saved workspace restored]
```

```
> y
```

```
[1] 1 2 1 1 1 2 2 4 3 6 2 1 3 0
```

```
> sort( y )
```

```
[1] 0 1 1 1 1 1 2 2 2 2 3 3 4 6
```

```
> table( y )
```

```
0 1 2 3 4 6  
1 5 4 2 1 1
```

# 4.1 Poisson Modeling

```
> stem( y, scale = 2 )
```

```
The decimal point is at the |
```

```
0 | 0
1 | 00000
2 | 0000
3 | 00
4 | 0
5 |
6 | 0
```

```
> mean( y )
```

```
[1] 2.071429
```

```
> sqrt( var( y ) )
```

```
[1] 1.54244
```

```
> q( )
```

```
Save workspace image? [y/n/c]: y
rosalind 1777>
```

One possible model for non-negative integer-valued outcomes is the **Poisson distribution**

$$P(Y_i = y_i) = \left\{ \begin{array}{ll} \frac{\lambda^{y_i} e^{-\lambda}}{y_i!} & \text{for } y_i = 0, 1, \dots \\ 0 & \text{otherwise} \end{array} \right\}, \quad (1)$$

for some  $\lambda > 0$ .

As usual Maple can be used to work out the **mean** and **variance** of this distribution:

```
rosalind 78> maple
```

```
  |^/|      Maple V Release 5 (University of California, Santa Cruz)
._|_|_|_|_|/|_|_ Copyright (c) 1981-1997 by Waterloo Maple Inc. All rights
 \ MAPLE / reserved. Maple and Maple V are registered trademarks of
 <-----> Waterloo Maple Inc.
  |      Type ? for help.
```

# Poisson Modeling (continued)

```
> assume( lambda > 0 );
```

```
> p := ( y, lambda ) -> lambda^y * exp( - lambda ) / y!;
```

$$p := (y, \lambda) \rightarrow \frac{\lambda^y \exp(-\lambda)}{y!}$$

```
> simplify( sum( p( y, lambda ), y = 0 .. infinity ) );
```

1

```
> simplify( sum( y * p( y, lambda ), y = 0 .. infinity ) );
```

$\lambda$

```
> simplify( sum( ( y - lambda )^2 * p( y, lambda ),  
  y = 0 .. infinity ) );
```

$\lambda$

**Thus** if  $Y \sim \text{Poisson}(\lambda)$ ,  $E(Y) = V(Y) = \lambda$ , which people sometimes express by saying that the **variance-to-mean ratio** (VTMR) for the Poisson is 1.

R can be used to check informally whether the Poisson is a **good fit** to the LOS data:

```
rosalind 77> R
```

```
R : Copyright 2001, The R Development Core Team  
Version 1.2.1 (2001-01-15)
```

```
> dpois( 0:7, mean( y ) )
```

```
[1] 0.126005645 0.261011693 0.270333539 0.186658872 0.096662630  
[6] 0.040045947 0.013825386 0.004091186
```

```
> print( n <- length( y ) )
```

```
[1] 14
```

```
> table( y ) / n
```

```
      0      1      2      3      4      6  
0.07142857 0.35714286 0.28571429 0.14285714 0.07142857 0.07142857
```

## Poisson Modeling (continued)

```
> cbind( c( dpois( 0:6, mean( y ) ),  
          1 - sum( dpois( 0:6, mean( y ) ) ) ),  
        apply( outer( y, 0:7, '==' ), 2, sum ) / n )
```

```
          [,1]      [,2]  
[1,] 0.126005645 0.07142857  
[2,] 0.261011693 0.35714286  
[3,] 0.270333539 0.28571429  
[4,] 0.186658872 0.14285714  
[5,] 0.096662630 0.07142857  
[6,] 0.040045947 0.00000000  
[7,] 0.013825386 0.07142857  
[8,] 0.005456286 0.00000000
```

The second column in the above table records the values of the **Poisson probabilities** for  $\lambda = 2.07$ , the mean of the  $y_i$ , and the third column is the **empirical relative frequencies**; informally the fit is reasonably good.

Another **informal check** comes from the fact that the sample mean and variance are 2.07 and  $1.542^2 \doteq 2.38$ , which are reasonably close.

**Exchangeability.** As with the AMI mortality case study, before the data arrive I recognize that my uncertainty about the  $Y_i$  is exchangeable, and you would expect from a generalization of the binary-outcomes version of de Finetti's Theorem that the structure of a **plausible Bayesian model** for the data might then be

$$\begin{aligned} \theta &\sim p(\theta) && \text{(prior)} && (2) \\ (Y_i|\theta) &\stackrel{\text{IID}}{\sim} F(\theta) && \text{(likelihood),} \end{aligned}$$

where  $\theta$  is some parameter (vector) and  $F(\theta)$  is some **family of distributions** on the non-negative integers indexed by  $\theta$ .

# Poisson Modeling (continued)

Thus, in view of the preliminary examination of the data above, a **plausible Bayesian model** for these data is

$$\begin{aligned}\lambda &\sim p(\lambda) && \text{(prior)} \\ (Y_i|\lambda) &\stackrel{\text{IID}}{\sim} \text{Poisson}(\lambda) && \text{(likelihood),} \\ &\text{where } \lambda \text{ is a } \mathbf{positive\ real\ number.}\end{aligned}\tag{3}$$

**NB** (1) This approach to model-building involves a form of **cheating**, because we've **used the data twice**: once to choose the model, and again to draw conclusions conditional on the chosen model.

The result is a failure to **assess** and **propagate model uncertainty** (e.g., Draper 1995).

(2) **Frequentist** modeling often employs this **same kind of cheating** in specifying the likelihood function.

(3) There are two Bayesian ways out of this dilemma: **cross-validation** and **Bayesian nonparametric/semi-parametric** methods (I'll have more to say about both in this course).

To get more practice with Bayesian calculations I'm going to **ignore the model uncertainty problem for now** and pretend that somehow we knew that the Poisson was a good choice.

**The likelihood function** in model (3) is

$$\begin{aligned}l(\lambda|y) &= c p_{Y_1, \dots, Y_n}(y_1, \dots, y_n|\lambda) \\ &= c \prod_{i=1}^n p_{Y_i}(y_i|\lambda) \\ &= c \prod_{i=1}^n \frac{\lambda^{y_i} e^{-\lambda}}{y_i!} \\ &= c \lambda^s e^{-n\lambda},\end{aligned}\tag{4}$$

# The Conjugate Prior

where  $y = (y_1, \dots, y_n)$  and  $s = \sum_{i=1}^n y_i$ ; here  $(\prod_{i=1}^n y_i!)^{-1}$  can be **ignored** because it doesn't involve  $\lambda$ .

Thus (as was true in the Bernoulli model)  $s = \sum_{i=1}^n y_i$  is **sufficient** for  $\lambda$  in the Poisson model, and we can write  $l(\lambda|s)$  instead of  $l(\lambda|y)$  if we want.

If a **conjugate** prior  $p(\lambda)$  for  $\lambda$  exists it must be such that the product  $p(\lambda)l(\lambda|s)$  has the same mathematical form as  $p(\lambda)$ .

Examination of (4) reveals that the same trick works here as with Bernoulli data, namely taking the **prior to be of the same form as the likelihood**:

$$p(\lambda) = c \lambda^{\alpha-1} e^{-\beta\lambda} \quad (5)$$

for some  $\alpha > 0, \beta > 0$ —this is the **Gamma** distribution  $\lambda \sim \Gamma(\alpha, \beta)$  for  $\lambda > 0$  (see Gelman et al. Appendix A).

As usual Maple can work out the **normalizing constant**:

```
rosalind 80> maple
```

```
 |^/|      Maple V Release 5 (University of California, Santa Cruz)
._|\\    |/|_. Copyright (c) 1981-1997 by Waterloo Maple Inc. All rights
 \ MAPLE / reserved. Maple and Maple V are registered trademarks of
 <____ >  Waterloo Maple Inc.
 |      Type ? for help.
```

```
> assume( lambda > 0, alpha > 0, beta > 0 );
```

```
> p1 := ( lambda, alpha, beta ) -> lambda^( alpha - 1 ) *
      exp( - beta * lambda );
```

```
                                (alpha - 1)
p1 := (lambda, alpha, beta) -> lambda      exp(-beta lambda)
```

