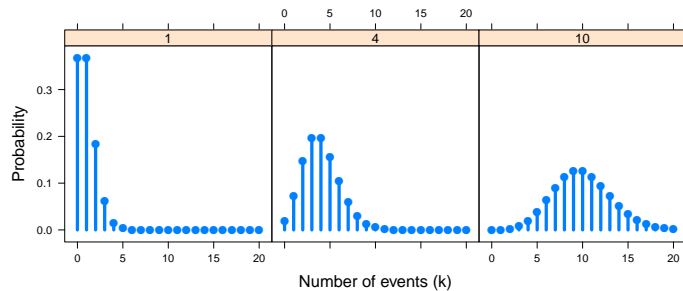


Discrete distributions

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Discrete distributions

Discrete distributions, such as the **binomial**, **Poisson**, **negative binomial** and others form building blocks for the analysis of categorical data (logistic regression, loglinear models, generalized linear models)

Such data consist of:

- **Counts of occurrences:** accidents, words in text, blood cells with some characteristic.
- **Data:** Basic outcome value, k , $k = 0, 1, \dots$, and number of observations, n_k , with that value.

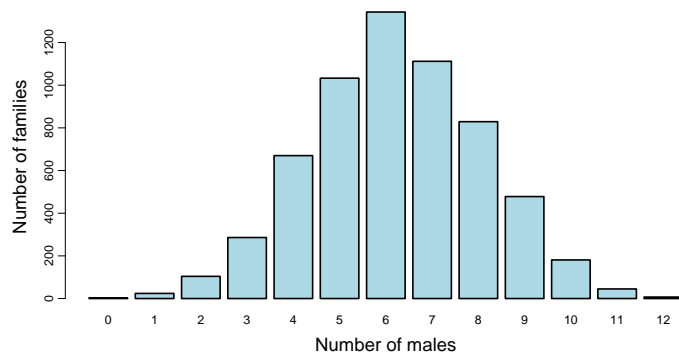
We distinguish between the **count**, k , and the **frequency**, n_k with which that count occurs.

Discrete distributions: Examples

Saxony families

Saxony families with 12 children having $k = 0, 1, \dots, 12$ sons.

k	0	1	2	3	4	5	6	7	8	9	10	11	12
n_k	3	24	104	286	670	1033	1343	1112	829	478	181	45	7



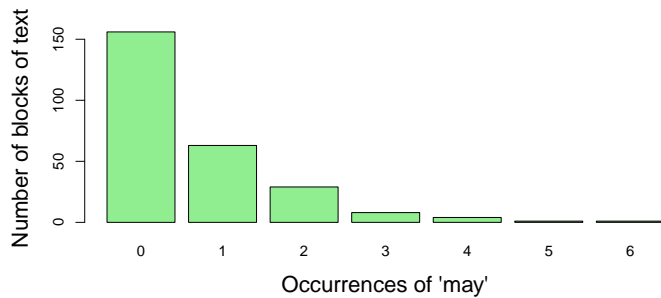
Discrete distributions: Examples I

Federalist papers—disputed authorship

- 77 essays by Hamilton, Jay & Madison: persuade NY voters to ratify Constitution, all signed with pseudonym (“Publius”)
- 65 known, 12 disputed (H & M both claimed sole authorship)
- Mosteller and Wallace (1984): Analysis of frequency distributions of key “marker” words: *from*, *may*, *whilst*,
- e.g., blocks of 200 words with *may*:

Occurrences (k)	0	1	2	3	4	5	6
Blocks (n_k)	156	63	29	8	4	1	1

Discrete distributions: Examples II



For each word,

- fit probability model (Poisson, NegBin)
- → estimate parameters $(\beta_1, \beta_2, \dots)$
- → estimate log Odds (Hamilton vs. Madison)
- ⇒ All 12 of the disputed papers were attributed to Madison

