

# **Statistical Audit Sampling with R**

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# Welcome

This book, **Statistical Audit Sampling with R**, is intended as a practical guide for auditors who wish to employ probability theory in their audit sampling activities. While the focus of this book is exclusively on audit sampling, it aims to discuss the topic from both the classical (frequentist) perspective and the Bayesian perspective. By examining the subject through these two lenses, the book explains the statistical theory behind commonly used audit sampling procedures and demonstrates how to perform these procedures in accordance with international auditing standards, using the **jfa** R package, in a statistically sound manner.



# 1. Introduction

This book is intended for auditors that want to obtain the knowledge and skill to utilize statistical audit sampling in their practice using the R programming language. It covers an array of traditional and innovative statistical tools that are available to auditors, explaining their function, the underlying assumptions, and when they are best utilized. In addition, it offers practical guidance on integrating advanced statistical sampling methodology into audit practice and demonstrates its value through real-world case studies. It is our hope that this book will serve as a valuable resource for auditors looking to effectively and efficiently utilize statistical methods in their practice.

The aim of this book is to address the need for a clear and transparent explanation of the use of statistical sampling methodology in audit practice. Most guidance about audit sampling (e.g., American Institute of Certified Public Accountants (AICPA) (2016a); American Institute of Certified Public Accountants (AICPA) (2016b)) lacks sufficient detail to allow for full transparency or a deep understanding. Additionally, the implementation of statistical sampling methodology in practice is often even less transparent, as theory and calculations are hidden from auditors in commercial closed-source tools or in Excel sheets from audit guides used internally by audit firms (one notable exception is Stewart (2012)). Thus, while attempting to comprehend the theoretical aspects of statistical audit sampling, auditors may encounter numerous relevant questions that are left unanswered by these tools. This book aims to clarify the statistical methodology utilized in practice, thereby empowering auditors through a comprehensive explanation.

This book discusses two philosophies to statistical audit sampling: the classical (frequentist) philosophy and the Bayesian philosophy. By utilizing these two approaches, the book elucidates the statistical theory that underlies commonly used audit sampling techniques and illustrates how to utilize these techniques in accordance with international auditing standards. Additionally, the book demonstrates the use of Bayesian statistical methods in auditing practice and highlights the practical advantages that these methods can offer for auditors.

The structure of this book is as follows: Chapter 2 introduces the basics of the R programming language. Chapter 3 discusses the fundamental statistical theory relevant to

## *1. Introduction*

classical and Bayesian audit sampling. Subsequent chapters 4, 5, 6 and 7 provide a more in-depth exploration of the use of these methods for statistical planning, selection, and evaluation of audit samples. These chapters illustrate the practical differences and similarities between the classical and the Bayesian approach through code and examples, thus requiring minimal programming knowledge to follow along. Finally, Chapter 8 and 9 discuss other open-source software implementations of audit sampling using R.

In each chapter, we aim to adhere to a consistent structure: beginning with motivating examples to provide a broader context, and then delving into the specifics. Every section of the book is accompanied by exercises designed to reinforce the concepts learned. Although it may be tempting to skip the exercises, the most effective way to learn is by applying the concepts to actual problems through practice.

### **1.1. Prerequisites**

To run the code in this book, you will need three things: R, RStudio, and the **jfa** package.

#### **1.1.1. R**

The **Comprehensive R Archive Network (CRAN)** is a collection of mirror servers distributed globally that can be utilized to obtain both R and R packages. When seeking to download R, it is recommended to utilize the cloud mirror located at <https://cloud.r-project.org>, as it will automatically determine the most suitable mirror for your location. Please ensure that you have at least R 3.5.0 installed for the purposes of this book.

It is advisable to regularly update R, as new major versions are released annually and minor releases occur two to three times per year. While upgrading can be inconvenient, particularly for major versions which require the reinstallation of all packages, failing to do so will only exacerbate the issue.

#### **1.1.2. RStudio**

RStudio is an Integrated Development Environment (IDE) specifically designed for the R programming language. It can be downloaded and installed from the official website (<https://posit.co/downloads/>). RStudio undergoes updates several times a year, and users

## 1.1. Prerequisites

will be notified when a new version becomes available. It is recommended to regularly upgrade RStudio to access the latest features. Please ensure that you have at least RStudio 1.0.0 installed for the purposes of this book.

When you start RStudio, you'll see three important regions in the interface: the console, the environment and the output panel.



The console in the left panel allows you to run R code. To execute some R code, type the code in the console (e.g., `1 + 1`) and press Enter. When you stored the results of a computation in a new variable (e.g., `x <- 1 + 1`), the variable is displayed in the environment in the top right panel. The environment allows you to keep track of the objects you have created during your R session. Finally, any plots that you request are displayed in the output panel in the bottom right.

### 1.1.3. jfa

R has many packages and libraries that extend its capabilities and provide additional functions and tools for data analysis and visualization. R packages are the core building blocks of reproducible R code. They consist of reusable functions, the documentation describing how to utilize them, and sample data. Some popular packages include dplyr for data manipulation, ggplot2 for data visualization, and caret for machine learning.

## 1. Introduction

### **i** Note

If you want to know more about creating your own R package, Wickam & Brian (2022) provides an excellent first-hand description of the principles and practices of creating R packages.

To illustrate its concepts and ideas, this book uses the **jfa** package, an R package for statistical auditing, which can also be downloaded from CRAN. This can be done via the `install.packages()` function by providing the package name in quotes. Thus, before running the examples in this book, you should install the **jfa** package by running the following command in R:

```
install.packages("jfa")
```

Once you have installed a package, you must load it into every R session. To load a package into your R session, call `library()` and provide the name of the package (without quotes) that you want to load. For example, before running the examples in this book, you should load the **jfa** package with:

```
library(jfa)
```

R packages are updated regularly. To update a package in your R library you should call `update.packages()` and provide the name of the package that you want to update in quotes. For example, each time there is a new release of the **jfa** package, you can update it by running:

```
update.packages("jfa")
```

### **i** Note

If you want to look at the source code of the **jfa** package, see the package website.

## 1.2. Running R Code

The code in this book appears as follows:

### 1.3. Colophon

```
1 + 1  
#> [1] 2
```

When executing the same code within your local console, the resulting output will appear as follows:

```
> 1 + 1  
[1] 2
```

There are two primary distinctions between the use of a console and the presentation of code in the book. Firstly, in a console, the user inputs their code after the prompt symbol (>) while the book does not display this symbol. Secondly, the output in the book is commented out with #>, while in a console it is displayed directly after the inputted code. Hence, those working with an electronic version of the book can directly copy code from the book to the console.

## 1.3. Colophon

An online version of this book is available at <https://koenderks.github.io/sasr/>. The source of the book is available at <https://github.com/koenderks/sasr>. The book is built with Quarto which makes it easy to turn R markdown files into HTML, PDF, and ePub.

This book was built with:

```
sessioninfo::session_info()  
#> - Session info  
#>   -----  
#>   setting  value  
#>   version   R version 4.2.2 (2022-10-31)  
#>   os        Ubuntu 22.04.1 LTS  
#>   system    x86_64, linux-gnu  
#>   ui        X11  
#>   language (EN)  
#>   collate   C.UTF-8  
#>   ctype     C.UTF-8  
#>   tz        UTC
```

## 1. Introduction

```
#> date      2023-02-14
#> pandoc   NA (via rmarkdown)
#>
#> - Packages -----
#>   └── -
#>     ! package      * version  date (UTC) lib source
#>       callr          3.7.3    2022-11-02 [1] CRAN (R 4.2.2)
#>       cli            3.6.0    2023-01-09 [1] CRAN (R 4.2.2)
#>       codetools       0.2-18   2020-11-04 [?] CRAN (R 4.2.2)
#>       colorspace      2.1-0    2023-01-23 [1] CRAN (R 4.2.2)
#>       crayon          1.5.2    2022-09-29 [1] CRAN (R 4.2.2)
#>       digest           0.6.31   2022-12-11 [1] CRAN (R 4.2.2)
#>       evaluate         0.20     2023-01-17 [1] CRAN (R 4.2.2)
#>       fansi            1.0.4    2023-01-22 [1] CRAN (R 4.2.2)
#>       fastmap          1.1.0    2021-01-25 [1] CRAN (R 4.2.2)
#>       ggplot2          * 3.4.1   2023-02-10 [1] CRAN (R 4.2.2)
#>       glue              1.6.2    2022-02-24 [1] CRAN (R 4.2.2)
#>       gridExtra         2.3      2017-09-09 [1] CRAN (R 4.2.2)
#>       gtable            0.3.1    2022-09-01 [1] CRAN (R 4.2.2)
#>       htmltools          0.5.4    2022-12-07 [1] CRAN (R 4.2.2)
#>       inline             0.3.19   2021-05-31 [1] CRAN (R 4.2.2)
#>       jfa                * 0.6.5   2023-02-14 [1] Github
#>     → (koenderks/jfa@dec66b6)
#>       jsonlite          1.8.4    2022-12-06 [1] CRAN (R 4.2.2)
#>       knitr              1.42     2023-01-25 [1] CRAN (R 4.2.2)
#>       lifecycle          1.0.3    2022-10-07 [1] CRAN (R 4.2.2)
#>       loo                 2.5.1    2022-03-24 [1] CRAN (R 4.2.2)
#>       magrittr            2.0.3    2022-03-30 [1] CRAN (R 4.2.2)
#>       matrixStats         0.63.0   2022-11-18 [1] CRAN (R 4.2.2)
#>       munsell             0.5.0    2018-06-12 [1] CRAN (R 4.2.2)
#>       pillar              1.8.1    2022-08-19 [1] CRAN (R 4.2.2)
#>       pkgbuild            1.4.0    2022-11-27 [1] CRAN (R 4.2.2)
#>       pkgconfig            2.0.3    2019-09-22 [1] CRAN (R 4.2.2)
#>       prettyunits          1.1.1    2020-01-24 [1] CRAN (R 4.2.2)
#>       processx            3.8.0    2022-10-26 [1] CRAN (R 4.2.2)
#>       ps                  1.7.2    2022-10-26 [1] CRAN (R 4.2.2)
#>       R6                  2.5.1    2021-08-19 [1] CRAN (R 4.2.2)
```

### 1.3. Colophon

```
#> Rcpp          1.0.10   2023-01-22 [1] CRAN (R 4.2.2)
#> RcppParallel  5.1.6    2023-01-09 [1] CRAN (R 4.2.2)
#> renv          0.16.0   2022-09-29 [1] CRAN (R 4.2.2)
#> rlang          1.0.6    2022-09-24 [1] CRAN (R 4.2.2)
#> rmarkdown      2.20     2023-01-19 [1] CRAN (R 4.2.2)
#> rstan          2.21.8   2023-01-17 [1] CRAN (R 4.2.2)
#> scales         1.2.1    2022-08-20 [1] CRAN (R 4.2.2)
#> sessioninfo    1.2.2    2021-12-06 [1] CRAN (R 4.2.2)
#> StanHeaders   2.21.0-7 2020-12-17 [1] CRAN (R 4.2.2)
#> tibble         3.1.8    2022-07-22 [1] CRAN (R 4.2.2)
#> utf8           1.2.3    2023-01-31 [1] CRAN (R 4.2.2)
#> vctrs          0.5.2    2023-01-23 [1] CRAN (R 4.2.2)
#> withr          2.5.0    2022-03-03 [1] CRAN (R 4.2.2)
#> xfun           0.37     2023-01-31 [1] CRAN (R 4.2.2)
#>
#> [1] /home/runner/.cache/R/renv/library/sasr-7f45ae81/R-
#>   ↵ 4.2/x86_64-pc-linux-gnu
#> [2] /home/runner/work/sasr/sasr/renv/sandbox/R-4.2/x86_64-pc-
#>   ↵ linux-gnu/99f2a2ef
#>
#> P -- Loaded and on-disk path mismatch.
#>
#> -----
#>   -----
```



# **Part I.**

## **The Basics**



## 2. Foundations of Auditing

**i** You are reading the work-in-progress first edition of Statistical Auditing with R. This chapter is currently a dumping ground of ideas, and it is incomplete.

Auditors use audit sampling as a technique to assess a selection of transactions or items within a population in order to form conclusions about the population as a whole. It is a cost-efficient method for examining the accuracy of financial information as it allows auditors to test a representative sample of the population rather than the entire population.

In the field of auditing, sampling becomes necessary when the truth about a population is not readily accessible or discernible through other means. With the advent of modern technology, auditors often have access to an abundance of information about a population, which sometimes enables them to perform integral testing. Nonetheless, there are situations where a sample is still necessary due to the unavailability of complete data. For instance, an auditor may utilize analytical procedures to verify the consistency of payments with payment orders, but then must subsequently confirm the validity of these orders through detailed testing.

In auditing, there are two primary methods of sampling: statistical and nonstatistical. Statistical sampling involves using probability theory to select a sample from the population and draw conclusions about the population based on the sample. Nonstatistical sampling, on the other hand, is based on the auditor's professional judgment and does not use statistical inference to come to a conclusion. This book does not cover nonstatistical sampling.