```
> simplify( integrate( p1( lambda, alpha, beta ),
      lambda = 0 .. infinity ) );
```

```
                                (-alpha~)
beta~      GAMMA(alpha~)
```

# The Gamma Distribution

Thus  $c^{-1} = \beta^{-\alpha} \Gamma(\alpha)$  and the **proper definition** of the Gamma distribution is

$$\text{If } \lambda \sim \Gamma(\alpha, \beta) \text{ then } p(\lambda) = \frac{\beta^\alpha}{\Gamma(\alpha)} \lambda^{\alpha-1} e^{-\beta \lambda} \quad (6)$$

for  $\alpha > 0, \beta > 0$ .

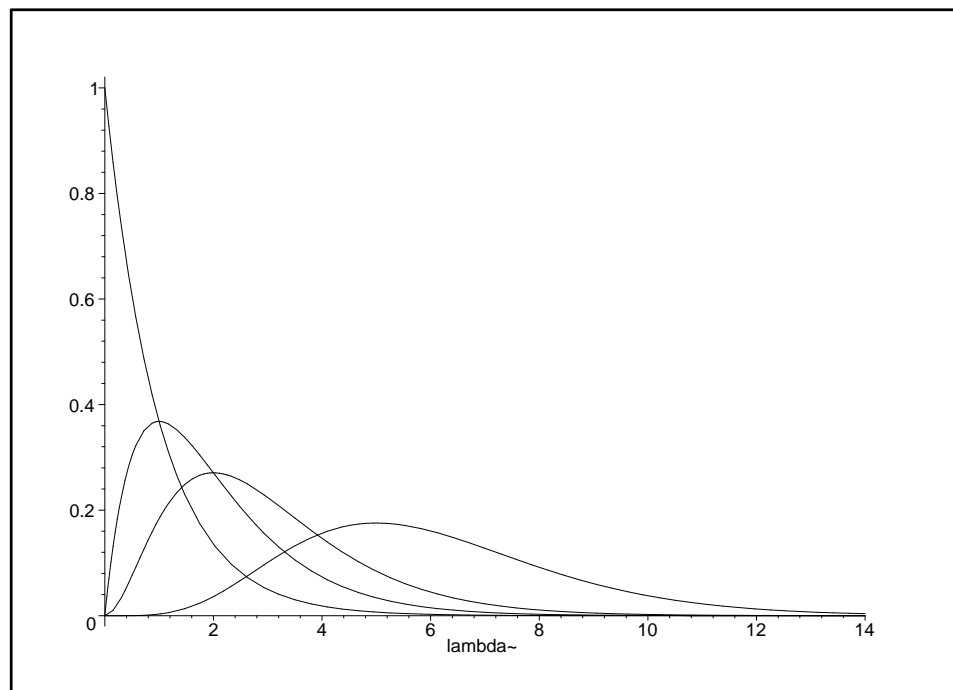
As usual Maple can be used to explore the behavior of this family of distributions **as a function of its inputs**  $\alpha$  and  $\beta$ :

```
> p := ( lambda, alpha, beta ) -> beta^alpha * lambda^( alpha - 1 ) *
    exp( - beta * lambda ) / GAMMA( alpha );

p := (lambda, alpha, beta) -> -----
                                alpha      (alpha - 1)
                                beta      lambda      exp(-beta lambda)
                                -----
                                GAMMA(alpha)

> plotsetup( x11 );

> plot( { p( lambda, 1, 1 ), p( lambda, 2, 1 ), p( lambda, 3, 1 ),
    p( lambda, 6, 1 ) }, lambda = 0 .. 14, color = black );
```



$\alpha$  evidently controls the **shape** of the Gamma family.

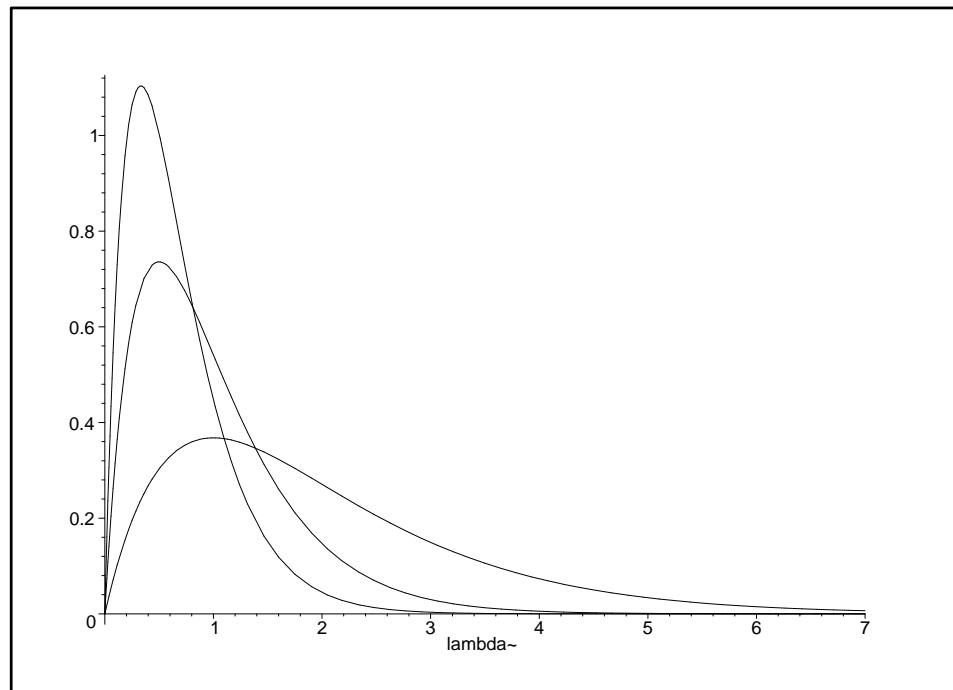


# Gamma Distribution (continued)

When  $\alpha = 1$  the Gamma distributions have a special form which you'll probably recognize—they're the **exponential** distributions  $\mathcal{E}(\beta)$ : for  $\beta > 0$

$$\text{If } \lambda \sim \mathcal{E}(\beta) \text{ then } p(\lambda) = \left\{ \begin{array}{ll} \beta e^{-\beta \lambda} & \text{for } \lambda > 0 \\ 0 & \text{otherwise} \end{array} \right\}. \quad (7)$$

```
> plot( { p( lambda, 2, 1 ), p( lambda, 2, 2 ), p( lambda, 2, 3 ) },  
        lambda = 0 .. 7, color = black );
```



In the Gamma family the parameter  $\beta$  controls the **spread** or **scale** of the distribution.

**Definition** Given a random quantity  $y$  whose density  $p(y|\sigma)$  depends on a parameter  $\sigma > 0$ , if it's possible to express  $p(y|\sigma)$  in the form  $\frac{1}{\sigma} f\left(\frac{y}{\sigma}\right)$ , where  $f(\cdot)$  is a function which does not depend on  $y$  or  $\sigma$ , then  $\sigma$  is called a **scale** parameter for the parametric family  $p$ .

# Gamma Distribution (continued)

Letting  $f(t) = e^{-t}$  and taking  $\sigma = \frac{1}{\beta}$ , you can see that the Gamma family can be expressed in this way, so  $\frac{1}{\beta}$  is a **scale parameter** for the Gamma distribution.

As usual Maple can also work out the **mean** and **variance** of this family:

```
> simplify( integrate( p( lambda, alpha, beta ),  
    lambda = 0 .. infinity ) );
```

1

```
> simplify( integrate( lambda * p( lambda, alpha, beta ),  
    lambda = 0 .. infinity ) );
```

$\frac{\alpha}{\beta}$