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Type-token distributions I

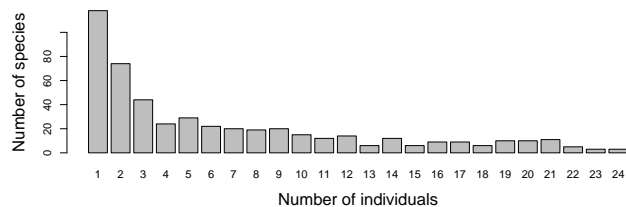
- Basic count, k : number of “types”; frequency, n_k : number of instances observed
 - Frequencies of distinct words in a book or literary corpus
 - Number of subjects listing words as members of the semantic category “fruit”
 - Distinct species of animals caught in traps
- Differs from other distributions in that the frequency for $k = 0$ is *unobserved*
- Distribution is often extremely skewed (J-shaped)

Table: Number of butterfly species n_k for which k individuals were collected

Individuals (k)	1	2	3	4	5	6	7	8	9	10	11	12	
Species (n_k)	118	74	44	24	29	22	20	19	20	15	12	14	
Individuals (k)	13	14	15	16	17	18	19	20	21	22	23	24	50
Species (n_k)	6	12	6	9	9	6	10	10	11	5	3	3	50

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Type-token distributions II



Questions:

- What is the total population of butterflies in Malaya?
- How many wolves remain in Canada’s Northwest territories?
- How many words did Shakespeare know?^a

^aIn known works, Shakespeare used 31,534 distinct words (types), totaling 884,647 words (tokens). Answers depend on fitting a distribution, and estimating the probability for $k = 0$

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Discrete distributions: Questions

General questions:

- What process gave rise to the distribution?
- Form of distribution: uniform, binomial, Poisson, negative binomial, geometric, etc.?
- Estimate parameters
- Visualize goodness of fit

For example:

- *Families in Saxony*: might expect a $\text{Bin}(n, p)$ distribution with $n = 12$. Perhaps $p = 0.5$ as well.
- *Federalist Papers*: might expect a $\text{Poisson}(\lambda)$ distribution.
- *Butterfly data*: perhaps a log-series distribution would be reasonable

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Discrete distributions: Lack of fit

Lack of fit:

- Lack of fit tells us something about the **process** giving rise to the data
- Poisson: assumes constant small probability of the basic event
- Binomial: assumes constant probability and independent trials
- Negative binomial: allows for *overdispersion*, relative to Poisson

Motivation:

- Models for more complex categorical data use these basic discrete distributions
- Binomial (with predictors) → logistic regression
- Poisson (with predictors) → poisson regression, loglinear models
- ⇒ many of these are special cases of *generalized linear models*

Common discrete distributions

Discrete distributions are all characterized by a probability function (or **probability mass function**), $\Pr(X = k) \equiv p(k)$ that the random variable X takes the value k .

The commonly used discrete distributions have the following forms:

Table: Discrete probability distributions

Discrete distribution	Probability function, $p(k)$	parameter(s)
Binomial	$\binom{n}{k} p^k (1-p)^{n-k}$	$p = \Pr(\text{success});$ $n = \# \text{ trials}$
Poisson	$e^{-\lambda} \lambda^k / k!$	$\lambda = \text{mean}$
Negative binomial	$\binom{n+k-1}{k} p^n (1-p)^k$	p, n
Geometric	$p(1-p)^k$	p
Logarithmic series	$\theta^k / [-k \log(1-\theta)]$	θ

Binomial distribution

The binomial distribution, $\text{Bin}(n, p)$,

$$\text{Bin}(n, p) : \Pr\{X = k\} \equiv p(k) = \binom{n}{k} p^k (1-p)^{n-k} \quad k = 0, 1, \dots, n, \quad (1)$$

arises as the distribution of the number of events of interest (“successes”) which occur in n *independent trials* when the probability of the event on any one trial is the *constant* value $p = \Pr(\text{event})$.