International auditing standards prescribe the manner in which statistical sampling should be conducted in an audit. The following section discusses what these standards say about statistical sampling.

## *2. Foundations of Auditing*

### **2.1. Auditing Standards**

There are three auditing standards related to statistical sampling in the audit:

- ISA 530: Auditing standard for international firms published by the International Auditing and Assurance Standards Board (IAASB).
- AU-C 530: Auditing standard for private firms published by the American Institute of Certified Public Accountants (AICPA).
- AS 2315: Auditing standard for public firms published by the Public Company Accounting Oversight Board (PCAOB).

All three standards present a similar explanation of statistical sampling. For instance, ISA 530 (International Auditing and Assurance Standards Board (IAASB), 2018) defines statistical audit sampling as a method that at minimum exhibits the following two characteristics:

- Random selection of sample items,
- The use of an appropriate statistical technique to evaluate sample results, including measurement of sampling risk

According to auditing standards, any sampling approach that lacks these two characteristics is considered nonstatistical sampling.

In order to effectively utilize statistical sampling during an audit, it is necessary to tailor the approach to the specific circumstances of the audit. This may involve considering factors such as the size and complexity of the population, the materiality of the items being tested, and the level of inherent risk in the audit area. It is also essential for the auditor to document the sampling process in order to demonstrate compliance with auditing standards. The following sections will delve further into these crucial concepts in the context of statistical audit sampling.

### **2.2. Important Concepts**

This section aims to delve into several theoretical concepts that are integral to statistical audit sampling.

### 2.2.1. Materiality

In an audit, materiality is the maximum amount of misstatement that can be present in the financial statements of the auditee before the auditor concludes that the financial statements are materially misstated, meaning that they contain misstatements that would influence the decisions of stakeholders relying on those statements.

The term performance materiality refers to the maximum amount of misstatement that can be present in a given population that is part of the financial statements before the auditor concludes that the population is materially misstated. Performance materiality is used by auditors to determine the appropriate level of testing to be performed on a population.

 Note

The performance materiality is usually defined to be lower than the materiality because an individual population that is subject to audit sampling is often only a (small) part of the financial statements.

For example, consider an audit of a company's financial statements for the year ended December 31, 2021. The auditor determines that the company's accounts receivable balance is a large part of the financial statements and decides to test a sample of the accounts receivable transactions to assess the accuracy of the balance. The auditor calculates the performance materiality for the accounts receivable balance by considering the materiality for the financial statements as a whole. If the auditor finds misstatements in the sample such that their estimate of the misstatement exceeds the performance materiality, the auditor would need to express an unqualified opinion on the population or would need to perform additional testing on the population. If the auditor finds misstatements in the sample such that their estimate of the misstatement does not exceed the performance materiality, the auditor would express a positive opinion on the financial statements.

### 2.2.2. Audit risk

After completing an audit and making any necessary corrections, an auditor will issue a written report stating whether the financial statements are accurate and free of material misstatement. The potential for this opinion to be incorrect is known as audit risk, and it is the auditor's job to minimize this risk as much as possible.

## *2. Foundations of Auditing*

For example, during an audit of a company's financial statements, the auditor may carefully review documentation, perform tests of details via audit sampling, and speak with management in order to reduce the audit risk and provide a reliable opinion on the accuracy of the financial statements as a whole.

### **2.2.3. Population**

In statistical inference, the term population refers to the entire group of individuals or items that have some common characteristic or interest, and about which we want to gather data or make inferences. A population can be as large as all the people in a country or, as is more sensible in auditing, as small as a group of employees in a specific department of a company.

For example, consider an audit of a company's payroll records. The population in this case would be all the employees of the company, and the goal of the audit would be to gather data on their salaries, benefits, and other payroll-related information. The audit team would collect this data from a representative group of employees (i.e., a sample) of the population and use statistical methods to draw conclusions about the entire population.

### **2.2.4. Sampling risk**

There is a possibility that the results of an audit based on a sample may differ from the results if the entire population were examined using the same procedures. This is known as sampling risk. Sampling risk can result in two types of incorrect conclusions:

1. The first type is when, in a test of controls, the controls are perceived to be more effective than they actually are, or in a test of details, a material misstatement is believed to not exist when it actually does. This type of erroneous conclusion is particularly concerning for auditors because it can compromise the effectiveness of the audit and may lead to an inappropriate audit opinion.
2. The second type of incorrect conclusion is when, in a test of controls, the controls are perceived to be less effective than they actually are, or in a test of details, a material misstatement is believed to exist when it actually does not. This type of erroneous conclusion impacts the efficiency of the audit as it may require additional work to determine that the initial conclusions were incorrect.

## 2.2. Important Concepts

Many audits are performed according to the *audit risk model (ARM)*, which determines that the uncertainty about the auditor's statement as a whole is a factor of three terms: the inherent risk, the control risk, and the detection risk (i.e., the sampling risk). Inherent risk is the risk posed by a misstatement in the auditee's financial statements that could be material, before consideration of any related control systems (e.g., computer systems). Control risk is the risk that a material misstatement is not prevented or detected by the auditee's internal control systems. Detection risk is the risk that the auditor will fail to find material misstatements that exist in the auditee's financial statements. The *ARM* is practically useful because, for a given level of audit risk, the tolerable detection risk bears an inverse relation to the other two risks.

$$\text{Audit risk} = \text{Inherent risk} \times \text{Control risk} \times \text{Detection risk} \quad (2.1)$$

Usually the auditor judges inherent risk and control risk on a three-point scale consisting of low, medium, and high. Different audit firms handle different standard percentages for these categories. Given an assessment of the inherent risk and the control risk, the detection risk can be calculated as:

$$\text{Detection risk} = \frac{\text{Audit risk}}{\text{Inherent risk} \times \text{Control risk}} \quad (2.2)$$

### i Note

The ARM is commonly used in practice, but is not a proper model of audit risk. For example, it is not possible to set one of the risks to zero, as that would result in an infinite detection risk (e.g.,  $\frac{0.05}{0 \times 1} = \infty$ ).

Let's consider an example. Suppose that, in their audit guide, an audit firm associates the following percentages with the categories high, medium and low:

- High: 100%
- Medium: 60%
- Low: 50%

If an auditor is working with an audit risk of 5%, and judges inherent and control risk to both be medium, the sampling risk can be calculated as:

$$\frac{0.05}{0.6 \times 0.6} = 0.139 \quad (2.3)$$

## *2. Foundations of Auditing*

### **2.2.5. Sample Size**

The sample size is an important consideration in the context of audit sampling, as it determines the number of items that will be selected for testing during the audit process. This factor has an impact on both effectiveness and efficiency. In general, a larger sample size can provide a higher level of assurance, but it requires more audit effort to obtain and inspect. On the other hand, a smaller sample size offers a lower level of assurance, but it is less costly.

### **2.2.6. Notation**

The table below summarizes the notation used in this book (middle column) and in the **jfa** R package (right column).

Meaning	Symbol	<b>jfa</b>
Probability of misstatement	$\theta$	
Performance materiality	$\theta_{max}$	materiality
Expected deviation rate	$\theta_{exp}$	expected
Type-I error probability	$\alpha$	1 - conf.level
Type-II error probability	$\beta$	
Population size	$N$	N.units
Population misstatements	$K$	
Sample size	$n$	n
Observed misstatements	$k$	x

# 3. Statistical Inference

**i** You are reading the work-in-progress first edition of Statistical Auditing with R. This chapter is currently a dumping ground of ideas, and it is incomplete.

## 3.1. Classical Inference

Frequentist statistics, also known as classical statistics, is a statistical framework that is based on the concept of probability as a long-term frequency of events. This approach assumes that statistical models are purely objective and that data is generated by a well-defined process, which can be described by a set of probabilistic assumptions. The philosophy behind frequentist statistics is that statistical estimates should be based on the frequency of events in a population, rather than on subjective or personal beliefs. This approach is particularly useful for making predictions or making decisions based on data, as it allows for the calculation of confidence intervals and statistical tests, which provide a measure of the reliability of the estimates. Overall, frequentist statistics is a rigorous and reliable approach that is widely used in the scientific community for making informed decisions based on data.

### 3.1.1. Estimation

The philosophy behind frequentist parameter estimation is based on the idea that statistical parameters are fixed, but unknown, quantities that can be estimated through the process of repeated sampling. This approach assumes that the sample data represent a random sample from a larger population, and that the sample statistics (i.e., the sample proportion of misstatements) can be used to estimate the corresponding population parameters (i.e., the population misstatement). The key principle of frequentist estimation is that the estimated parameter values should be unbiased and have a certain level of uncertainty, which can be quantified through confidence bounds or intervals.

### 3. Statistical Inference

#### 3.1.1.1. Example

As an example, the `binom.test()` function in R can be used to estimate the rate of misstatement in a population given a data sample of  $n$  items containing  $k$  misstatements. Suppose an auditor audited a sample of  $n = 60$  items containing  $k = 0$  misstatements. To use the `binom.test()` function to perform estimation, the auditor must input the number of items in the sample  $n = 60$ , the number of misstatements in the sample  $x = 0$ , and the hypothesized proportion of misstatement in the population (i.e., the performance materiality), which is irrelevant and should thus be set to  $p = 1$ . The sampling risk is set to 5%, which the auditor can provide to the function with `conf.level = 1 - 0.05`. Finally, the auditor can specify the alternative hypothesis as `alternative = "less"` to compute a one-sided confidence interval since they are interested in obtaining the upper confidence bound.

```
binom.test(x = 0, n = 60, p = 1, alternative = "less", conf.level =
  ↪ 0.95)
#>
#> Exact binomial test
#>
#> data: 0 and 60
#> number of successes = 0, number of trials = 60, p-value < 2.2e-16
#> alternative hypothesis: true probability of success is less than
  ↪ 1
#> 95 percent confidence interval:
#> 0.00000000 0.04870291
#> sample estimates:
#> probability of success
#> 0
```

The most likely misstatement in the population is displayed under `sample estimates` and is 0%. The 95% upper confidence bound for the estimate of the population misstatement is displayed under `95 percent confidence interval` and is 4.87%.

#### 3.1.2. Hypothesis Testing

Frequentist hypothesis testing is a statistical method that involves evaluating the probability of obtaining a certain sample outcome or more extreme, given a certain assumption

### 3.1. Classical Inference

or hypothesis. This probability, known as the  $p$  value, is used to determine the likelihood of the hypothesis being true.

For example, in a typical audit sampling hypothesis test using the binomial distribution, we may be interested in testing the hypothesis that the misstatement is higher or lower than the performance materiality. We would inspect a sample and calculate the  $p$  value based on the observed frequency of misstatements versus the expected frequency under the assumption of material misstatement. If the  $p$  value is below the sampling risk  $\alpha$ , we reject the hypothesis that the population is materially misstated and conclude that it is not materially misstated.

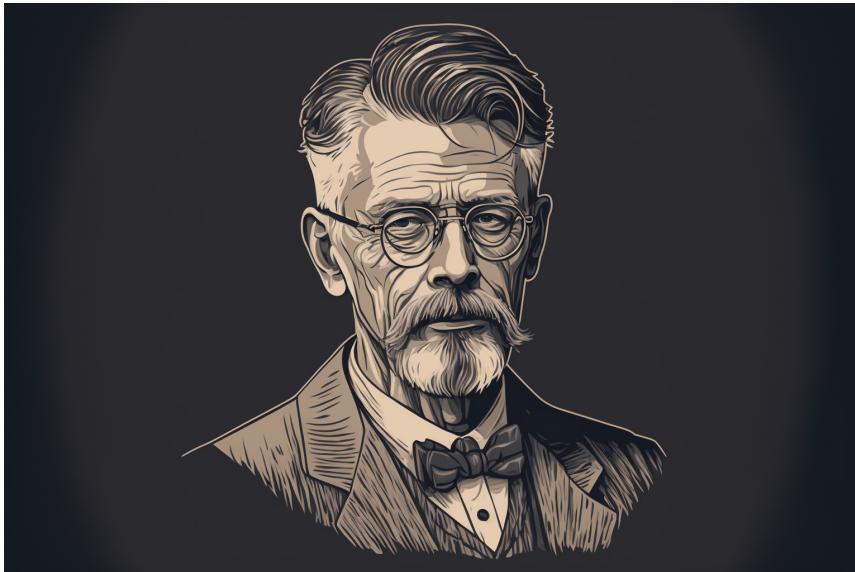


Figure 3.1.: Innovating statistical methods and shaping the field of genetics, Sir Ronald Fisher was a pioneer in the world of science. Image available under a CC-BY-NC 4.0 license.