```
> simplify( integrate( ( lambda - alpha / beta )^2 *  
    p( lambda, alpha, beta ), lambda = 0 .. infinity ) );
```

$\frac{\alpha}{\beta^2}$

Thus if  $\lambda \sim \Gamma(\alpha, \beta)$  then  $E(\lambda) = \frac{\alpha}{\beta}$  and  $V(\lambda) = \frac{\alpha}{\beta^2}$ .

**Conjugate updating** is now **straightforward**: with  $y = (y_1, \dots, y_n)$  and  $s = \sum_{i=1}^n y_i$ , by Bayes' Theorem

$$\begin{aligned} p(\lambda|y) &= c p(\lambda) l(\lambda|y) \\ &= c (c \lambda^{\alpha-1} e^{-\beta\lambda}) (c \lambda^s e^{-n\lambda}) \\ &= c \lambda^{(\alpha+s)-1} e^{-(\beta+n)\lambda}, \end{aligned} \tag{8}$$

and the **resulting distribution** is just  $\Gamma(\alpha + s, \beta + n)$ .

# Conjugate Poisson Analysis

This can be **summarized** as follows:

$$\left\{ \begin{array}{l} (\lambda|\alpha, \beta) \sim \Gamma(\alpha, \beta) \\ (Y_i|\lambda) \stackrel{\text{IID}}{\sim} \text{Poisson}(\lambda), \\ i = 1, \dots, n \end{array} \right\} \rightarrow (\lambda|s) \sim \Gamma(\alpha^*, \beta^*), \quad (9)$$

where  $(\alpha^*, \beta^*) = (\alpha + s, \beta + n)$  and  $s = \sum_{i=1}^n y_i$  is a **sufficient statistic** for  $\lambda$  in this model.

The posterior mean of  $\lambda$  here is evidently  $\frac{\alpha^*}{\beta^*} = \frac{\alpha+s}{\beta+n}$ , and the prior and data means are  $\frac{\alpha}{\beta}$  and  $\bar{y} = \frac{s}{n}$ , so (as was the case in the Bernoulli model) the posterior mean can be written as a **weighted average** of the prior and data means:

$$\frac{\alpha + s}{\beta + n} = \left( \frac{\beta}{\beta + n} \right) \left( \frac{\alpha}{\beta} \right) + \left( \frac{n}{\beta + n} \right) \left( \frac{s}{n} \right). \quad (10)$$

Thus the **prior sample size**  $n_0$  in this model is just  $\beta$  (which makes sense given that  $\frac{1}{\beta}$  is the scale parameter for the Gamma distribution), and the prior acts like a **dataset** consisting of  $\beta$  observations with mean  $\frac{\alpha}{\beta}$ .

**LOS data analysis.** Suppose that, before the current data set is scheduled to arrive, I know **little** about the mean length of hospital stay of women giving birth to premature babies.

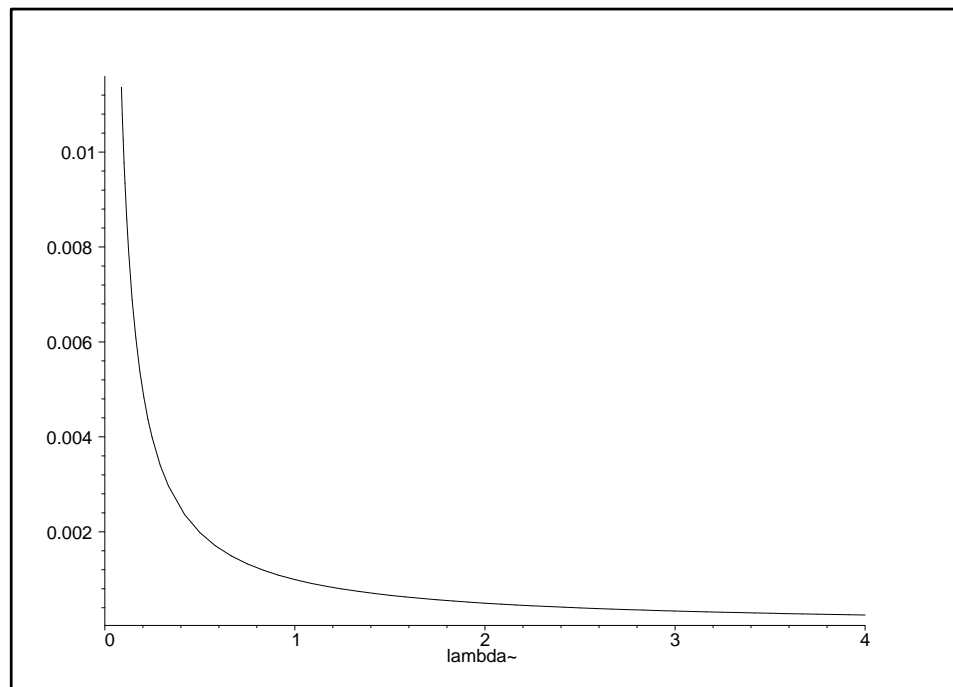
Then for my prior on  $\lambda$  I'd like to specify a member of the  $\Gamma(\alpha, \beta)$  family which is relatively **flat in the region in which the likelihood function is appreciable**.

# The $\Gamma(\epsilon, \epsilon)$ Prior

A **convenient** and **fairly all-purpose default choice** of this type is  $\Gamma(\epsilon, \epsilon)$  for some small  $\epsilon$  like 0.001.

When used as a prior this distribution has **prior sample size**  $\epsilon$ ; it also has mean 1, but that usually doesn't matter when  $\epsilon$  is **tiny**.