Examples:

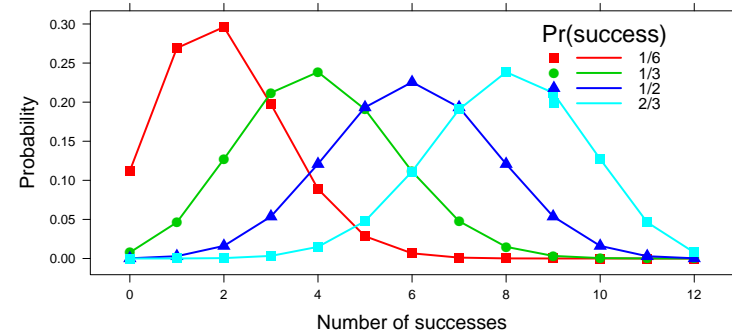
- Toss 10 fair coins— how many heads: $\text{Bin}(10, \frac{1}{2})$
- Toss 12 fair dice— how many 5s or 6s: $\text{Bin}(12, \frac{1}{3})$

Mean & variance:

$$\begin{aligned} \text{Mean}[X] &= np \\ \text{Var}[X] &= np(1-p) \end{aligned}$$

Binomial distribution

Binomial distributions for $k = 0, \dots, 12$ successes in $n = 12$ trials, and four values of p



Poisson distribution

The Poisson distribution, $\text{Pois}(\lambda)$,

$$\text{Pois}(\lambda) : \Pr\{X = k\} \equiv p(k) = \frac{e^{-\lambda} \lambda^k}{k!} \quad k = 0, 1, \dots \quad (2)$$

gives the probability of an event occurring $k = 0, 1, 2, \dots$ times over a *large number of independent* trials, when the probability, p , that the event occurs on any one trial (in time or space) is *small and constant*.

Examples:

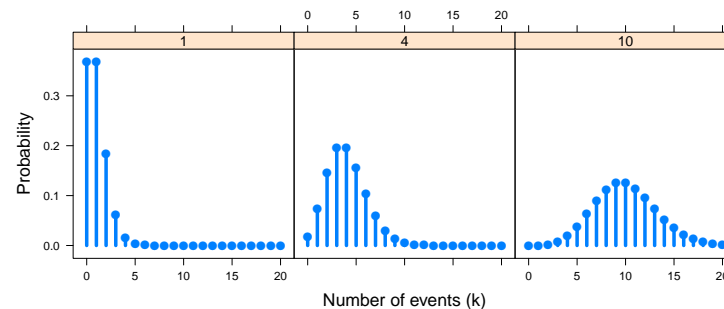
- Number of highway accidents at some given location
- Defects in a manufacturing process
- Number of goals scored in soccer games

Table: Total goals scored in 380 games in the Premier Football League, 1995/95 season

Total goals	0	1	2	3	4	5	6	7
Number of games	27	88	91	73	49	31	18	3

Poisson distribution

Poisson distributions for $\lambda = 1, 4, 10$



Mean, variance & skewness:

$$\text{Mean}[X] = \lambda$$

$$\text{Var}[X] = \lambda$$

$$\text{Skew}[X] = \lambda^{-1/2}$$

Negative binomial distribution

The Negative binomial distribution, $\text{NBin}(n, p)$,

$$\text{NBin}(n, p) : \Pr\{X = k\} \equiv p(k) = \binom{n+k-1}{k} p^n (1-p)^k \quad k = 0, 1, \dots, \infty$$

arises when a series of independent Bernoulli trials is observed with constant probability p of some event, and we ask how many non-events (failures), k , it takes to observe n successful events.