#### 3.1.2.1. Example

Next to estimation, the `binom.test()` function in R can also be used to test if a population contains is free of material misstatement, which in this case means that the population contains less than 3 percent misstatements. Suppose an auditor obtained a sample of  $n = 100$  items containing  $k = 0$  misstatements. To use the `binom.test()` function, the auditor must input the number of items in the sample  $n = 100$ , the number of misstatements in the sample  $x = 0$ , and the hypothesized proportion of misstatement in the population

### 3. Statistical Inference

(i.e., the performance materiality)  $p = 0.03$ . The sampling risk is set to 5%, which the auditor can provide to the function with `conf.level = 1 - 0.05`. Finally, the auditor can specify the alternative hypothesis as `alternative = "less"` to test if the proportion of misstatements in the sample is less than the hypothesized proportion.

```
binom.test(x = 0, n = 100, p = 0.03, alternative = "less",
            conf.level = 0.95)
#>
#> Exact binomial test
#>
#> data: 0 and 100
#> number of successes = 0, number of trials = 100, p-value =
#>      0.04755
#> alternative hypothesis: true probability of success is less than
#>      0.03
#> 95 percent confidence interval:
#>  0.00000000 0.02951305
#> sample estimates:
#> probability of success
#>                      0
```

The  $p$  value is shown under `p-value` and is 0.04755. Since the  $p$  value is lower than the specified sampling risk  $\alpha$ , the auditor can reject the hypothesis that the population contains material misstatement and should conclude that the population does not contain material misstatement.

## 3.2. Bayesian Inference

Bayesian inference is based on the idea that the parameters in a statistical model are not fixed but uncertain. In this approach, the parameter is considered to be a random variable with a certain distribution, and the goal is to use the data and any prior knowledge about the parameter to update our belief about its value. This is typically done using Bayes' theorem, which states that the posterior probability (i.e., the updated belief about the parameter after seeing the data) is equal to the prior probability (i.e., the belief about the parameter before seeing the data) times the likelihood (i.e., the probability of the data given the parameter).

$$\text{Posterior} \propto \text{Likelihood} \times \text{Prior} \quad (3.1)$$

Bayesian statistics is a more nuanced approach that allows for more efficiency in statistical audit sampling, but it requires the specification of prior distributions that can be difficult to quantify. That is because, especially in an audit, all information that is incorporated into the statistical analysis should be based on audit evidence and should be properly justified.

### 3.2.1. Estimation

One major difference between classical and Bayesian statistics is the way they handle uncertainty. In classical statistics, uncertainty is represented by the standard error of an estimate, which is a measure of the precision of an estimate. In Bayesian statistics, uncertainty is represented by the posterior distribution, which is a distribution of the possible values of the population parameter given the sample data and our prior beliefs. Bayesian inferences uses Bayes' theorem to update the prior beliefs about the population parameter with the new information from the sample data. Bayes' theorem is given by the following formula:

$$p(\theta|y) = \frac{p(y|\theta)p(\theta)}{p(y)} \quad (3.2)$$

where  $p(\theta|y)$  is the posterior probability of the population parameter  $\theta$  given the sample data  $y$ ,  $p(y|\theta)$  is the likelihood of the sample data given  $\theta$ ,  $p(\theta)$  is the prior probability of  $\theta$ , and  $p(y)$  is the total probability of the sample data occurring. Because with a fixed sample  $p(y)$  is a constant, Bayes' theorem is often given as follows:

$$p(\theta|y) \propto p(y|\theta) \times p(\theta) \quad (3.3)$$

#### 3.2.1.1. Example

Bayesian inference involves first specifying a prior distribution that captures the available information about the probability of misstatement in the population. For illustrative purposes, we use a simple prior distribution that is indifferent about the possible values of the misstatement. Note that this prior distribution does not contain any information

### *3. Statistical Inference*

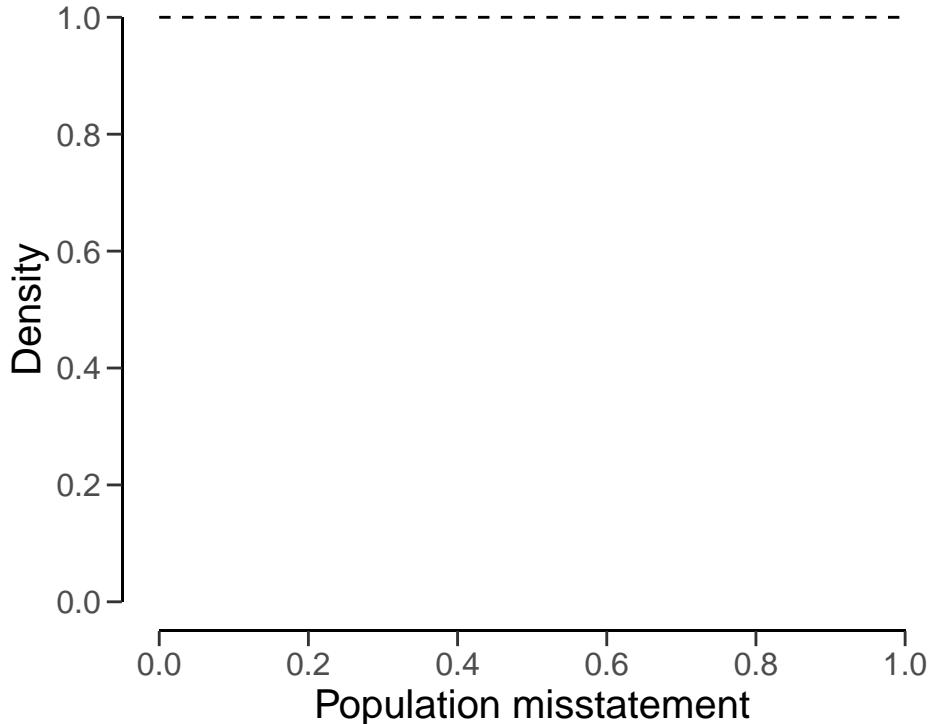


Figure 3.2.: Thomas Bayes revolutionized the world of statistics and probability with his groundbreaking work on Bayes' Theorem. His contributions continue to shape the way we understand and analyze data today. Image available under a CC-BY-NC 4.0 license.

### 3.2. Bayesian Inference

about the probability of misstatement, but yields statistical results that closely resemble classical outcomes. Chapters 3, 4, 5 and 6 dive deeper into the R functions from the **jfa** package used in this example, such as the `auditPrior()` function below.

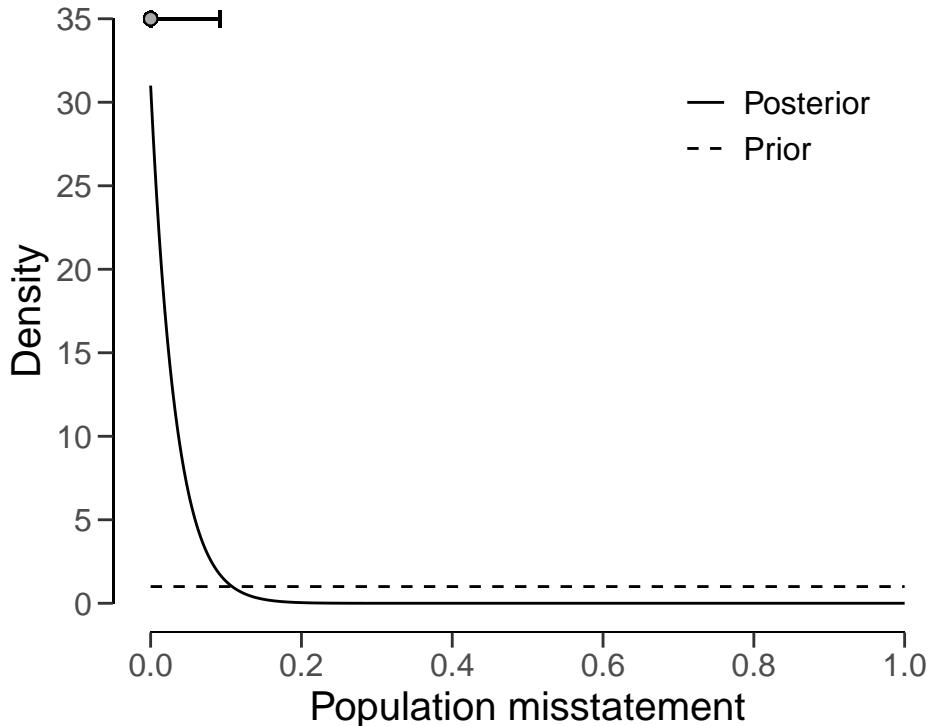
```
prior <- auditPrior(method = "default", likelihood = "binomial")
plot(prior)
```



After seeing an item from the population, the prior distribution is updated to the posterior distribution by means of Bayes' theorem. Next, the posterior is used as a prior distribution for the following item, which is once again updated to a posterior distribution after seeing another the item. This process of updating the prior distribution to a posterior distribution, and using the posterior as a prior can continue indefinitely. For example, after seeing 30 items from the population, of which none contained a misstatement, the posterior distribution peaks at zero, reflecting the fact that no misstatements were found, and its mass has shifted towards zero when compared to the prior distribution, reflecting the fact that the data contained information that indicates a low probability of misstatement.

### 3. Statistical Inference

```
eval <- evaluation(x = 0, n = 30, method = "binomial", prior =
  ↪ prior)
plot(eval)
```

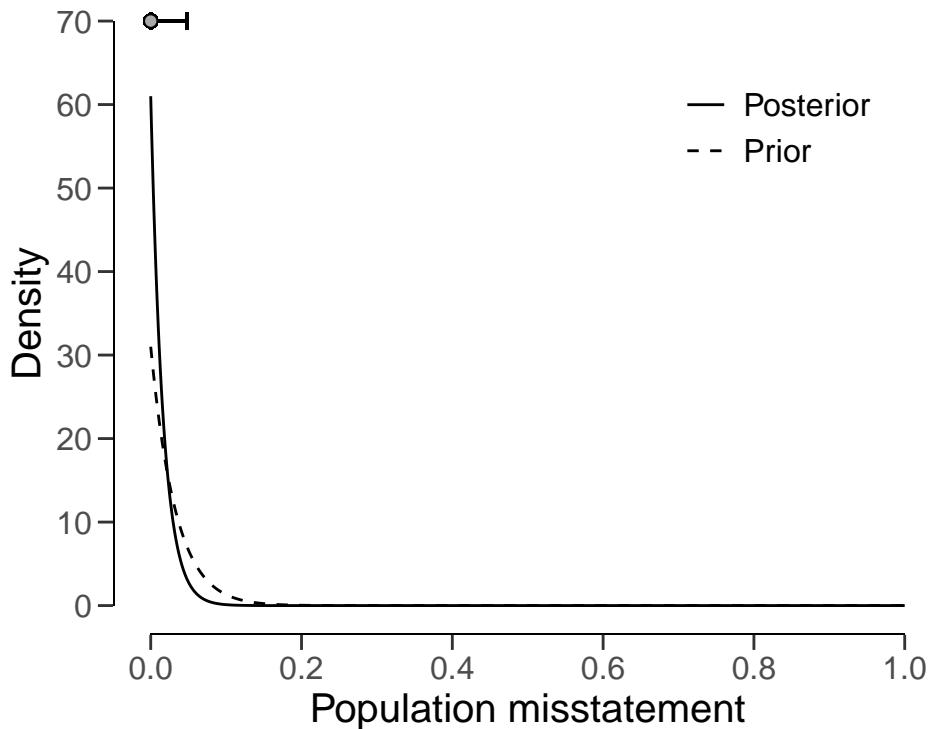


The most likely value of the population misstatement based on these data is shown as a point above the highest point of the posterior distribution. The uncertainty about the population misstatement can be quantified using a credible interval (shown as a line above the posterior distribution). In this case, the figure above shows a 95% credible interval, which contains the true value of the population misstatement with a 95% probability.

After seeing 30 more observations, of which none contained a misstatement, the mass of the posterior distribution has shifted towards zero even more. The credible interval shown above the posterior distribution encompasses a smaller range of values, reflecting the fact that additional information has been observed and thus that there is less uncertainty about the population misstatement than before.