```
> plot( p( lambda, 0.001, 0.001 ), lambda = 0 .. 4, color = black );
```



With the LOS data  $s = 29$  and  $n = 14$ , so the **likelihood** for  $\lambda$  is like a  $\Gamma(30, 14)$  density, which has mean  $\frac{30}{14} \doteq 2.14$  and

$$\text{SD } \sqrt{\frac{30}{14^2}} \doteq 0.39.$$

Thus by the **Empirical Rule** the likelihood is appreciable in the range  $(\text{mean} \pm 3\text{SD}) \doteq (2.14 \pm 1.17) \doteq (1.0, 3.3)$ , and you can see from the plot above that the prior is indeed **relatively flat** in this region.

From the **Bayesian updating** in (9), with a  $\Gamma(0.001, 0.001)$  prior the **posterior** is  $\Gamma(29.001, 14.001)$ .

# LOS Data Analysis

It's useful, in summarizing the **updating** from prior through likelihood to posterior, to make a table that records measures of **center** and **spread** at each point along the way.

For example, the  $\Gamma(0.001, 0.001)$  **prior**, when regarded (as usual) as a **density** for  $\lambda$ , has mean 1.000 and SD  $\sqrt{1000} \doteq 31.6$  (i.e., informally, as far as we're concerned, before the data arrive  $\lambda$  could be **anywhere between 0 and (say) 100**).

And the  $\Gamma(29.001, 14.001)$  **posterior** has mean  $\frac{29.001}{14.001} \doteq 2.071$  and SD  $\sqrt{\frac{29.001}{14.001^2}} \doteq 0.385$ , so after the data have arrived we know **quite a bit more than before**.

There are two main ways to summarize the **likelihood**—Fisher's approach based on **maximizing** it, and the Bayesian approach based on regarding it as a density and **integrating** it—and it's instructive to compute them both and **compare**.

The **likelihood-integrating** approach (which is actually equivalent to another of Fisher's ideas: **fiducial** inference) treats the  $\Gamma(30, 14)$  likelihood as a density for  $\lambda$ , with mean

$$\frac{30}{14} \doteq 2.143 \text{ and SD } \sqrt{\frac{30}{14^2}} \doteq 0.391.$$

As for the **likelihood-maximizing** approach, from (4) the log likelihood function is

$$ll(\lambda|y) = ll(\lambda|s) = \log(c \lambda^s e^{-n\lambda}) = c + s \log \lambda - n\lambda, \quad (11)$$

and this is **maximized** as usual (check that it's the max) by setting the **derivative** equal to 0 and solving:

$$\frac{\partial}{\partial \lambda} ll(\lambda|s) = \frac{s}{\lambda} - n = 0 \quad \text{iff} \quad \lambda = \hat{\lambda}_{\text{MLE}} = \frac{s}{n} = \bar{y}. \quad (12)$$

## LOS Analysis (continued)

Since the MLE  $\hat{\lambda}_{MLE}$  turns out to be our old friend the **sample mean**  $\bar{y}$ , you might be tempted to conclude immediately that  $\widehat{SE}(\hat{\lambda}_{MLE}) = \frac{\hat{\sigma}}{\sqrt{n}}$ , where  $\hat{\sigma} = 1.54$  is the sample SD, and indeed it's true in repeated sampling that  $V(\bar{Y}) = \frac{V(Y_1)}{n}$ ; but the **Poisson distribution** has variance  $V(Y_1) = \lambda$ , so that  $\sqrt{V(\bar{Y})} = \frac{\sqrt{\lambda}}{\sqrt{n}}$ , and there's no guarantee in the Poisson model that the best way to estimate  $\sqrt{\lambda}$  in this standard error calculation is with the sample SD  $\hat{\sigma}$  (in fact we have a **strong hint** from the above MLE calculation that the sample variance is **irrelevant** to the estimation of  $\lambda$  in the Poisson model).

The right (large-sample) likelihood-based **standard error** for  $\hat{\lambda}_{MLE}$ , using the **Fisher information** logic we examined earlier, is obtained from the following calculation:

$$\begin{aligned} \frac{\partial^2}{\partial \lambda^2} \log l(\lambda|y) &= -\frac{s}{\lambda^2}, \quad \text{so} & (13) \\ \hat{I}(\hat{\lambda}_{MLE}) &= \left[ -\frac{\partial^2}{\partial \lambda^2} \log l(\lambda|y) \right]_{\lambda=\hat{\lambda}_{MLE}} \\ &= \left( \frac{s}{\lambda^2} \right)_{\lambda=\bar{y}} = \frac{s}{\bar{y}^2} = \frac{n}{\bar{y}}, \quad \text{and} \\ \hat{V}(\hat{\lambda}_{MLE}) &= \hat{I}^{-1}(\hat{\lambda}_{MLE}) = \frac{\bar{y}}{n} = \frac{\hat{\lambda}_{MLE}}{n}. \end{aligned}$$

So in this case study Fisher's **likelihood-maximizing** approach would **estimate**  $\lambda$  by  $\hat{\lambda}_{MLE} = \bar{y} = \frac{29}{14} \doteq 2.071$ , with a **give-or-take** of  $\widehat{SE}(\hat{\lambda}_{MLE}) = \frac{\sqrt{\hat{\lambda}_{MLE}}}{\sqrt{n}} = \frac{1.44}{\sqrt{14}} \doteq 0.385$ .

# LOS Analysis (continued)

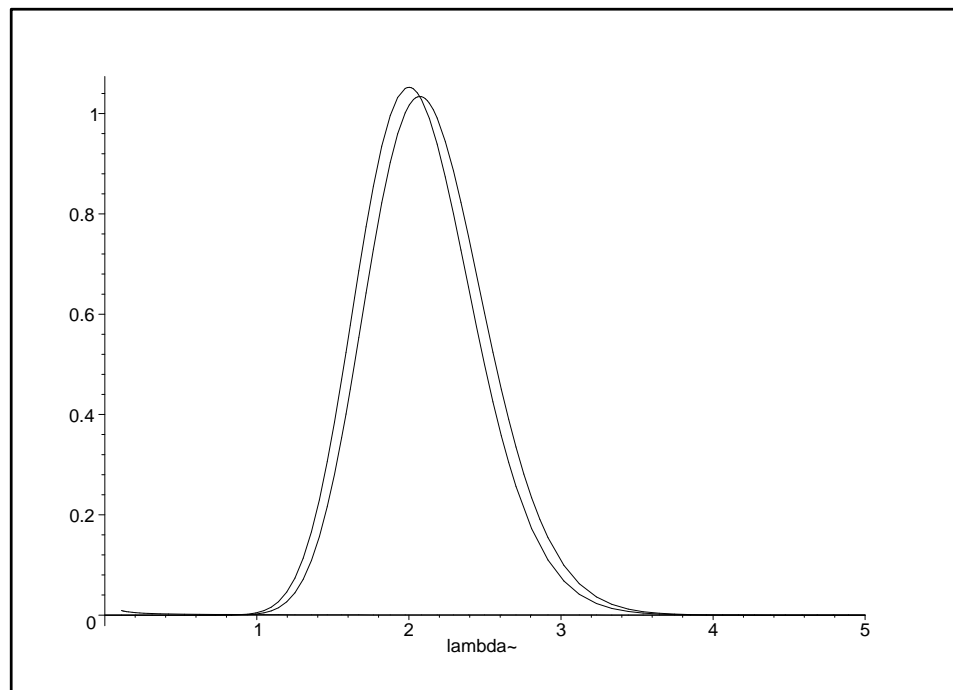
All of this may be **summarized** in the following table:

	Prior	Likelihood		Posterior
		Maximizing	Integrating	
Mean/Estimate	1.00	2.071	2.143	2.071
SD/SE	31.6	0.385	0.391	0.385

The **discrepancies** between the likelihood-maximizing and likelihood-integrating columns in this table would be smaller with a larger sample size and would **tend to 0** as  $n \rightarrow \infty$ .

The **prior-likelihood-posterior plot** comes out like this:

```
> plot( { p( lambda, 0.001, 0.001 ), p( lambda, 30, 14 ),  
        p( lambda, 29.001, 14.001 ) }, lambda = 0 .. 5, color = black );
```



# LOS Analysis (continued)

For **interval estimation** in the maximum-likelihood approach the best we could do, using the technology I've described to you so far, would be to appeal to the **CLT** (even though  $n$  is only 14) and use  $\hat{\lambda}_{MLE} \pm 1.96 \widehat{SE}(\hat{\lambda}_{MLE}) \doteq 2.071 \pm (1.96)(0.385) \doteq (1.316, 2.826)$  as an **approximate 95% confidence interval** for  $\lambda$ .

You can see from the previous plot that the likelihood function is **skewed**, so a more careful method (e.g., the **bootstrap**; Efron 1979) would be needed to create a better interval estimate from the likelihood point of view.

Some trial and error with Maple can be used to find the lower and upper limits of the **central 95% posterior interval** for  $\lambda$ :

```
> evalf( Int( p( lambda, 29.001, 14.001 ), lambda = 0 .. 1.316 ) );  
                                .01365067305  
> evalf( Int( p( lambda, 29.001, 14.001 ), lambda = 0 .. 1.4 ) );  
                                .02764660367  
> evalf( Int( p( lambda, 29.001, 14.001 ), lambda = 0 .. 1.387 ) );  
                                .02495470339  
> evalf( Int( p( lambda, 29.001, 14.001 ), lambda = 2.826 .. infinity ) );  
                                .03403487851  
> evalf( Int( p( lambda, 29.001, 14.001 ), lambda = 2.890 .. 5 ) );  
                                .02505306648  
> evalf( Int( p( lambda, 29.001, 14.001 ),  
            lambda = 2.890 .. infinity ) );  
                                .02505307631
```



# LOS Analysis (continued)

Thus a **95% (central) posterior interval** for  $\lambda$ , given a diffuse prior, runs from **1.387** to **2.890**, and is (correctly) **asymmetric** around the posterior mean of 2.071.

R can be used to work out the **limits of this interval** even more readily:

```
> help( qgamma )
```

```
GammaDist
```

```
package:base
```

```
R Documentation
```

```
The Gamma Distribution
```

```
Description:
```

```
Density, distribution function, quantile function and random generation for the Gamma distribution with parameters 'shape' and 'scale'.
```

```
Usage:
```

```
dgamma(x, shape, scale=1, log = FALSE)
pgamma(q, shape, scale=1, lower.tail = TRUE, log.p = FALSE)
qgamma(p, shape, scale=1, lower.tail = TRUE, log.p = FALSE)
rgamma(n, shape, scale=1)
```

```
Arguments:
```

```
x, q: vector of quantiles.
```

```
p: vector of probabilities.
```

```
n: number of observations.
```

```
shape, scale: shape and scale parameters.
```

```
log, log.p: logical; if TRUE, probabilities p are given as log(p).
```

```
lower.tail: logical; if TRUE (default), probabilities are P[X <= x], otherwise, P[X > x].
```

# LOS Analysis (continued)

Details:

If 'scale' is omitted, it assumes the default value of '1'.

The Gamma distribution with parameters 'shape' = a and 'scale' = s has density

$$f(x) = 1/(s^a \Gamma(a)) x^{(a-1)} e^{-(x/s)}$$

for  $x > 0$ ,  $a > 0$  and  $s > 0$ . The mean and variance are  $E(X) = a*s$  and  $\text{Var}(X) = a*s^2$ .

Value:

'dgamma' gives the density, 'pgamma' gives the distribution function 'qgamma' gives the quantile function, and 'rgamma' generates random deviates.

Note:

The cumulative hazard  $H(t) = -\log(1 - F(t))$  is '-pgamma(t, ..., lower = FALSE, log = TRUE)'

See Also:

'gamma' for the Gamma function, 'dbeta' for the Beta distribution and 'dchisq' for the chi-squared distribution which is a special case of the Gamma distribution.

Examples:

```
-log(dgamma(1:4, shape=1))
p <- (1:9)/10
pgamma(qgamma(p,shape=2), shape=2)
1 - 1/exp(qgamma(p, shape=1))
```

```
> qgamma( 0.025, 29.001, 1 / 14.001 )
```

```
[1] 1.387228
```

```
> qgamma( 0.975, 29.001, 1 / 14.001 )
```

```
[1] 2.890435
```

# LOS Analysis (continued)

Maple or R can also be used to obtain the **probability content**, according to the posterior distribution, of the approximate 95% (large-sample) likelihood-based interval:

```
> evalf( Int( p( lambda, 29.001, 14.001 ), lambda = 1.316 .. 2.826 ) );
.9523144484
```

So the **maximization** approach has led to **decent approximations** here (later I'll give examples where maximum likelihood doesn't do so well in small samples).

**Predictive distributions** in this model can be computed by Maple **in the usual way**: for instance, to compute  $p(y_{n+1}|y)$  for  $y = (y_1, \dots, y_n)$  we want to evaluate

$$\begin{aligned}
 p(y_{n+1}|y) &= \int_0^{\infty} p(y_{n+1}, \lambda|y) d\lambda \\
 &= \int_0^{\infty} p(y_{n+1}|\lambda, y) p(\lambda|y) d\lambda && (14) \\
 &= \int_0^{\infty} p(y_{n+1}|\lambda) p(\lambda|y) d\lambda \\
 &= \int_0^{\infty} \frac{\lambda^{y_{n+1}} e^{-\lambda}}{y_{n+1}!} \frac{(\beta^*)^{\alpha^*}}{\Gamma(\alpha^*)} \lambda^{\alpha^*-1} e^{-\beta^*\lambda} d\lambda, \\
 &= \frac{(\beta^*)^{\alpha^*}}{\Gamma(\alpha^*) y_{n+1}!} \int_0^{\infty} \lambda^{(\alpha^*+y_{n+1})-1} e^{-(\beta^*+1)\lambda} d\lambda,
 \end{aligned}$$

where  $\alpha^* = \alpha + s$  and  $\beta^* = \beta + n$ ; in these expressions  $y_{n+1}$  is a **non-negative integer**.

```
> assume( astar > 0, bstar > 0, yf > 0 );
```

```
> simplify( bstar^astar * int( lambda^( astar + yf - 1 ) *
  exp( - ( bstar + 1 ) * lambda ), lambda = 0 .. infinity ) /
  ( GAMMA( astar ) * yf! ) );
```

$$\frac{bstar^{\astar} (-astar - yf)}{(bstar + 1) \text{GAMMA}(astar + yf)}$$


---


$$\text{GAMMA}(astar) \text{GAMMA}(yf + 1)$$

# Predictive Distributions

A bit of **rearranging** then gives that for  $y_{n+1} = 0, 1, \dots$ ,

$$p(y_{n+1}|y) = \frac{\Gamma(\alpha^* + y_{n+1})}{\Gamma(\alpha^*) \Gamma(y_{n+1} + 1)} \left( \frac{\beta^*}{\beta^* + 1} \right)^{\alpha^*} \left( \frac{1}{\beta^* + 1} \right)^{y_{n+1}}. \quad (15)$$

This is called the **Poisson-Gamma** distribution, because (14) is asking us to take a **mixture** (weighted average) of Poisson distributions, using probabilities from a Gamma distribution as the mixing weights.

(15) is a generalization of the **negative binomial** distribution (e.g., Johnson and Kotz 1994), which you've probably encountered in your earlier study of probability and/or statistics.

Maple can try to get simple expressions for the **mean** and **variance** of this distribution:

```
> pg := ( y, alpha, beta ) -> GAMMA( alpha + y ) *
  ( beta / ( beta + 1 ) )^alpha * ( 1 / ( beta + 1 ) )^y /
  ( GAMMA( alpha ) * GAMMA( y + 1 ) );

                                     / beta \alpha / 1 \y
                                     |-----| |-----|
GAMMA(alpha + y) |-----|
                                     \beta + 1/  \beta + 1/

pg := (y, alpha, beta) -> -----
                               GAMMA(alpha) GAMMA(y + 1)

> simplify( sum( pg( y, alpha, beta ), y = 0 .. infinity ) );

                                     1

> simplify( sum( y * pg( y, alpha, beta ), y = 0 .. infinity ) );

                                     alpha
                                     -----
                                     beta
```

So the **mean** of the distribution in (15) is  $E(y_{n+1}|y) = \frac{\alpha^*}{\beta^*}$ .

# Inference and Prediction

```
> simplify( sum( ( y - alpha / beta )^2 * pg( y, alpha, beta ),
  y = 0 .. infinity ) );
```

$$\frac{2}{\beta} \frac{\alpha}{\beta + 1} \text{hypergeom}\left(\left[\alpha, -\frac{\alpha - \beta}{\beta}, -\frac{\alpha - \beta}{\beta}\right], \left[-\frac{\alpha}{\beta}, -\frac{\alpha}{\beta}\right], \frac{1}{\beta + 1}\right) / \frac{2}{\beta}$$

Maple has failed to realize that this expression may be **considerably simplified**: Bernardo and Smith (1994) note that the variance of the distribution in (15) is just

$$V(y_{n+1}|y) = \frac{\alpha^*}{\beta^*} \left(1 + \frac{1}{\beta^*}\right). \tag{16}$$

This provides an interesting **contrast** between **inference** and **prediction**: we've already seen in this model that the posterior mean and variance of  $\lambda$  are  $\frac{\alpha^*}{\beta^*} = \frac{\alpha+s}{\beta+n}$  and

$$\frac{\alpha^*}{(\beta^*)^2} = \frac{\alpha+s}{(\beta+n)^2}, \text{ respectively.}$$

Quantity	Posterior	
	Mean	Variance
$\lambda$	$\frac{\alpha+s}{\beta+n}$	$\frac{\alpha+s}{(\beta+n)^2} = \frac{\alpha+s}{\beta+n} \left(0 + \frac{1}{\beta+n}\right)$
$y_{n+1}$	$\frac{\alpha+s}{\beta+n}$	$\frac{\alpha+s}{\beta+n} \left(1 + \frac{1}{\beta+n}\right)$

Thus  $\lambda$  (the **inferential** objective) and  $y_{n+1}$  (the **predictive** objective) have the same posterior mean, but the posterior variance of  $y_{n+1}$  is **much larger**, as can be seen by the following argument.

(1) Denoting by  $\mu$  the mean of the **population** from which the  $Y_i$  are thought of as (like) a random sample, when  $n$  is large  $\alpha$  and  $\beta$  will be **small** in relation to  $s$  and  $n$ , respectively, and the ratio  $\bar{y} = \frac{s}{n}$  should **more and more closely approach**  $\mu$ —thus for large  $n$ ,

$$E(\lambda|y) = E(y_{n+1}|y) \doteq \mu. \tag{17}$$

# Inference and Prediction

(2) For the Poisson distribution the (population) mean  $\mu$  and variance  $\sigma^2$  are **equal**, meaning that for large  $n$  the ratio  $\frac{\alpha+s}{\beta+n}$  will be close both to  $\mu$  and to  $\sigma^2$ .

Thus for large  $n$ ,

$$V(\lambda|y) \doteq \frac{\sigma^2}{n} \quad \text{but} \quad V(y_{n+1}|y) \doteq \sigma^2. \quad (18)$$

An informal way to restate (18) is to say that accurate **prediction** of new data is an **order of magnitude harder** (in powers of  $n$ ) than accurate **inference** about population parameters.

## 4.2 Bayesian model-checking with predictive distributions.

One way to **check** a model like (1) is as follows.

for ( i in 1:n ) {

Temporarily **set aside** observation  $y_i$ , obtaining a new dataset  $y_{-i} = (y_1, \dots, y_{i-1}, y_{i+1}, \dots, y_n)$  with  $(n - 1)$  observations.

Use the current Bayesian model applied to  $y_{-i}$  to **predict**  $y_i$ , and summarize the extent to which the actual value of  $y_i$  is **surprising** in view of this predictive distribution.

}

One possible measure of surprise is **predictive z-scores**:

$$z_i = \frac{y_i - E[y_i|y_{-i}]}{\sqrt{V[y_i|y_{-i}]}}. \quad (19)$$

Compare the surprise measure with its **expected behavior** if the model had been **“correct”** (e.g.,  $z = (z_1, \dots, z_n)$  should have mean 0 and SD 1).

# Predictive Model-Checking

Example: the LOS data. Here's some R code to carry out this program on the **LOS data**.