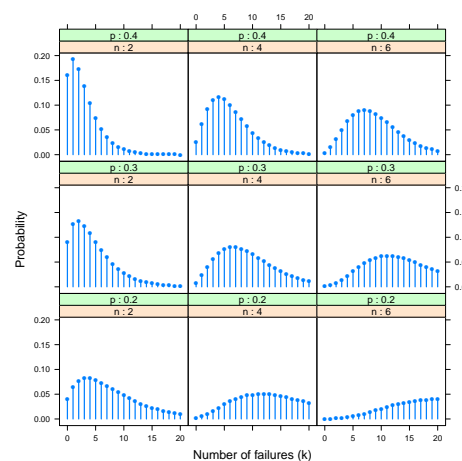
Example: Toss a coin; what is probability of getting $k = 0, 1, 2, \dots$ tails before $n = 3$ heads?

This distribution is often used as an alternative to the Poisson when

- constant probability p or independence are violated
- variance is greater than the mean (overdispersion)

Negative binomial distribution

Negative binomial distributions for $n = 2, 4, 6$ and $p = 0.2, 0.3, 0.4$



Mean increases with n and decreases with p .

Fitting discrete distributions

Fitting a discrete distribution involves the following steps:

- 1 Estimate the parameter(s) from the data, e.g., p for binomial, λ for Poisson, etc. Typically done using maximum likelihood, but some distributions have simple expressions:
 - Binomial, $\hat{p} = \sum kn_k / (n \sum n_k) = \text{mean} / n$
 - Poisson, $\hat{\lambda} = \sum kn_k / \sum n_k = \text{mean}$
- 2 Calculate fitted probabilities, $\hat{p}(k)$ for the distribution, and then fitted frequencies, $N\hat{p}(k)$.
- 3 Assess Goodness of fit: Pearson X^2 or likelihood-ratio G^2

$$X^2 = \sum_{k=1}^K \frac{(n_k - N\hat{p}_k)^2}{N\hat{p}_k} \quad G^2 = \sum_{k=1}^K n_k \log\left(\frac{n_k}{N\hat{p}_k}\right)$$

Both have asymptotic chisquare distributions, χ_{K-s}^2 with s estimated parameters, under the hypothesis that the data follows the chosen distribution.

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Fitting and graphing discrete distributions

In R, the `vcd` and `vcdExtra` packages contain methods to fit, visualize, and diagnose discrete distributions:

- **Fitting:** `goodfit()` fits uniform, binomial, Poisson, negative binomial, geometric, logarithmic series distributions (or any specified multinomial)
- **Hanging rootograms:** Sensitive assess departure between Observed, Fitted counts (`rootogram()`)
- **Ord plots:** Diagnose form of a discrete distribution (`Ordplot()`)
- **Robust distribution plots for various distributions** (`distplot()`)

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Example: Saxony data

```
library(vcd)
data(Saxony)
Saxony

## nMales
## 0 1 2 3 4 5 6 7 8 9 10 11 12
## 3 24 104 286 670 1033 1343 1112 829 478 181 45 7
```

Use `goodfit()` to fit the binomial; test with `summary()`:

```
Sax.fit <- goodfit(Saxony, type="binomial")
summary(Sax.fit)
```

```
##
## Goodness-of-fit test for binomial distribution
##
##           X^2 df    P(> X^2)
## Likelihood Ratio 97.007 11 6.9782e-16
```

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Example: Saxony data

The `print()` method shows the details:

```
Sax.fit # print

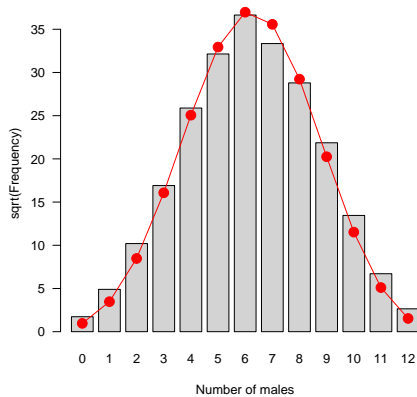
##
## Observed and fitted values for binomial distribution
## with parameters estimated by `ML`
##
## count observed fitted
## 0 3 0.93284
## 1 24 12.08884
## 2 104 71.80317
## 3 286 258.47513
## 4 670 628.05501
## 5 1033 1085.21070
## 6 1343 1367.27936
## 7 1112 1265.63031
## 8 829 854.24665
## 9 478 410.01256
## 10 181 132.83570
## 11 45 26.08246
## 12 7 2.34727
```

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What's wrong with histograms?