### 3.2. Bayesian Inference

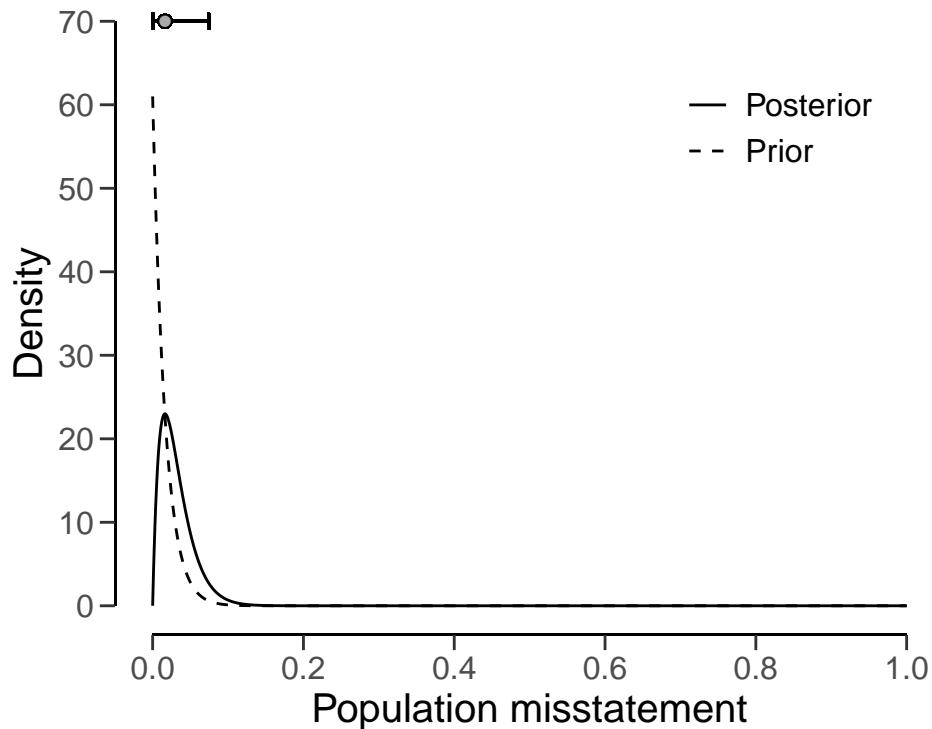
```
eval <- evaluation(x = 0, n = 30, method = "binomial", prior =
  ↵ eval$posterior)
plot(eval)
```



The updating process works the same for the scenario in which the auditor finds misstatements in the sample. For example, the posterior distribution after finding a single misstatement is has its mass shifted away from zero, reflecting the fact that a probability of zero is unlikely given the sample data.

```
eval <- evaluation(x = 1, n = 1, method = "binomial", prior =
  ↵ eval$posterior)
plot(eval)
```

### 3. Statistical Inference



#### 3.2.2. Hypothesis Testing

The Bayes factor is a measure used in Bayesian inference to compare the relative strength of evidence between two competing hypotheses. The Bayes factor is calculated by comparing the probability of the observed data given each of the two competing hypotheses. This probability is known as the likelihood of the data. The Bayes factor is then the ratio of the likelihood of the data under one hypothesis to the likelihood of the data under the other hypothesis. The Bayes factor can be used in the context of an audit, where the auditor is trying to determine the likelihood that a particular financial statement is represented fairly or not.

For example, an auditor might be evaluating the fairness of a company's financial statements for the year. They have two hypotheses: the first is that the statements are accurate, and the second is that the statements are not accurate. The auditor gathers data from a statistical audit sample and uses this data to calculate the Bayes factor.

The Bayes factor is calculated by taking the ratio of the probability of the first hypothesis (that the statements are accurate) given the observed data, to the probability of the second

### *3.2. Bayesian Inference*

hypothesis (that the statements are not accurate) given the observed data. The higher the Bayes factor, the more likely it is that the first hypothesis is true.

The Bayes factor can be used to assess the strength of evidence for one hypothesis over the other and to determine which hypothesis is more likely to be true given the observed data. It is often used in scientific research to help evaluate the validity of different hypotheses and to make informed decisions based on the available evidence. For auditors, the Bayes factor can be a useful tool to determine the likelihood of different hypotheses being true based on the data they have collected, and it can help them make informed decisions about the fairness of the financial statements.

For example, if the Bayes factor is 5, this means that the probability of the statements being accurate given the observed data is 5 times higher than the probability of them being not accurate. In this case, the auditor would be more likely to conclude that the financial statements are accurate.

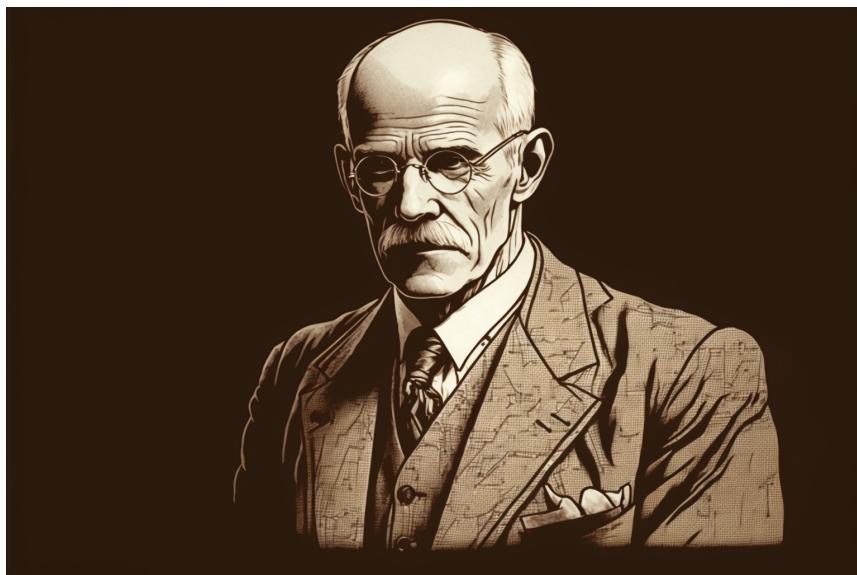


Figure 3.3.: Sir Harold Jeffreys innovated statistical hypothesis testing with his Bayes factor approach, helping us make better decision in the face of uncertainty. Image available under a CC-BY-NC 4.0 license.

### 3. Statistical Inference

#### 3.2.2.1. Example

Suppose an auditor obtained a sample of  $n = 100$  items containing  $k = 0$  misstatements. Given the number of items in the sample  $n = 100$ , the number of misstatements in the sample  $x = 0$ , and the hypothesized proportion of misstatement in the population (i.e., the performance materiality)  $p = 0.03$  the Bayes factor is displayed under BF10 and is 668.65, meaning that if the data are about 668 times more likely to occur under the hypothesis of tolerable misstatement than under the hypothesis of intolerable misstatement.

```
evaluation(materiality = 0.03, x = 0, n = 100, method = "binomial",
  ↪ prior = TRUE)
#>
#> Bayesian Audit Sample Evaluation
#>
#> data: 0 and 100
#> number of errors = 0, number of samples = 100, taint = 0, BF10 =
#> 668.65
#> alternative hypothesis: true misstatement rate is less than 0.03
#> 95 percent credible interval:
#> 0.00000000 0.02922515
#> most likely estimate:
#> 0
#> results obtained via method 'binomial' + 'prior'
```

## **Part II.**

# **Workflow**



# 4. Planning

**i** You are reading the work-in-progress first edition of Statistical Auditing with R. This chapter is currently a dumping ground of ideas, and it is incomplete.

One of the key considerations in audit sampling is determining the appropriate sample size to reduce the sampling risk to an appropriately low level, while minimizing audit effort. To quantify the sampling risk, it is necessary to specify the statistical model that connects the data to the population misstatement, referred to as the likelihood. This chapter will delve into three standard likelihoods commonly employed in audit sampling: the hypergeometric likelihood, the binomial likelihood, and the Poisson likelihood.

Note that planning is a game of optimization that could be avoided. If you are using the Bayesian approach to audit sampling, it is not required to plan a specific sample size in advance (Derks et al., 2022b). That is because in Bayesian inference, the posterior distribution after seeing each item is used as the prior distribution for the next item. That means that you can simply start sampling and monitor the evidence in the data over time. However, to get an idea of how many samples are required to reduce the sampling risk to an level, planning a sample using a Bayesian approach can still be good practice.

## 4.1. Required Information

First, planning a minimum sample requires knowledge of the conditions that lead to acceptance or rejection of the population (i.e., the sampling objectives). Typically, sampling objectives can be classified into one or both of the following:

- **Hypothesis testing:** The goal of the sample is to obtain evidence for or against the claim that the misstatement in the population is lower than a given value (i.e., the performance materiality). Note that if this sampling objective is not specified, the performance materiality can be set to 1.

#### 4. Planning

- **Estimation:** The goal of the sample is to obtain an accurate estimate of the misstatement in the population (with a minimum precision). Note that if this sampling objective is not specified, the minimum precision can be set to 1.

Second, it is advised to specify the expected (or tolerable) misstatements in the sample. The expected misstatements are the misstatements that you allow in the sample, while still retaining the desired amount of assurance about the population. It is strongly recommended to set the value for the expected misstatements in the sample conservatively to minimize the chance of the observed misstatements in the sample exceeding the expected misstatements, which would imply that insufficient work has been done in the end to reduce the sampling risk to an appropriately low level.

Finally, next to determining the sampling objective(s) and the expected misstatements, it is important to determine the statistical distribution linking the sample outcomes to the population misstatement. This distribution is called the likelihood (i.e., poisson, binomial, or hypergeometric). All three aforementioned likelihoods are commonly used in an audit sampling context, however, poisson is the default likelihood in **jfa** because it is the most conservative of the three. In the subsections below, we elaborate on the three standard likelihoods for audit sampling and demonstrate how they can be used to obtain a minimum sample size.

In **jfa**, determining an appropriate sample size is achieved via the `planning()` function.

## 4.2. The Hypergeometric Likelihood

The hypergeometric distribution is a discrete probability distribution that is commonly used to model the number of events occurring in a fixed number of trials when the population size is known. It assumes that samples are drawn from the population without replacement, and is therefore the likelihood that most closely resembles the audit practice. For our purpose, we can use the hypergeometric distribution as a likelihood to model the number of misstatements that are expected to be found in the sample.

The probability mass function (PMF) of the hypergeometric distribution is given by:

$$p(X = k) = \frac{\binom{K}{k} \binom{N-K}{n-k}}{\binom{N}{n}}, \quad (4.1)$$

## 4.2. The Hypergeometric Likelihood



Figure 4.1.: When the sampling objectives, the expected misstatements and the likelihood are set, there exists only one sample size that minimizes the amount of audit effort. Image available under a CC-BY-NC 4.0 license.

where  $k$  is the number of misstatements in the sample,  $n$  is the sample size,  $N$  is the population size and  $K$  is the total number of misstatements assumed in the population. The assumed misstatements  $K$  is a whole number, that is, a linear extrapolation of the maximum tolerable misstatement rate (i.e., the performance materiality)  $\theta_{max}$  to the total population of size  $N$ :

$$K = \lceil \theta_{max}N \rceil. \quad (4.2)$$

### i Note

[...] is the ceiling function, which means that  $\lceil 1.2 \rceil = 2$ .

Let's consider how to use the hypergeometric likelihood to calculate the minimum sample size needed to reduce the sampling risk to an appropriately low level.

## 4. Planning

### 4.2.1. Classical planning

In classical planning using the hypergeometric likelihood, the following statistical model is specified:

$$k \sim \text{Hypergeometric}(n, N, K) \quad (4.3)$$

Given the performance materiality  $\theta_{max}$ , we can compute  $K$  and solve for the minimum sample size  $n$  needed to reduce the sampling risk to an appropriately low level. This sample size is also dependent on the number of misstatements that the auditor expects, or tolerates, in the sample.

#### 4.2.1.1. No Expected Misstatements

If the auditor does not expect any misstatements in the sample, they can set  $k = 0$ , which consequently determines how the sample size can be calculated. For example, if we want to achieve an assurance level of 95% ( $\alpha = 0.05$ ) for a performance materiality of  $\theta_{max} = 0.03$  in a population of  $N = 1000$  items, then  $K = [0.03 \cdot 1000] = 30$  and the minimum sample size under the assumption of no expected misstatements in the sample is  $n = 94$ .

```
plan <- planning(materiality = 0.03, expected = 0, conf.level =
  ↪ 0.95, likelihood = "hypergeometric", N.units = 1000)
plan
#>
#> Classical Audit Sample Planning
#>
#> minimum sample size = 94
#> sample size obtained in 95 iterations via method
  ↪ 'hypergeometric'
```

The sample size of 94 can be confirmed by checking that 94 is the minimum integer that results in less than 5% probability of finding 0 misstatements, given the assumption that the population misstatement is truly 3%. The `dhyper()` function calculates the probability of observing  $k$  missates in a sample of  $n$  items given the assumed hypergeometric distribution with  $N$  items and  $K$  assumed misstatements in the population. By calculating this probability for  $n = 93$ , we can show that this sample size is insufficient as the relevant probability is higher than the sampling risk  $\alpha$ .