```
rosalind 25> R
```

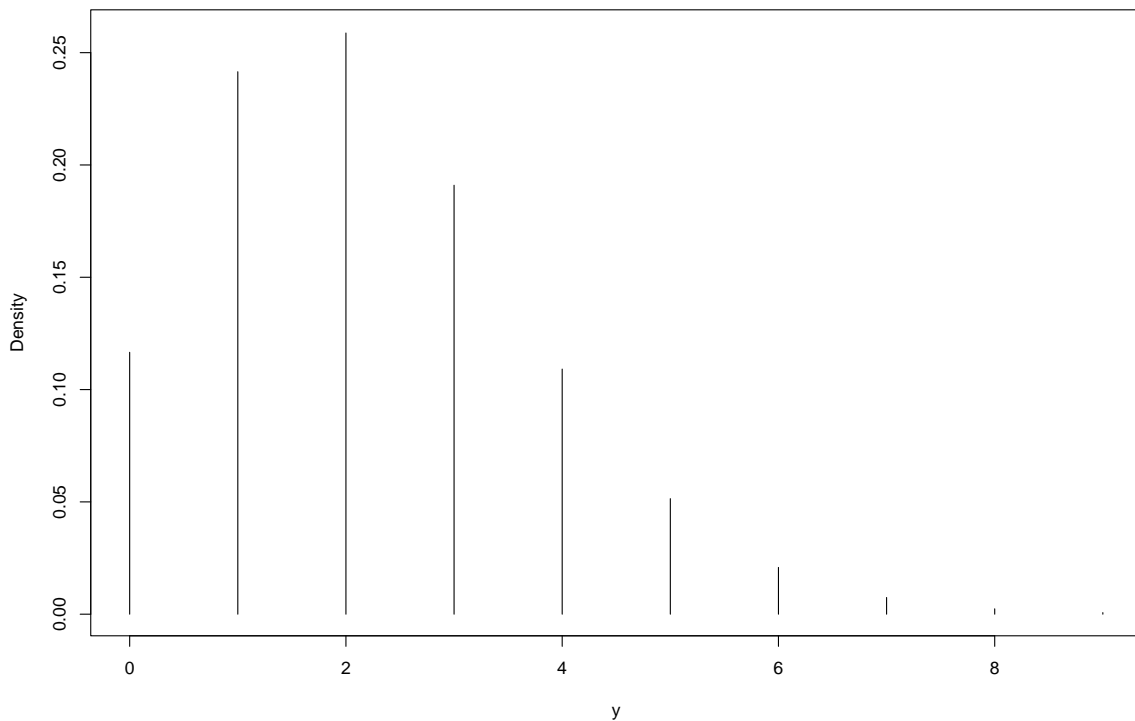
```
R : Copyright 2001, The R Development Core Team  
Version 1.2.1 (2001-01-15)
```

```
> poisson.gamma <- function( y, alpha, beta ) {  
  
  log.density <- lgamma( alpha + y ) + alpha *  
    log( beta / ( beta + 1 ) ) + y * log( 1 / ( beta + 1 ) ) -  
    lgamma( alpha ) - lgamma( y + 1 )  
  
  return( exp( log.density ) )  
  
}  
  
> print( y <- sort( y ) )  
  
[1] 0 1 1 1 1 1 2 2 2 2 3 3 4 6  
  
> print( y.current <- y[ -1 ] )  
  
[1] 1 1 1 1 1 2 2 2 2 3 3 4 6  
  
> print( n.current <- length( y.current ) )  
  
[1] 13  
  
> alpha <- beta <- 0.001  
  
> print( s.current <- sum( y.current ) )  
  
[1] 29  
  
> print( alpha.star <- alpha + s.current )  
  
[1] 29.001  
  
> print( beta.star <- beta + n.current )  
  
[1] 13.001
```

# Predictive Model-Checking

```
> print( pg.current <- poisson.gamma( 0:9, alpha.star, beta.star ) )  
  
[1] 0.1165953406 0.2415099974 0.2587508547 0.1909752933 0.1091243547  
[6] 0.0514422231 0.0208209774 0.0074357447 0.0023899565 0.0007017815  
  
> postscript( "pg1.ps" )  
  
> plot( 0:9, pg.current, type = 'n', xlab = 'y', ylab = 'Density' )  
  
> for ( i in 0:9 ) {  
    segments( i, 0, i, pg.current[ i + 1 ] )  
}  
  
> dev.off( )
```

```
null device  
1
```



The omitted observed value of **0** is **not too unusual** in this predictive distribution.



# Predictive Model-Checking

The following R code **loops** through the whole dataset to get the **predictive  $z$ -scores**.

```
alpha <- beta <- 0.001

z <- rep( 0, n )

for ( i in 1:n ) {

  y.current <- y[ -i ]

  n.current <- length( y.current )

  s.current <- sum( y.current )

  alpha.star <- alpha + s.current

  beta.star <- beta + n.current

  predictive.mean.current <- alpha.star / beta.star

  predictive.SD.current <- sqrt( ( alpha.star / beta.star ) *
    ( 1 + 1 / beta.star ) )

  z[ i ] <- ( y[ i ] - predictive.mean.current ) /
    predictive.SD.current

}

> z

[1] -1.43921925 -0.75757382 -0.75757382 -0.75757382 -0.75757382
[6] -0.75757382 -0.05138023 -0.05138023 -0.05138023 -0.05138023
[11] 0.68145253 0.68145253 1.44329065 3.06513271

> mean( z )

[1] 0.03133708

> sqrt( var( z ) )

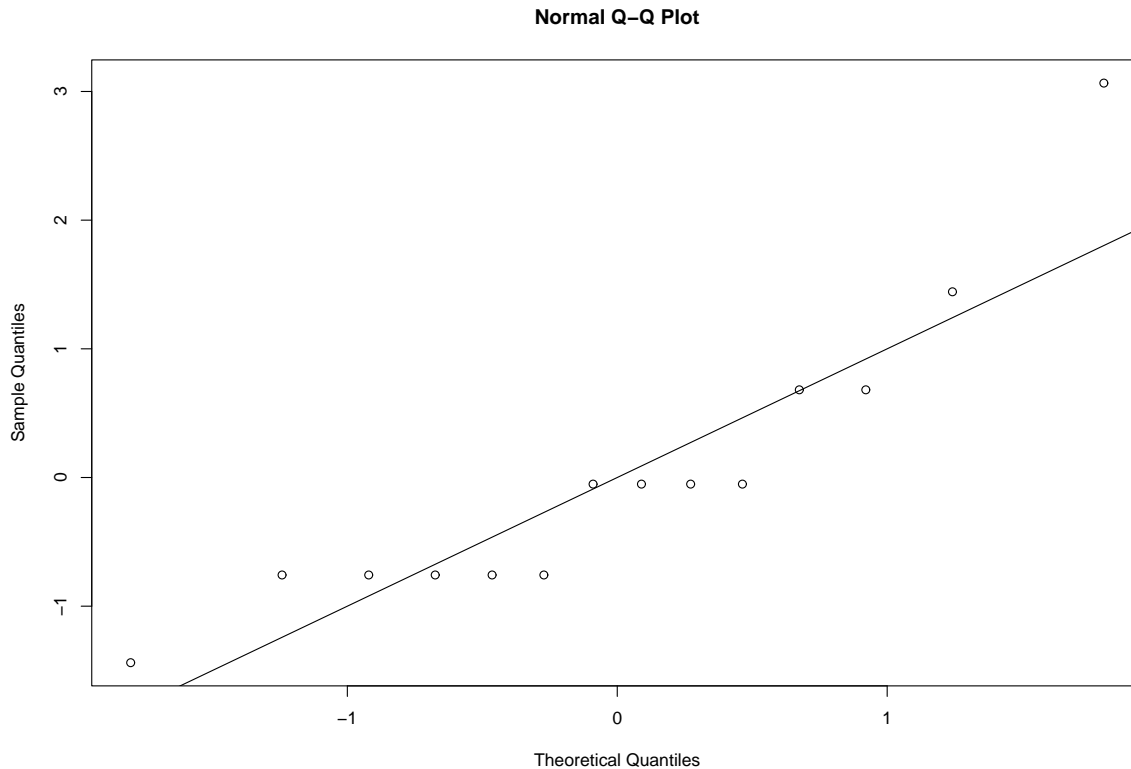
[1] 1.155077
```

# Predictive Model-Checking