Discrete distributions are often graphed as histograms, with a theoretical fitted distribution superimposed.

```
plot(Sax.fit, type="standing", xlab="Number of males")
```



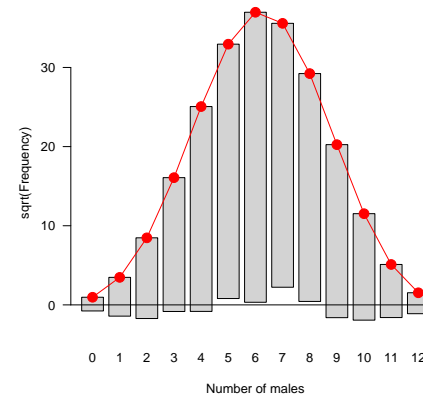
Problems:

- largest frequencies dominate display
- must assess deviations vs. a curve

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Hang & root them → Hanging rootograms

```
plot(Sax.fit, xlab="Number of males")
```



Tukey (1972, 1977):

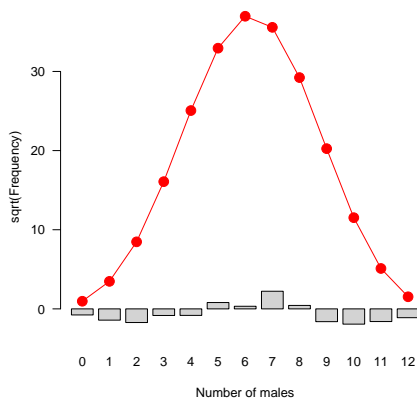
- shift histogram bars to the fitted curve
- → judge deviations vs. horizontal line.
- plot $\sqrt{\text{freq}}$ → smaller frequencies are emphasized.

We can now see clearly *where* the binomial doesn't fit

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Highlight differences → Deviation rootograms

```
plot(Sax.fit, type="deviation", xlab="Number of males")
```



Deviation rootogram:

- emphasize differences between observed and fitted frequencies
- bars now show the residuals (gaps) directly

There are more families with very low or very high number of sons than the binomial predicts.

Q: Why is this so much better than the lack-of-fit test?

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Example: Federalist papers

```
data(Federalist, package="vcd")
Federalist
```

```
## nMay
## 0 1 2 3 4 5 6
## 156 63 29 8 4 1 1
```

Fit the Poisson distribution:

```
Fed.fit0 <- goodfit(Federalist, type="poisson")
summary(Fed.fit0)
```

```
##
## Goodness-of-fit test for poisson distribution
##
##
## X^2 df P(> X^2)
## Likelihood Ratio 25.243 5 0.00012505
```

This fits very poorly!

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Example: Federalist papers

Fit the Negative binomial distribution:

```
Fed.fit1 <- goodfit(Federalist, type="nbinomial")
summary(Fed.fit1)

##
## Goodness-of-fit test for nbinomial distribution
##
##           X^2 df P(> X^2)
## Likelihood Ratio 1.964 4 0.74238
```

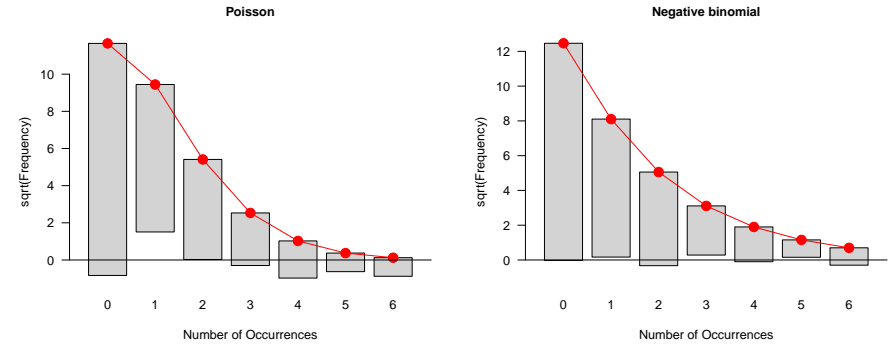
This now fits very well, indeed! Why?