## 4.2. The Hypergeometric Likelihood

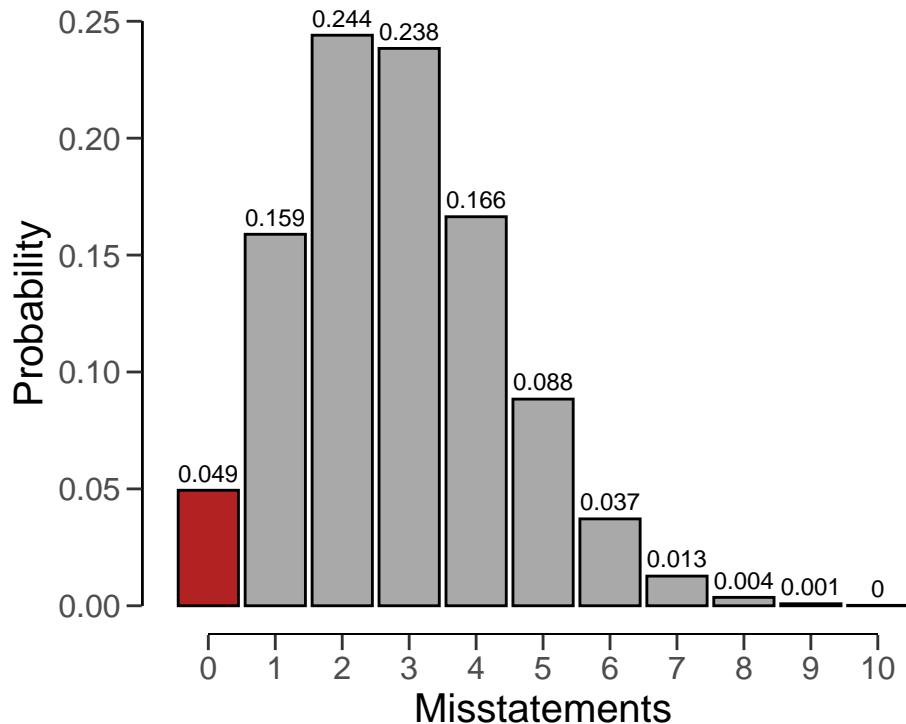
```
K <- ceiling(0.03 * 1000)
dhyper(x = 0, m = K, n = 1000 - K, k = 93) < 0.05
#> [1] FALSE
```

However, for  $n = 94$  the relevant probability is lower than the sampling risk  $\alpha$  and thus the sample size is considered to be sufficient.

```
dhyper(x = 0, m = K, n = 1000 - K, k = 94) < 0.05
#> [1] TRUE
```

We can make this sample size visually intuitive by showing the hypergeometric( $k | 94, 1000, 30$ ) distribution and highlighting the probability for  $k = 0$ . This probability is lower than the required sampling risk  $\alpha = 0.05$ .

```
plot(plan)
```



## 4. Planning

### 💡 Additional arguments to planning()

The `planning()` function has two additional arguments that are not shown in the call above: `by` and `max`. The argument `by` sets the increment between possible sample sizes for consideration. For example, `by = 5` considers only samples of size 10, 20, 30, etc:

```
planning(materiality = 0.03, expected = 0, conf.level = 0.95,
  ↪ likelihood = "hypergeometric", N.units = 1000, by = 10)
#>
#> Classical Audit Sample Planning
#>
#> minimum sample size = 100
#> sample size obtained in 11 iterations via method
  ↪ 'hypergeometric'
```

The argument `max` sets the sample size at which the algorithm terminates. This can be used to avoid too many iterations of the algorithm at very low values of the performance materiality. For instance, `max = 50` throws an error if more than 100 samples are required.

```
planning(materiality = 0.03, expected = 0, conf.level = 0.95,
  ↪ likelihood = "hypergeometric", N.units = 1000, max = 50)
#> Error in planning(materiality = 0.03, expected = 0,
  ↪ conf.level = 0.95, : the sample size is larger than 'max'
```

### 4.2.1.2. Expected Misstatements

If the auditor expects misstatements in the sample, they can set  $k$  to any integer value, which consequently determines how the sample size can be calculated. As another example, if we want to achieve an assurance level of 95% ( $\alpha = 0.05$ ) for a performance materiality of  $\theta_{max} = 0.03$  in a population of  $N = 1000$  items, then the required sample size under the assumption of one expected misstatement in the sample is  $n = 147$ .

## 4.2. The Hypergeometric Likelihood

```
plan <- planning(materiality = 0.03, expected = 1, conf.level =
  ↵ 0.95, likelihood = "hypergeometric", N.units = 1000)
plan
#>
#> Classical Audit Sample Planning
#>
#> minimum sample size = 147
#> sample size obtained in 146 iterations via method
  ↵ 'hypergeometric'
```

Once again, the sample size of 147 can be confirmed by checking that 147 is the minimum integer that results in less than 5% probability of finding 0 or 1 misstatements, given the assumption that the population misstatement is truly 3%. By calculating this probability for  $n = 146$ , we can show that this sample size is insufficient as the relevant probability is higher than the sampling risk  $\alpha$ .

```
sum(dhyper(x = 0:1, m = K, n = 1000 - K, k = 146)) < 0.05
#> [1] FALSE
```

However, for  $n = 147$  the relevant probability is lower than the sampling risk  $\alpha$  and thus the sample size is considered to be sufficient.

```
sum(dhyper(x = 0:1, m = K, n = 1000 - K, k = 147)) < 0.05
#> [1] TRUE
```

Like before, we can make this sample size visually intuitive by showing the  $\text{hypergeometric}(k \mid 147, 1000, 30)$  distribution and highlighting the probabilities for  $k = 0$  and  $k = 1$ . The sum of these probabilities is lower than the required sampling risk  $\alpha = 0.05$ .

```
plot(plan)
```

#### 4. Planning



#### 4.2.2. Bayesian Planning

Performing Bayesian planning with the hypergeometric likelihood (Dyer & Pierce, 1993) requires that you specify a prior distribution for the total misstatements  $K$ . Practically, this means that you should provide an input for the `prior` argument in the `planning()` function.

Setting `prior = TRUE` performs Bayesian planning using a default prior conjugate to the specified likelihood (i.e., a beta-binomial prior). Because this is a Bayesian analysis, the following statistical model is specified:

$$k \sim \text{Hypergeometric}(n, N, K) \quad (4.4)$$

$$K \sim \text{Beta-binomial}(N, \alpha, \beta) \quad (4.5)$$

**i Note**

The beta-binomial prior distribution is the conjugate prior for the hypergeometric likelihood (see this list of conjugate priors), which means that the posterior distribution of  $K$  can be determined analytically. For example, if the prior distribution for  $K$  is:

$$K \sim \text{Beta-binomial}(N, \alpha, \beta) \quad K = 0, \dots, N \quad (4.6)$$

and the auditor has observed a sample of  $n$  items containing  $k$  misstatements, then the posterior distribution for  $K$  is:

$$K \sim \text{Beta-binomial}(N - n, \alpha + k, \beta + k - n) \quad K = k, k + 1, \dots, N - n + k. \quad (4.7)$$

#### 4.2.2.1. No Expected Misstatements

Planning for no expected misstatements in the sample can be done by setting the value for the expected argument to zero. If we want to achieve an assurance level of 95% ( $\alpha = 0.05$ ) for a performance materiality of  $\theta_{max} = 0.1$  in a population of  $N = 20$  items, then the required sample size under the assumption of zero expected misstatements in the sample is  $n = 15$ . The command below uses a default beta-binomial( $N, 1, 1$ ) prior distribution to plan this sample, since planning() is given the hypergeometric likelihood.

```
plan <- planning(materiality = 0.1, expected = 0, conf.level = 0.95,
                   likelihood = "hypergeometric", N.units = 20, prior = TRUE)
```

The summary() function can be used to obtain relevant information about the planning.

```
summary(plan)
#>
#> Bayesian Audit Sample Planning Summary
#>
#> Options:
#>   Confidence level:          0.95
#>   Population size:           20
```

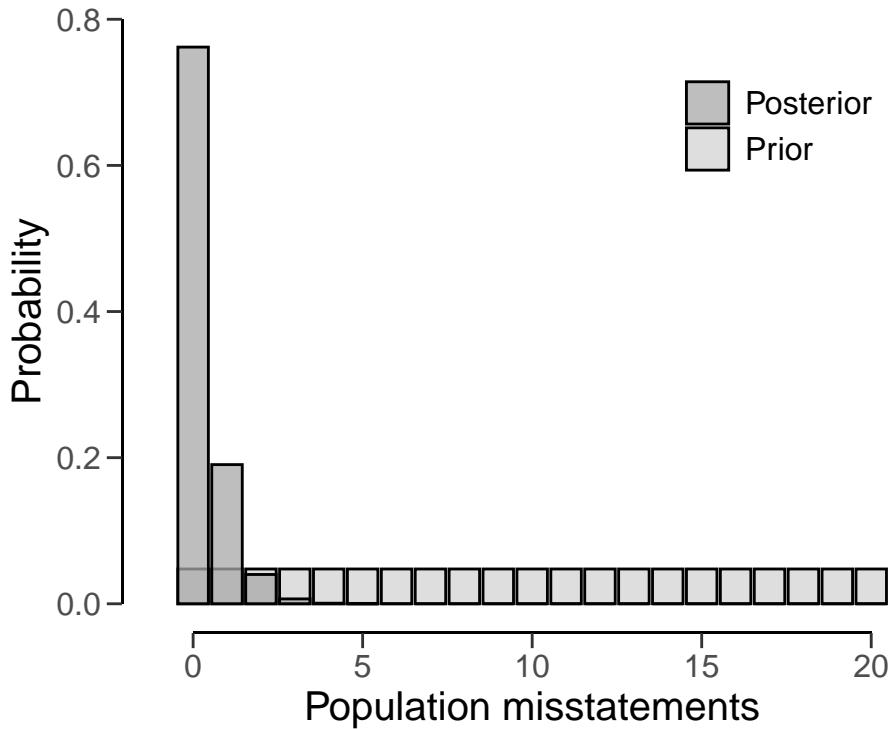
#### 4. Planning

```
#> Materiality:          0.1
#> Hypotheses:           H0 :  $\bar{X} > 0.1$  vs. H1 :  $\bar{X} < 0.1$ 
#> Expected:              0
#> Likelihood:            hypergeometric
#> Prior distribution:    beta-binomial(N = 20,  $\bar{X}_0 = 1$ ,  $\bar{X}_1 = 1$ )
#>
#> Results:
#> Minimum sample size:   15
#> Tolerable errors:      0
#> Posterior distribution: beta-binomial(N = 5,  $\bar{X}_0 = 1$ ,  $\bar{X}_1 = 16$ )
#> Expected most likely error: 0
#> Expected upper bound:   0.05
#> Expected precision:     0.05
#> Expected BF10:          190
```

You can inspect how the prior distribution compares to the expected posterior distribution by using the `plot()` function. The expected posterior distribution is the posterior distribution that would occur if you actually observed the planned sample containing the expected misstatements. Note that the posterior distribution is only defined in the range  $[k; N - n + k]$ , since a part of the population has already been seen.

```
plot(plan)
```

## 4.2. The Hypergeometric Likelihood



### 4.2.2.2. Expected Misstatements

Planning for expected misstatements in the sample can be done by setting the value for the expected argument to a different value than zero. For example, the command below calculates the minimum sample size to achieve an assurance level of 95% ( $\alpha = 0.05$ ) for a performance materiality of  $\theta_{max} = 0.1$  in a population of  $N = 50$  items, given one expected misstatement in the sample. This sample size is  $n = 32$ .

```
plan <- planning(materiality = 0.1, expected = 1, conf.level = 0.95,
  ↵ likelihood = "hypergeometric", N.units = 50, prior = TRUE)
plan
#>
#> Bayesian Audit Sample Planning
#>
#> minimum sample size = 32
```

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```
#> sample size obtained in 31 iterations via method  
↳ 'hypergeometric' + 'prior'
```

Like before, you can inspect how the prior distribution compares to the expected posterior distribution by using the `plot()` function.

```
plot(plan)
```



### 4.3. The Binomial Likelihood

The binomial distribution is a discrete probability distribution that is commonly used to model the number of events occurring in a fixed number of trials. It is similar to the hypergeometric distribution, however, it assumes that samples are drawn from the population with replacement. For our purpose, we can use the binomial distribution as

a likelihood to model the number of misstatements that are expected to be found in the sample.

### **i** Note

In audit sampling, the binomial likelihood is often used to approximate the hypergeometric likelihood since it is easier to work with (i.e., it only has two parameters:  $\theta$  and  $n$ , while the hypergeometric has three:  $n$ ,  $N$ , and  $K$ ). However, the binomial likelihood is more conservative than the hypergeometric likelihood, meaning that resulting sample sizes will be higher.

The probability mass function (PMF) of the binomial distribution is given by:

$$p(k; n, \theta) = \binom{n}{k} \theta^k (1 - \theta)^{n-k}, \quad (4.8)$$

where  $k$  is the number of misstatements in the sample,  $n$  is the sample size and  $\theta$  is the probability of misstatement in the population. Let's consider how to use the binomial likelihood to calculate the minimum sample size needed to reduce the sampling risk to an appropriately low level.

#### 4.3.1. Classical Planning

In classical planning using the binomial likelihood, the following statistical model is specified:

$$k \sim \text{Binomial}(n, \theta_{max}) \quad (4.9)$$

##### 4.3.1.1. No Expected Misstatements

If the auditor does not expect any misstatements in the sample, they can set  $k = 0$ , which consequently determines how the sample size can be calculated. Given a performance materiality  $\theta_{max}$ , we can solve for the minimum sample size  $n$  needed to reduce the sampling risk to an appropriately low level. A useful trick to utilize is that, if we do not expect any misstatements in the sample, the formula for the minimum required sample size reduces to:

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$$n = \lceil \frac{\ln(\alpha)}{\ln(1 - \theta_{max})} \rceil. \quad (4.10)$$

For example, if we want to achieve an assurance level of 95% ( $\alpha = 0.05$ ) for a performance materiality of  $\theta_{max} = 0.03$ , then the required sample size under the assumption of zero expected misstatements in the sample is  $n = 99$ .