```
> postscript( "pg2.ps" )
```

```
> qqnorm( z )
```

```
> abline( 0, 1 )
```



The 14 predictive  $z$ -scores have mean **0.03** (about right) and SD **1.16** (close enough to 1 when sampling variability is considered?), and the **normal qqplot** above shows that the only really surprising observation in the data, as far as the Poisson model was concerned, is the value of **6**, which has a  $z$ -score of **3.07**.

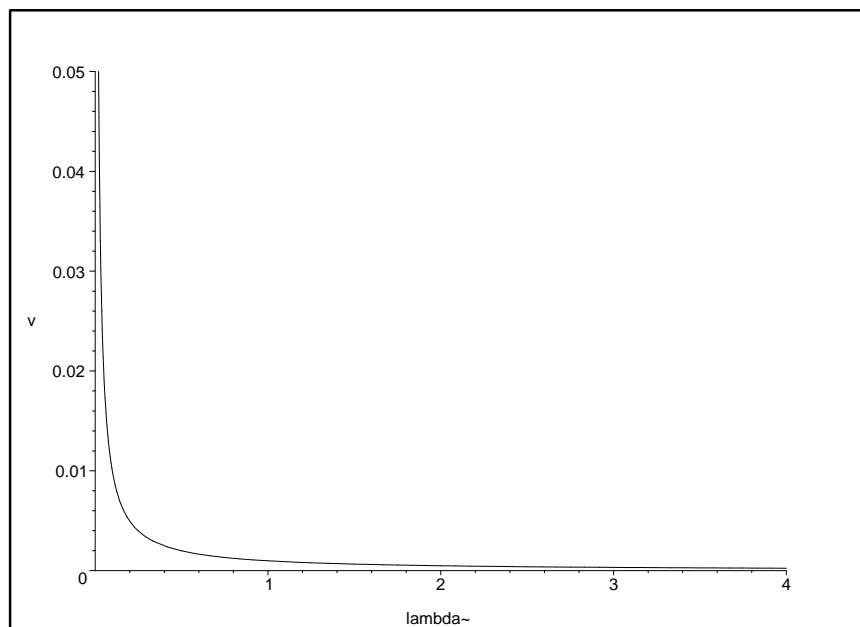
**NB** The figure above is only a **crude approximation** to the right qqplot, which would have to be created by **simulation**; even so it's enough to **suggest** how the model might be **improved**.

I would conclude **informally** (a) that the Poisson is a **decent** model for these data, but (b) if you wanted to expand the model in a direction suggested by this diagnostic you should look for a model with **extra-Poisson variation**: the sample VTMR in this dataset was about **1.15**.

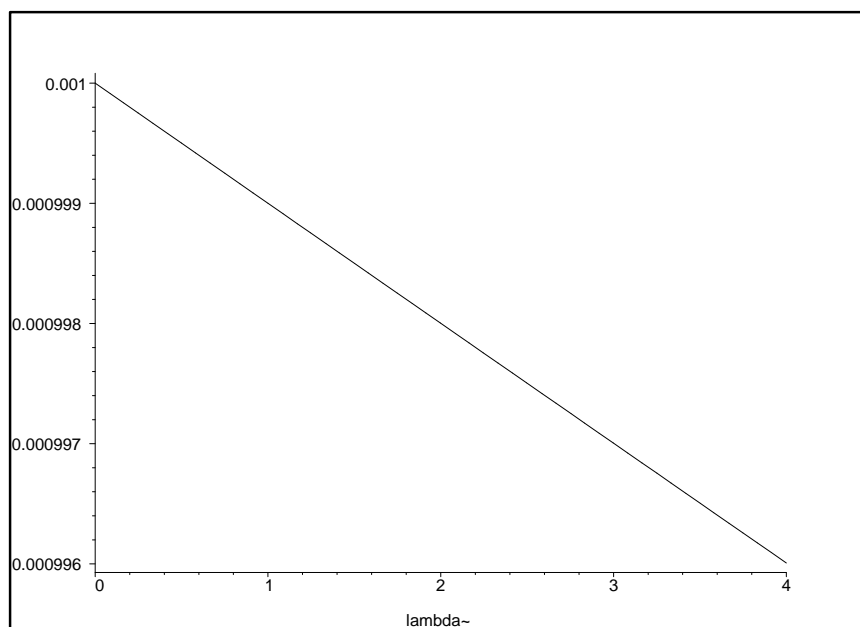
## 4.3 Diffuse Priors in the LOS Case Study

In specifying a **diffuse** prior for  $\lambda$  in the LOS case study, several **alternatives** to  $\Gamma(\epsilon, \epsilon)$  might occur to you, including  $\Gamma(1, \epsilon)$ ,  $\Gamma(\alpha, \beta)$  for some large  $\alpha$  (like 20, to get a roughly **normal** prior) and small  $\beta$  (like 1, to have a **small prior sample size**), and  $U(0, C)$  for some cutoff  $C$  (like 4) chosen to avoid **truncation** of the likelihood function, where  $U(a, b)$  denotes the **uniform** distribution on  $(a, b)$ .

```
> plot( p( lambda, 0.001, 0.001 ), lambda = 0 .. 4, v = 0 .. 0.05,  
       color = black );
```



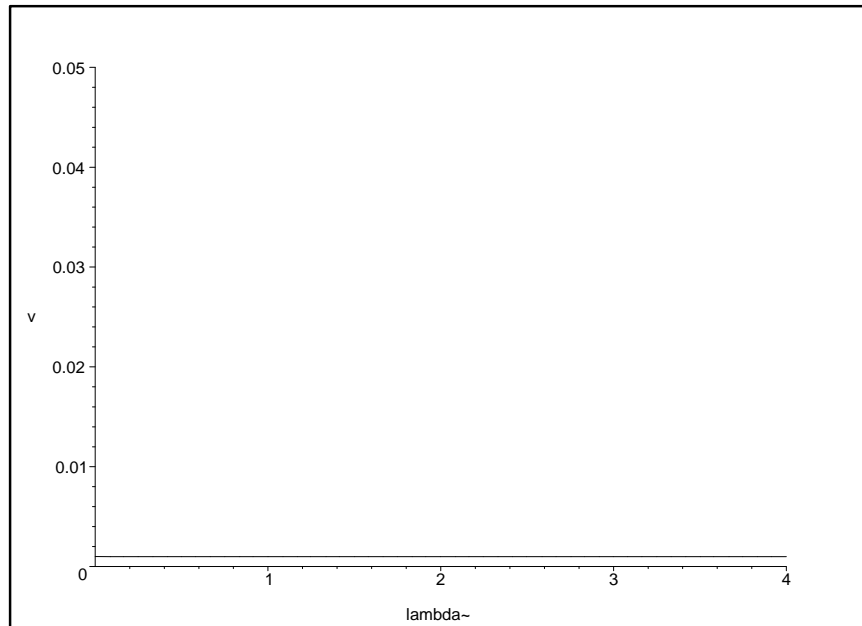
```
> plot( p( lambda, 1.0, 0.001 ), lambda = 0 .. 4, color = black );
```



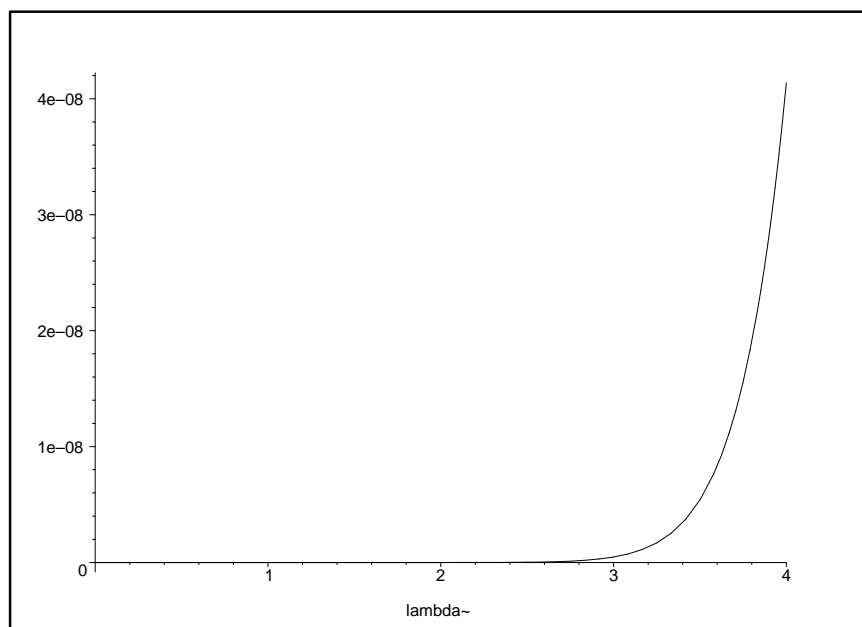
# Diffuse Priors (continued)

$\Gamma(1, \epsilon)$  doesn't look promising initially as a **flat** prior, but that's a consequence of Maple's default choice of **vertical axis**.