- Poisson assumes that the probability of a given word (“may”) is constant across all blocks of text.
- Negative binomial allows the rate parameter λ to vary over blocks of text

Example: Federalist papers: Rootograms

Hanging rootograms for the Federalist Papers data, comparing the Poisson and negative binomial models:

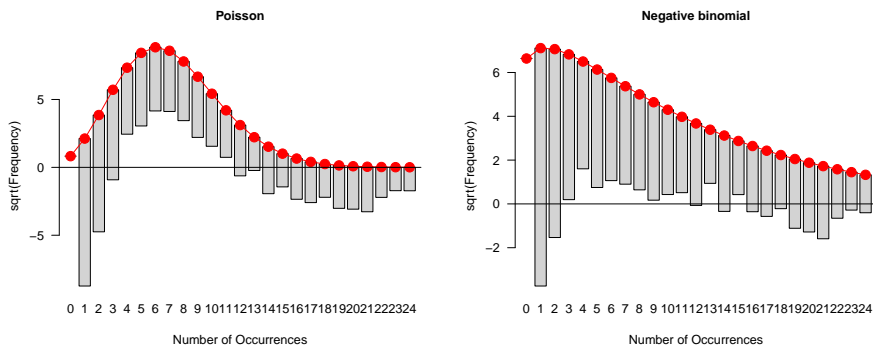
```
plot(Fed.fit0, main="Poisson")
plot(Fed.fit1, main="Negative binomial")
```



Example: Butterfly data

Butterfly data: neither Poisson or Negative binomial fit:

```
But.fit1 <- goodfit(Butterfly, type="poisson")
But.fit2 <- goodfit(Butterfly, type="nbinomial")
plot(But.fit1, main="Poisson")
plot(But.fit2, main="Negative binomial")
```



Ord plots: Diagnose form of discrete distribution

How to tell which discrete distributions are likely candidates?

- Ord (1967): for each of Poisson, Binomial, Negative binomial, and Logarithmic series distributions,
 - plot of kp_k/p_{k-1} against k is linear
 - signs of intercept and slope \rightarrow determine the form, give rough estimates of parameters

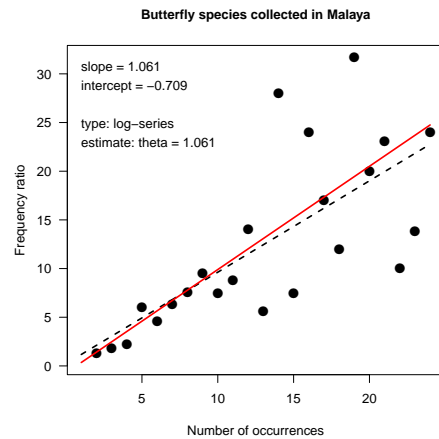
Slope (b)	Intercept (a)	Distribution (parameter)	Parameter estimate
0	+	Poisson (λ)	$\lambda = a$
-	+	Binomial (n, p)	$p = b/(b - 1)$
+	+	Neg. binomial (n,p)	$p = 1 - b$
+	-	Log. series (θ)	$\theta = b$ $\theta = -a$

- Fit line by WLS, using $\sqrt{n_k - 1}$ as weights
- A heuristic method: doesn't always work, but often a good start.