```
ceiling(log(1 - 0.95) / log(1 - 0.03))
#> [1] 99
```

In **jfa**, this sample size can be replicated using the following code:

```
plan <- planning(materiality = 0.03, expected = 0, conf.level =
  ↪ 0.95, likelihood = "binomial")
plan
#>
#> Classical Audit Sample Planning
#>
#> minimum sample size = 99
#> sample size obtained in 100 iterations via method 'binomial'
```

The sample size of 99 can be confirmed by checking that 99 is the minimum integer that results in less than 5% probability of finding 0 misstatements, given the assumption that the population misstatement is truly 3%. The `dbinom()` function calculates the probability of observing  $k$  missstatements in a sample of  $n$  items given an assumed misstatement probability  $\theta_{max}$ . By calculating this probability for  $n = 98$ , we can show that this sample size is insufficient as the relevant probability is higher than the sampling risk  $\alpha$ .

```
dbinom(x = 0, size = 98, prob = 0.03) < 0.05
#> [1] FALSE
```

However, for  $n = 99$  the relevant probability is lower than the sampling risk  $\alpha$  and thus the sample size is considered to be sufficient.

```
dbinom(x = 0, size = 99, prob = 0.03) < 0.05
#> [1] TRUE
```

### 4.3. The Binomial Likelihood

We can make this sample size visually intuitive by showing the  $\text{binomial}(k \mid 99, 0.03)$  distribution and highlighting the probability for  $k = 0$ . This probability is lower than the required sampling risk  $\alpha = 0.05$ .

```
plot(plan)
```



#### 4.3.1.2. Expected Misstatements

However, if the number of expected misstatements in the sample is non-zero, it becomes more difficult to solve the formula for  $n$ . Hence, they will need to set  $k$  to a different integer value, which consequently determines how the sample size is calculated. Here, we can iteratively try every value of  $n$  and return the smallest integer that satisfies the sampling objectives.

In **jfa**, this can be done by adjusting the `expected` argument in the `planning()` function. For example, if we want to achieve an assurance level of 95% ( $\alpha = 0.05$ ) for a performance

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materiality of  $\theta_{max} = 0.03$ , then the required sample size under the assumption of one expected misstatement in the sample is  $n = 157$ .

```
plan <- planning(materiality = 0.03, expected = 1, conf.level =
  ↵ 0.95, likelihood = "binomial")
```

Once again, the sample size of 157 can be confirmed by checking that 157 is the minimum integer that results in less than 5% probability of finding 0 or 1 misstatements, given the assumption that the population misstatement is truly 3%. By calculating this probability for  $n = 156$ , we can show that this sample size is insufficient as the relevant probability is higher than the sampling risk  $\alpha$ .

```
sum(dbinom(x = 0:1, size = 156, prob = 0.03)) < 0.05
#> [1] FALSE
```

However, for  $n = 157$  the relevant probability is lower than the sampling risk  $\alpha$  and thus the sample size is considered to be sufficient.

```
sum(dbinom(x = 0:1, size = 157, prob = 0.03)) < 0.05
#> [1] TRUE
```

Like before, we can make this sample size visually intuitive by showing the  $\text{binomial}(k | 157, 0.03)$  distribution and highlighting the probabilities for  $k = 0$  and  $k = 1$ . The sum of these probabilities is lower than the required sampling risk  $\alpha = 0.05$ .

```
plot(plan)
```



#### 4.3.1.3. Expected Misstatement Rate

When the expected misstatement rate in the sample  $\theta_{exp}$  is assessed, the value for  $k$  can be determined as  $k = n\theta_{exp}$ , which consequently determines how the sample size can be calculated.

To account for the fact that  $k$  can have non-integer values in this case, we can use a well-known similarity between the binomial distribution and the beta distribution to plan the sample size. The upper bound for any  $\text{binomial}(k; n, \theta)$  distributed variable can also be obtained via percentiles of the  $\text{beta}(1 + k, n - k)$  distribution.

For example, the upper bound for a sample of  $n = 10$  items containing  $k = 2$  misstatements, when calculated via the traditional `binom.test()` is:

```
ub_binom <- binom.test(x = 2, n = 10, p = 0.03, conf.level = 0.95,
  ↵ alternative = "less")$conf.int[2]
ub_binom
```

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```
#> [1] 0.5069013
```

When calculated via the beta relationship, the upper bound is:

```
ub_beta <- qbeta(p = 0.95, shape1 = 1 + 2, shape2 = 10 - 2)
ub_beta
#> [1] 0.5069013
```

It can be validated that the two approaches result in the same upper bound via:

```
ub_binom == ub_beta
#> [1] TRUE
```

This relationship between the binomial likelihood and the beta distribution is deliberately **not** used in **jfa**. That is because, in the case of the binomial distribution, the auditing standards round the tolerable misstatements upwards to a whole number. For example, if we try to call the `planning()` function with the argument `expected = 1.5`, **jfa** will internally convert this to `expected = 2` and base the sample size on this in order to stay compliant with American Institute of Certified Public Accountants (AICPA) (2016a). The resulting sample size is  $n = 208$  in this case.

```
planning(materiality = 0.03, expected = 1.5, conf.level = 0.95,
  ↪ likelihood = "binomial")
#> Using 'expected = 2' since 'expected' must be a single integer
  ↪ >= 0
#>
#> Classical Audit Sample Planning
#>
#> minimum sample size = 208
#> sample size obtained in 206 iterations via method 'binomial'
```

##### 4.3.2. Bayesian Planning

Performing Bayesian planning using the binomial likelihood requires that you specify a prior distribution for the parameter  $\theta$ . Practically, this means that you should provide an input for the `prior` argument in the `planning()` function.

### 4.3. The Binomial Likelihood

Setting `prior = TRUE` performs Bayesian planning using a default prior conjugate to the specified likelihood (i.e., a beta prior). Because this is a Bayesian analysis, the following statistical model is specified:

$$k \sim \text{Binomial}(n, \theta) \quad (4.11)$$

$$\theta \sim \text{Beta}(\alpha, \beta) \quad (4.12)$$

#### i Note

The beta prior distribution is the conjugate prior for the binomial likelihood (see this list of conjugate priors), which means that the posterior distribution of  $\theta$  can be determined analytically. For example, if the prior distribution for  $\theta$  is:

$$\theta \sim \text{Beta}(\alpha, \beta) \quad \theta \in [0, 1] \quad (4.13)$$

and the auditor has observed a sample of  $n$  items containing  $k$  misstatements, then the posterior distribution for  $\theta$  is:

$$\theta \sim \text{Beta}(\alpha + k, \beta + n - k) \quad \theta \in [0, 1]. \quad (4.14)$$

For example, the command below uses a default  $\text{beta}(\alpha = 1, \beta = 1)$  prior distribution to plan the sample, since `planning()` is given the binomial likelihood. If we want to achieve an assurance level of 95% ( $\alpha = 0.05$ ) for a performance materiality of  $\theta_{max} = 0.03$ , then the required sample size under the assumption of zero expected misstatements in the sample is  $n = 98$ .

```
plan <- planning(materiality = 0.03, expected = 0, conf.level =
  ↪ 0.95, likelihood = "binomial", prior = TRUE)
```

The `summary()` function can be used to obtain relevant information about the planning.

```
summary(plan)
#>
#> Bayesian Audit Sample Planning Summary
#>
#> Options:
```

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```
#> Confidence level:          0.95
#> Materiality:              0.03
#> Hypotheses:                H0:  $\bar{y} > 0.03$  vs. H1:  $\bar{y} < 0.03$ 
#> Expected:                  0
#> Likelihood:                binomial
#> Prior distribution:        beta( $\alpha = 1$ ,  $\beta = 1$ )
#>
#> Results:
#> Minimum sample size:       98
#> Tolerable errors:          0
#> Posterior distribution:    beta( $\alpha = 1$ ,  $\beta = 99$ )
#> Expected most likely error: 0
#> Expected upper bound:      0.029807
#> Expected precision:        0.029807
#> Expected BF10:             627.22
```

You can inspect how the prior distribution compares to the expected posterior distribution by using the `plot()` function. The expected posterior distribution is the posterior distribution that would occur if you actually observed the planned sample containing the expected misstatements.

```
plot(plan)
```

### 4.3. The Binomial Likelihood



The input for the prior argument can also be an object created by the `auditPrior` function. If `planning()` receives a prior for which there is no conjugate likelihood available, it will numerically derive the posterior distribution. For example, the command below uses a  $\text{Normal}(0, 0.05)$  prior distribution to plan the sample using the binomial likelihood. Because this is a Bayesian analysis, the following statistical model is specified:

$$k \sim \text{Binomial}(n, \theta) \quad (4.15)$$

$$\theta \sim \text{Normal}(\mu = 0, \sigma = 0.05) \quad (4.16)$$

```
prior <- auditPrior(method = "param", likelihood = "normal", alpha
                     = 0, beta = 0.05)
plan <- planning(materiality = 0.03, expected = 0, conf.level =
                  0.95, likelihood = "poisson", prior = prior)
```

#### 4. Planning

The `summary()` function can be used to obtain relevant information about the planning.

```
summary(plan)
#>
#> Bayesian Audit Sample Planning Summary
#>
#> Options:
#>   Confidence level:          0.95
#>   Materiality:              0.03
#>   Hypotheses:                H0:  $\bar{x} > 0.03$  vs. H1:  $\bar{x} < 0.03$ 
#>   Expected:                  0
#>   Likelihood:                poisson
#>   Prior distribution:        normal( $\bar{x} = 0$ ,  $\sigma^2 = 0.05$ )T[0,1]
#>
#> Results:
#>   Minimum sample size:       91
#>   Tolerable errors:          0
#>   Posterior distribution:    Nonparametric
#>   Expected most likely error: 0
#>   Expected upper bound:      0.029
#>   Expected precision:        0.029
#>   Expected BF10:            26.749
```

The resulting sample size under this prior is  $n = 90$ , a reduction of 8 samples when compared to the default beta(1, 1) prior distribution.

```
plot(plan)
```

#### 4.4. The Poisson Likelihood



## 4.4. The Poisson Likelihood

The Poisson distribution is a discrete probability distribution that is commonly used to model the number of events occurring in a fixed time or space. We can use the Poisson distribution as a likelihood to model the number of misstatements that are expected to be found in the sample.

### Note

In audit sampling, the Poisson likelihood is often used to approximate the binomial likelihood since it is easier to work with (i.e., it only has one parameter:  $\lambda$ , while the binomial has two parameters:  $\theta$  and  $n$ ). However, the Poisson likelihood is more conservative than the binomial likelihood, meaning that resulting sample sizes will be higher.

The probability mass function (PMF) of the Poisson distribution is given by:

## 4. Planning

$$p(k; \lambda) = \frac{\lambda^k e^{-\lambda}}{k!}, \quad (4.17)$$

where  $k$  is the number of misstatements in the sample, and  $\lambda$  is the average number of misstatements expected in the sample. The average number of misstatements is related to the misstatement rate in the population, denoted by  $\theta$ , and the sample size,  $n$ , by the following equation:

$$\lambda = n\theta. \quad (4.18)$$

Let's consider how to use the Poisson likelihood to calculate the minimum sample size needed to reduce the sampling risk to an appropriately low level.

### 4.4.1. Classical planning

In classical planning using the Poisson likelihood, the following statistical model is specified:

$$k \sim \text{Poisson}(n\theta_{max}) \quad (4.19)$$

#### 4.4.1.1. No Expected Misstatements

Given the performance materiality  $\theta_{max}$  and the Poisson likelihood, we can solve for the minimum sample size  $n$  needed to reduce the sampling risk to an appropriately low level. A useful trick to utilize is that, if we do not expect any misstatements in the sample, the formula for the required sample size reduces to:

$$n = \lceil -\frac{\ln(\alpha)}{\theta_{max}} \rceil. \quad (4.20)$$

For example, if we want to achieve an assurance level of 95% ( $\alpha = 0.05$ ) for a performance materiality of  $\theta_{max} = 0.03$ , then the required sample size under the assumption of zero expected misstatements in the sample is  $n = 100$ .

#### 4.4. The Poisson Likelihood

```
ceiling(-log(1 - 0.95) / 0.03)
#> [1] 100
```

In **jfa**, this sample size can be replicated using the following code:

```
plan <- planning(materiality = 0.03, expected = 0, conf.level =
  ~ 0.95, likelihood = "poisson")
```

The sample size of 100 can be confirmed by checking that 100 is the minimum integer that results in less than 5% probability of finding 0 misstatements, given the assumption that the population misstatement is truly 3%. The `dpois()` function calculates the probability of observing  $k$  missstatements in a sample of  $n$  items given an assumed misstatement probability  $\theta_{max}$ . By calculating this probability for  $n = 99$ , we can show that this sample size is insufficient as the relevant probability is higher than the sampling risk  $\alpha$ .