```
> plot( p( lambda, 1.0, 0.001 ), lambda = 0 .. 4, v = 0 .. 0.05, color = black );
```

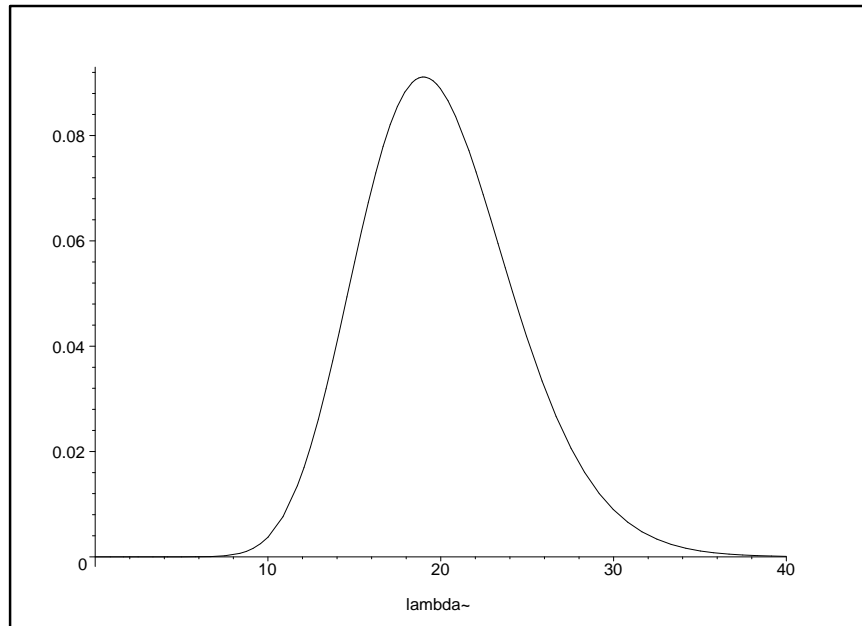


```
> plot( p( lambda, 20, 1 ), lambda = 0 .. 4, color = black );
```



# Diffuse Priors (continued)

```
> plot( p( lambda, 20, 1 ), lambda = 0 .. 40, color = black );
```



$\Gamma(20, 1)$  does indeed look **not far from Gaussian**, and at first it may appear that it is indeed **relatively flat** in the region where the likelihood is appreciable ( $\lambda \in (1.0, 3.3)$ ), but we'll see below that it's actually **rather more informative** than we intend.

Recalling that the **mean** and **SD** of a  $\Gamma(\alpha, \beta)$  random quantity are  $\frac{\alpha}{\beta}$  and  $\sqrt{\frac{\alpha}{\beta^2}}$ , respectively, and that when used as a prior with the Poisson likelihood the  $\Gamma(\alpha, \beta)$  distribution acts like a dataset with **prior sample size**  $\beta$ , you can construct the following table:

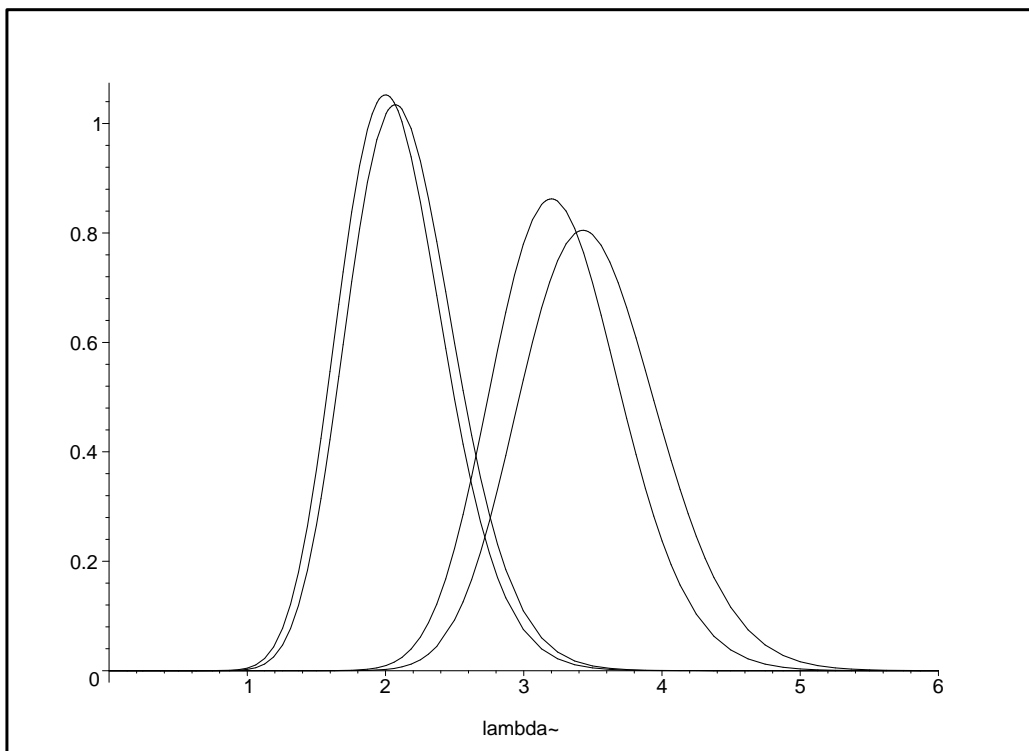
Prior				Posterior			
$\alpha$	$\beta =$ Sample Size	Mean	SD	$\alpha^*$	$\beta^*$	Mean	SD
0.001	0.001	1	31.6	29.001	14.001	2.071	0.385
1	0.001	1000	1000	30	14.001	2.143	0.391
20	1	20	4.47	49	15	3.267	0.467
20	0.001	20000	4472	49	14.001	3.500	0.500
$U(0, C)$ for $C > 4$		$\frac{C}{2}$	$\frac{C}{\sqrt{12}}$	30	14	2.143	0.391

## Diffuse Priors (continued)

The  $\Gamma(1, \epsilon)$  prior leads to an analysis that's **essentially equivalent** to the **integrated likelihood (fiducial)** approach back on p. 13, and the  $U(0, C)$  prior for  $C > 4$  (say) produces similar results:  $U(0, C)$  yields the  $\Gamma(s + 1, n)$  posterior **truncated** to the right of  $C$  (and this truncation has **no effect** if you choose  $C$  big enough).

You might say that the  $U(0, C)$  distribution has a **prior sample size of 0** in this analysis, and its prior mean  $\frac{C}{2}$  and SD  $\frac{C}{\sqrt{12}}$  (both of which can be made arbitrarily large by letting  $C$  grow without bound) are **irrelevant** (this is an example of how intuition can change when you depart from the class of **conjugate** priors).

```
> plot( { p( lambda, 29.001, 14.001 ), p( lambda, 30, 14.001 ),  
        p( lambda, 49, 15 ), p( lambda, 49, 14.001 ) }, lambda = 0 .. 6,  
        color = black );
```



The **moral** is that with only  $n = 14$  observations, some care is needed (e.g., through **pre-posterior** analysis) to achieve a prior that **doesn't affect the posterior very much**, if that's your goal.

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