Ord plots: Examples

Ord plot for the Butterfly data. The slope and intercept in the plot correctly diagnoses the log-series distribution.

```
Ord_plot(Butterfly,
        main = "Butterfly species collected in Malaya", gp=gpar(cex=1))
```

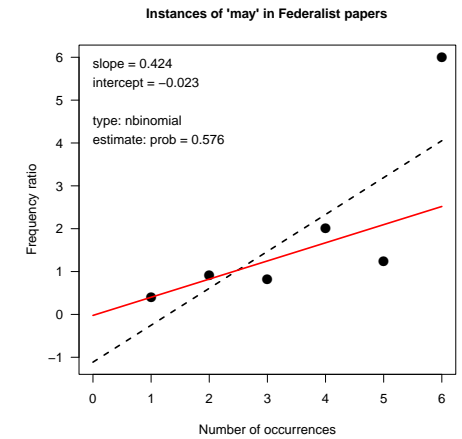
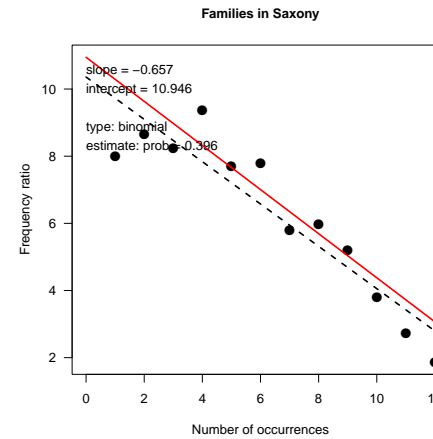


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Ord plots: Examples

Happily, these are all members of a family called the power series distributions. Ord plots for the Saxony and Federalist data sets:

```
Ord_plot(Saxony, main = "Families in Saxony", gp=gpar(cex=1), pch=16)
Ord_plot(Federalist, main = "Instances of 'may' in Federalist papers", gp=
```



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Robust distribution plots: Poisson

- Ord plots lack robustness
 - one discrepant frequency, n_k affects points for both k and $k + 1$
 - the use of WLS to fit the line is a small attempt to minimize this
- Robust plots for Poisson distribution (Hoaglin and Tukey, 1985)
 - For Poisson, plot **count metameter** $= \phi(n_k) = \log_e(k! n_k / N)$ vs. k
 - Linear relation \Rightarrow Poisson, slope gives $\hat{\lambda}$
 - CI for points, diagnostic (influence) plot
 - Implemented in `distplot()` in the `vcd` package

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Poissonness plots: Details

- If the distribution of n_k is $\text{Poisson}(\lambda)$ for some fixed λ , then each observed frequency, $n_k \approx m_k = Np_k$.
- Then, setting $n_k = Np_k = e^{-\lambda} \lambda^k / k!$, and taking logs of both sides gives

$$\log(n_k) = \log N - \lambda + k \log \lambda - \log k!$$

which can be rearranged to

$$\phi(n_k) \equiv \log\left(\frac{k! n_k}{N}\right) = -\lambda + (\log \lambda) k$$

- \Rightarrow if the distribution is Poisson, plotting $\phi(n_k)$ vs. k should give a line with
 - intercept = $-\lambda$
 - slope = $\log \lambda$
- Nonlinear relation \rightarrow distribution is *not* Poisson
- Hoaglin and Tukey (1985) give details on calculation of confidence intervals and influence measures.

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Distribution plots: Other distributions

This idea extends readily to other discrete data distributions:

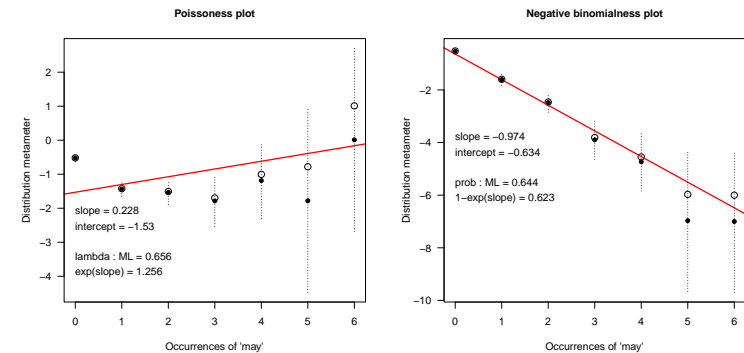
- The binomial, Poisson, negative binomial, geometric and logseries distributions are all members of a general **power series family** of discrete distributions. See: *VCDR*, Table 3.10 for details.
- This allows all of these to be represented in a plot of a suitable count metameter, $\phi(n_k)$ vs. k . See: *VCDR*, Table 3.12 for details.
- In these plots, a straight line confirms that the data follow the given distribution.
- Confidence intervals around the points indicate **uncertainty** for the count metameter.
- The slope and intercept of the line give **estimates** of the distribution parameters.

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distplot: Example: Federalist

Diagnostic distribution plots for the Federalist papers data.

```
distplot(Federalist, type="poisson", xlab="Occurrences of 'may'")
distplot(Federalist, type="nbinomial", xlab="Occurrences of 'may'")
```



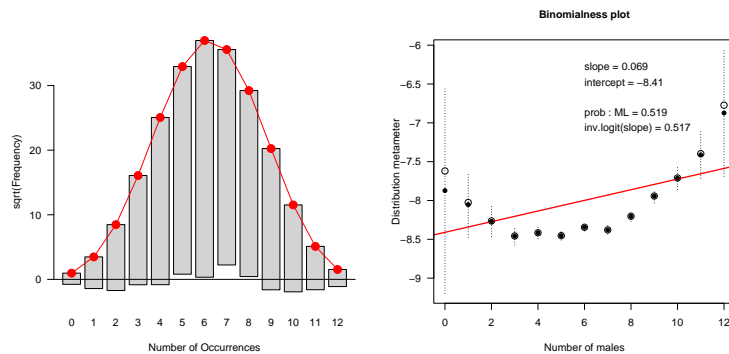
Again, the Poisson distribution is seen not to fit, while the Negative binomial appears reasonable.

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distplot: Example: Saxony

For purported binomial distributions, the result is a "Binomialness" plot.

```
plot(goodfit(Saxony, type="binomial", par=list(size=12)))
distplot(Saxony, type="binomial", size=12, xlab="Number of males")
```



Both plots show heavier tails than in a binomial distribution.

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What have we learned?

Main points:

- Discrete distributions involve basic **counts** of occurrences of some event occurring with varying **frequency**.
- The ideas and methods for one-way tables are building blocks for analysis of more complex data.
- Commonly used discrete distributions include the binomial, Poisson, negative binomial, and logarithmic series distributions, all members of a **power series family**.
- Fitting observed data to a distribution \rightarrow fitted frequencies, $N\hat{p}_k$, \rightarrow goodness-of-fit tests (Pearson X^2 , LR G^2)
- R: **goodfit()** provides **print()**, **summary()** and **plot()** methods.
- Plotting with rootgrams, Ord plots and generalized distribution plots can reveal **how** or **where** a distribution does not fit.

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What have we learned?

Some explanations:

- The Saxony data were part of a much larger data set from Geissler (1889) (Geissler in [vcdExtra](#)).
 - For the binomial, with families of size $n = 12$, our analyses give $\hat{p} = \Pr(\text{male}) = 0.52$.
 - Other analyses (using more complex models) conclude that p varies among families with the same size.
 - One explanation is that family decisions to have another child are influenced by the boy–girl ratio in earlier children.
- As suggested earlier, the lack of fit of the Poisson distribution for words in the Federalist papers can be explained by [context](#) of the writing:
 - Given “marker” words appear more or less often over time and subject than predicted by constant rates (λ) for a given author (Madison or Hamilton)
 - The negative binomial distribution fit much better.
 - The estimated parameters for these texts allowed assigning all 12 disputed papers to Madison.

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