```
dpois(x = 0, lambda = 99 * 0.03) < 0.05
#> [1] FALSE
```

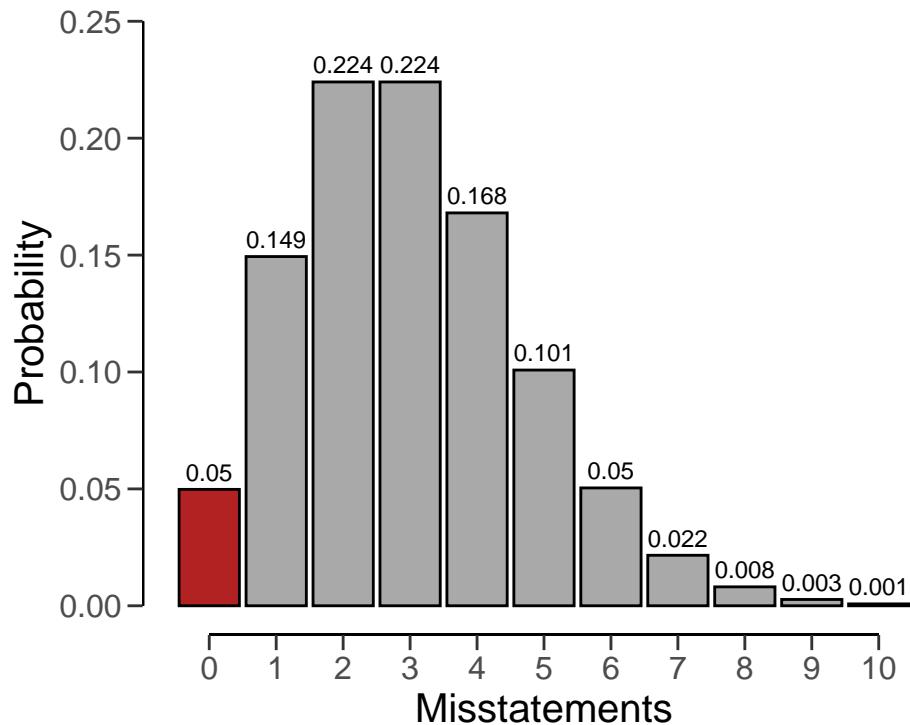
However, for  $n = 100$  the relevant probability is lower than the sampling risk  $\alpha$  and thus the sample size is considered to be sufficient.

```
dpois(x = 0, lambda = 100 * 0.03) < 0.05
#> [1] TRUE
```

We can make this visually intuitive by showing the  $\text{Poisson}(k \mid 100 \times 0.03)$  distribution and highlighting the probability for  $k = 0$ . This probability is lower than the required sampling risk  $\alpha = 0.05$ .

```
plot(plan)
```

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##### 4.4.1.2. Expected Misstatements

However, if the number of expected misstatements in the sample is non-zero, it becomes more difficult to solve the formula for  $n$  algebraically. Hence, they will need to set  $k$  to a different integer value. Next, we can iteratively try every value of  $n$  and return the smallest integer that satisfies the sampling objectives.

For example, if we want to achieve an assurance level of 95% ( $\alpha = 0.05$ ) for a performance materiality of  $\theta_{max} = 0.03$ , then the required sample size under the assumption of one expected misstatement in the sample is  $n = 159$ .

```
plan <- planning(materiality = 0.03, expected = 1, conf.level =
  ↪ 0.95, likelihood = "poisson")
```

Once again, the sample size of 159 can be confirmed by checking that 159 is the minimum integer that results in less than 5% probability of finding 0 or 1 misstatements, given the assumption that the population misstatement is truly 3%. By calculating this probability

#### 4.4. The Poisson Likelihood

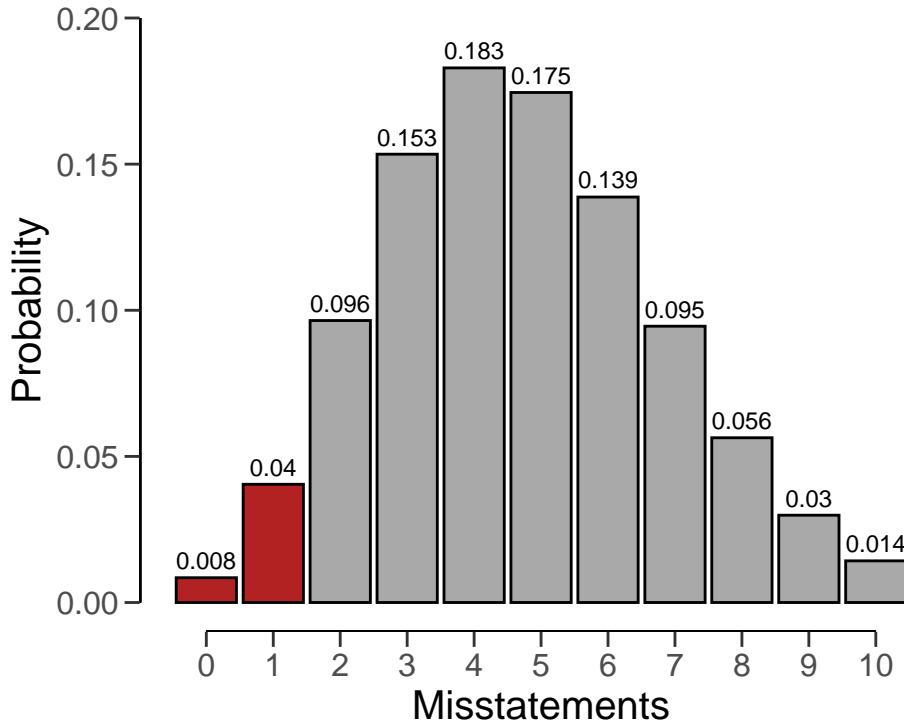
for  $n = 158$ , we can show that this sample size is insufficient as the relevant probability is higher than the sampling risk  $\alpha$ .

```
sum(dpois(x = 0:1, lambda = 158 * 0.03)) < 0.05
#> [1] FALSE
```

However, for  $n = 159$  the relevant probability is lower than the sampling risk  $\alpha$  and thus the sample size is considered to be sufficient.

```
sum(dpois(x = 0:1, lambda = 159 * 0.03)) < 0.05
#> [1] TRUE
```

Like before, we can make this visually intuitive by showing the  $\text{Poisson}(k \mid 159 \times 0.03)$  distribution and highlighting the probabilities for  $k = 0$  and  $k = 1$ . The sum of these probabilities is lower than the required sampling risk  $\alpha = 0.05$ .



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### 4.4.1.3. Expected Misstatement Rate

When the expected misstatements in the sample  $\theta_{exp}$  is assessed, the value for  $k$  can be determined as  $k = n\theta_{exp}$ , which consequently determines how the sample size can be calculated.

To account for the fact that  $k$  can have non-integer values in this case, we use a well-known similarity between the Poisson distribution and the gamma distribution to plan the sample size. The upper bound for any  $\text{Poisson}(k; n\theta)$  distributed variable can also be obtained via percentiles of the  $\text{gamma}(1 + k, n)$  distribution.

For example, the upper bound for a sample of  $n = 10$  items containing  $k = 2$  misstatements, when calculated via the traditional `poisson.test()` is:

```
ub_pois <- poisson.test(x = 2, T = 10, r = 0.03, conf.level = 0.95,
                         alternative = "less")$conf.int[2]
ub_pois
#> [1] 0.6295794
```

When calculated via the relationship with the gamma distribution, the upper bound is:

```
ub_gamma <- qgamma(p = 0.95, shape = 1 + 2, rate = 10)
ub_gamma
#> [1] 0.6295794
```

It can be validated that the two approaches result in the same upper bound via:

```
ub_pois == ub_gamma
#> [1] TRUE
```

This relationship between the Poisson likelihood and the gamma distribution is used under the hood in `jfa`. For example, if we want to achieve an assurance level of 95% ( $\alpha = 0.05$ ) for a performance materiality of  $\theta_{max} = 0.03$ , then the required sample size under the assumption of 1.5 expected misstatements in the sample is  $n = 185$ .

```
planning(materiality = 0.03, expected = 1.5, conf.level = 0.95,
          likelihood = "poisson")
#>
```

## 4.4. The Poisson Likelihood

```
#> Classical Audit Sample Planning  
#>  
#> minimum sample size = 185  
#> sample size obtained in 184 iterations via method 'poisson'
```

The sample size of 185 can be confirmed by checking that 185 is the minimum integer that results in less than 5% probability of finding a misstatement rate in the population equal to, or higher than, 3%. By calculating this probability for  $n = 184$ , we can show that this sample size is insufficient as the relevant upper bound is higher than the performance materiality  $\theta_{max}$ .

```
qgamma(p = 0.95, shape = 1 + 1.5, rate = 184) < 0.03  
#> [1] FALSE
```

However, for  $n = 185$  the relevant upper bound is lower than the performance materiality  $\theta_{max}$  and thus the sample size is sufficient.

```
qgamma(p = 0.95, shape = 1 + 1.5, rate = 185) < 0.03  
#> [1] TRUE
```

### 4.4.2. Bayesian Planning

Performing Bayesian planning with the Poisson likelihood requires that you specify a prior distribution for the parameter  $\theta$ . Practically, this means that you should provide an input for the `prior` argument in the `planning()` function.

Setting `prior = TRUE` performs Bayesian planning using a default prior conjugate to the specified likelihood (i.e., a gamma prior). Because this is a Bayesian analysis, the following statistical model is specified:

$$k \sim \text{Poisson}(n\theta) \quad (4.21)$$

$$\theta \sim \text{Gamma}(\alpha, \beta) \quad (4.22)$$

#### 4. Planning

##### **i** Note

The gamma prior distribution is the conjugate prior for the Poisson likelihood (see this list of conjugate priors), which means that the posterior distribution of  $\theta$  can be determined analytically. For example, if the prior distribution for  $\theta$  is:

$$\theta \sim \text{Gamma}(\alpha, \beta) \quad \theta \in [0, \infty] \quad (4.23)$$

and the auditor has observed a sample of  $n$  items containing  $k$  misstatements, then the posterior distribution for  $\theta$  is:

$$\theta \sim \text{Gamma}(\alpha + k, \beta + n) \quad \theta \in [0, \infty]. \quad (4.24)$$

For example, the command below uses a default  $\text{gamma}(\alpha = 1, \beta = 1)$  prior distribution to plan the sample, since `planning()` is given the Poisson likelihood. If we want to achieve an assurance level of 95% ( $\alpha = 0.05$ ) for a performance materiality of  $\theta_{max} = 0.03$ , then the required sample size under the assumption of zero expected misstatements in the sample is  $n = 99$ .

```
plan <- planning(materiality = 0.03, expected = 0, conf.level =
  ↵  0.95, likelihood = "poisson", prior = TRUE)
```

The `summary()` function can be used to obtain relevant information about the planning.

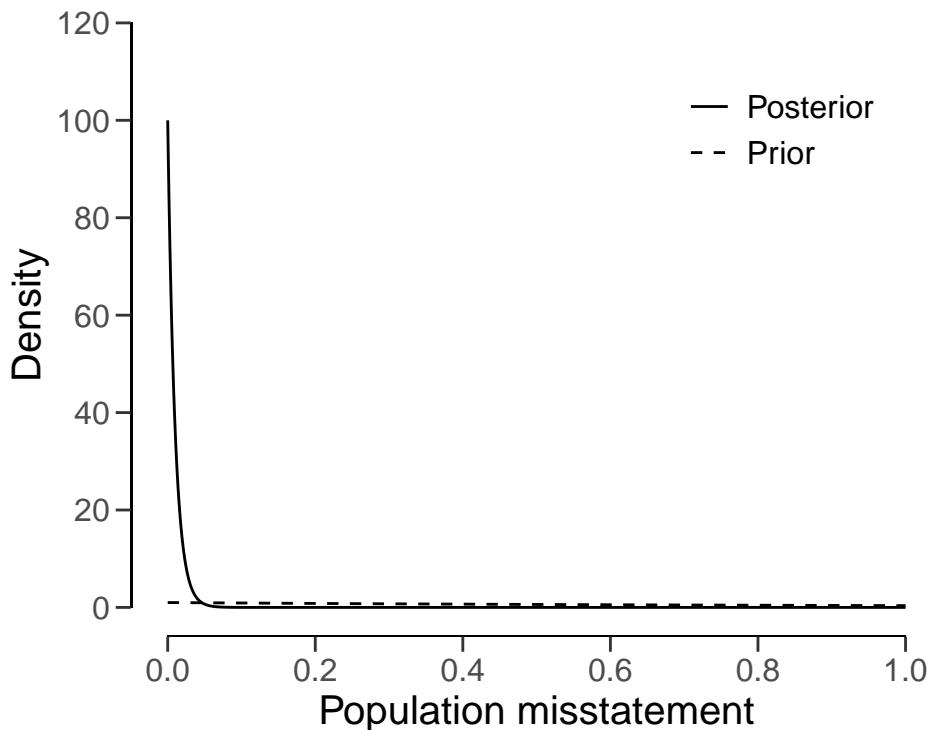
```
summary(plan)
#>
#> Bayesian Audit Sample Planning Summary
#>
#> Options:
#>   Confidence level:          0.95
#>   Materiality:              0.03
#>   Hypotheses:                H0: ? > 0.03 vs. H1: ? < 0.03
#>   Expected:                  0
#>   Likelihood:                poisson
#>   Prior distribution:        gamma(? = 1, ? = 1)
#>
#> Results:
```

#### 4.4. The Poisson Likelihood

```
#> Minimum sample size: 99  
#> Tolerable errors: 0  
#> Posterior distribution: gamma(¶ = 1, ¶ = 100)  
#> Expected most likely error: 0  
#> Expected upper bound: 0.029957  
#> Expected precision: 0.029957  
#> Expected BF10: 626.69
```

You can inspect how the prior distribution compares to the expected posterior distribution by using the `plot()` function. The expected posterior distribution is the posterior distribution that would occur if you actually observed the planned sample containing the expected misstatements.

```
plot(plan)
```



The input for the `prior` argument can also be an object created by the `auditPrior` func-

#### 4. Planning

tion. If `planning()` receives a prior for which there is no conjugate likelihood available, it will numerically derive the posterior distribution. For example, the command below uses a  $\text{Normal}(0, 0.05)$  prior distribution to plan the sample using the Poisson likelihood. Concretely, this means that the following statistical model is specified:

$$k \sim \text{Poisson}(n\theta) \quad (4.25)$$

$$\theta \sim \text{Normal}(\mu = 0, \sigma = 0.05) \quad (4.26)$$

```
prior <- auditPrior(method = "param", likelihood = "normal", alpha
                     = 0, beta = 0.05)
plan <- planning(materiality = 0.03, expected = 0, conf.level =
                  0.95, likelihood = "poisson", prior = prior)
```

The `summary()` function can be used to obtain relevant information about the planning.

```
summary(plan)
#>
#> Bayesian Audit Sample Planning Summary
#>
#> Options:
#>   Confidence level:          0.95
#>   Materiality:              0.03
#>   Hypotheses:                H0:  $\theta > 0.03$  vs. H1:  $\theta < 0.03$ 
#>   Expected:                  0
#>   Likelihood:                poisson
#>   Prior distribution:        normal( $\theta = 0$ ,  $\sigma^2 = 0.05$ )T[0,1]
#>
#> Results:
#>   Minimum sample size:       91
#>   Tolerable errors:          0
#>   Posterior distribution:    Nonparametric
#>   Expected most likely error: 0
#>   Expected upper bound:      0.029
#>   Expected precision:        0.029
#>   Expected BF10:            26.063
```

#### 4.5. Prior Distributions

The resulting sample size under this prior is  $n = 91$ , a reduction of 8 samples when compared to the default gamma(1, 1) prior.

```
plot(plan)
```



## 4.5. Prior Distributions

The `auditPrior()` function is used to specify a prior distribution for audit sampling. Below is an enumeration of the several ways that a prior distribution can be constructed using this function.

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### 4.5.1. Default Prior

The default prior distributions are created using method = 'default'. **jfa**'s default priors satisfy two criteria: 1) they contain relatively little information about the population misstatement and 2) they are proper (i.e., they integrate to 1). The default priors in **jfa** are:

- likelihood = 'poisson': gamma( $\alpha = 1, \beta = 1$ )
- likelihood = 'binomial': beta( $\alpha = 1, \beta = 1$ )
- likelihood = 'hypergeometric': beta-binomial( $N, \alpha = 1, \beta = 1$ )
- likelihood = 'normal': normal( $\mu = 0, \sigma = 1000$ )
- likelihood = 'uniform': uniform(min = 0, max = 1)
- likelihood = 'cauchy': Cauchy( $x_0 = 0, \gamma = 1000$ )
- likelihood = 't': Student-t(df = 1)
- likelihood = 'chisq': chi-squared(df = 1)
- likelihood = 'exponential': exponential( $\lambda = 1$ )

```
prior <- auditPrior(method = "default", likelihood = "binomial")
summary(prior)
#>
#> Prior Distribution Summary
#>
#> Options:
#>   Likelihood:           binomial
#>   Specifics:          default prior
#>
#> Results:
#>   Functional form:     beta(α = 1, β = 1)
#>   Mode:                NaN
#>   Mean:                0.5
#>   Median:              0.5
#>   Variance:            0.083333
#>   Skewness:             0
#>   Information entropy (nat): 0
#>   95 percent upper bound: 0.95
#>   Precision:            NaN
```

All prior distributions can be visually inspected via the plot() function.

#### 4.5. Prior Distributions

```
plot(prior)
```



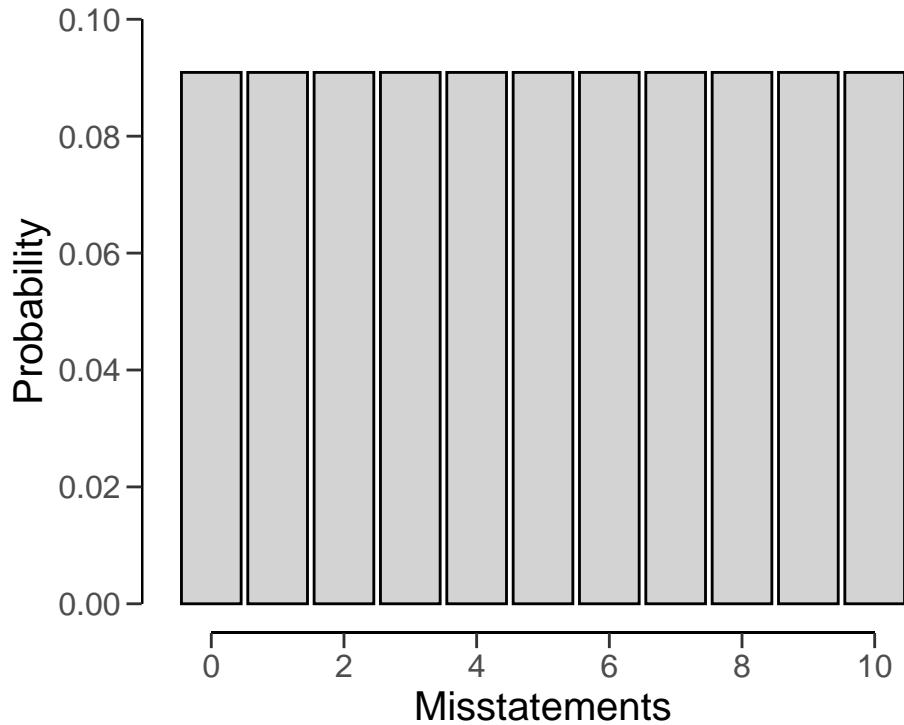
Furthermore, the `predict()` function produces the predictions of the prior distribution on the data level for a sample of n items. For example, the command below requests the prediction of the default beta(1, 1) prior for a hypothetical sample of 6 items.

```
predict(prior, n = 6)
#>      x=0      x=1      x=2      x=3      x=4      x=5
#>      x=6
#> 0.1428571 0.1428571 0.1428571 0.1428571 0.1428571 0.1428571
#>      0.1428571
```

The predictions of the prior distribution can be visualized using the `plot()` function.

```
plot(predict(prior, n = 10))
```

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##### 4.5.2. Parametric Prior

You can manually specify the parameters of the prior distribution with `method = 'param'` and the `alpha` and `beta` arguments, which correspond to the first and (optionally) second parameter of the prior as described above. For example, the commands below create a `beta(2, 10)` prior distribution, a `normal(0.025, 0.05)` prior distribution and a `Student-t(0.01)` prior distribution.

```
auditPrior(method = "param", likelihood = "binomial", alpha = 2,  
          beta = 10)  
#>  
#> Prior Distribution for Audit Sampling  
#>  
#> functional form: beta(2, 10)  
#> parameters obtained via method 'param'
```

```

auditPrior(method = "param", likelihood = "normal", alpha = 0.025,
  ↵ beta = 0.05)
#>
#> Prior Distribution for Audit Sampling
#>
#> functional form: normal(̢ = 0.025, ̣ = 0.05)T[0,1]
#> parameters obtained via method 'param'
auditPrior(method = "param", likelihood = "t", alpha = 0.01)
#>
#> Prior Distribution for Audit Sampling
#>
#> functional form: Student-t(df = 0.01)T[0,1]
#> parameters obtained via method 'param'

```

### 4.5.3. Improper Prior

You can construct an improper prior distribution with classical properties using `method = 'strict'`. The posterior distribution from this prior yields the same results as the classical methodology with respect to sample sizes and upper limits, but is only proper once a single non-misstated unit is present in the sample (Derkx et al., 2022a). For example, the command below creates an improper beta(1, 0) prior distribution.

**i** This method requires the poisson, binomial or hypergeometric likelihood.

```

auditPrior(method = "strict", likelihood = "binomial")
#>
#> Prior Distribution for Audit Sampling
#>
#> functional form: beta(̢ = 1, ̣ = 0)
#> parameters obtained via method 'strict'

```

#### 4. Planning

##### 4.5.4. Impartial Prior

You can incorporate the assumption that tolerable misstatement is equally likely as intolerable misstatement (Derks et al., 2022a) using `method = 'impartial'`. For example, the command below creates an impartial beta prior distribution for a performance materiality of 5 percent.

**i** This method requires that you specify a value for the materiality.

```
auditPrior(method = "impartial", likelihood = "binomial",
           ↪ materiality = 0.05)
#>
#> Prior Distribution for Audit Sampling
#>
#> functional form: beta(α = 1, β = 13.513)
#> parameters obtained via method 'impartial'
```

##### 4.5.5. Probability of Tolerable Misstatement

You can manually assign prior probabilities to the hypothesis of tolerable misstatement and the hypotheses of intolerable misstatement (Derks, Swart, Batenburg, et al., 2021) with `method = 'hyp'` in combination with `p.hmin`. For example, the command below incorporates the information that the hypothesis of tolerable misstatement has a probability of 60% into a beta prior distribution.

**i** This method requires that you specify a value for the materiality.

```
auditPrior(method = "hyp", likelihood = "binomial", materiality =
           ↪ 0.05, p.hmin = 0.6)
#>
#> Prior Distribution for Audit Sampling
#>
#> functional form: beta(α = 1, β = 17.864)
#> parameters obtained via method 'hyp'
```

### 4.5.6. Audit Risk Model

You can translate risk assessments from the Audit Risk Model (inherent risk and internal control risk) into a prior distribution (Derks, Swart, Batenburg, et al., 2021) using `method = 'arm'` in combination with the `ir` and `cr` arguments. For example, the command below incorporates the information that the inherent risk is equal to 90% and internal control risk is equal to 60% into a beta prior distribution.

**i** This method requires the poisson, binomial or hypergeometric likelihood.

```
auditPrior(method = "arm", likelihood = "binomial", materiality =
  ↵ 0.05, ir = 0.9, cr = 0.6)
#>
#> Prior Distribution for Audit Sampling
#>
#> functional form: beta(保住 = 1, 保上 = 12)
#> parameters obtained via method 'arm'
```

### 4.5.7. Bayesian Risk Assessment Model

You can incorporate information about the mode and the upper bound of the prior distribution using `method = 'bram'`. For example, the code below incorporates the information that the mode of the prior distribution is 1% and the upper bound is 60% into a beta prior distribution.

**i** This method requires the poisson, binomial or hypergeometric likelihood.

```
auditPrior(method = "bram", likelihood = "binomial", materiality =
  ↵ 0.05, expected = 0.01, ub = 0.6)
#>
#> Prior Distribution for Audit Sampling
#>
#> functional form: beta(保住 = 1.023, 保上 = 3.317)
#> parameters obtained via method 'bram'
```

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##### 4.5.8. Earlier Sample

You can incorporate information from an earlier sample into the prior distribution (Derks, Swart, Batenburg, et al., 2021) using `method = 'sample'` in combination with `x` and `n`. For example, the command below incorporates the information from an earlier sample of 30 items in which 0 misstatements were found into a beta prior distribution.

**i** This method requires the poisson, binomial or hypergeometric likelihood.

```
auditPrior(method = "sample", likelihood = "binomial", x = 0, n =
  ↪ 30)
#>
#> Prior Distribution for Audit Sampling
#>
#> functional form: beta(0 = 1, 0 = 30)
#> parameters obtained via method 'sample'
```

##### 4.5.9. Weighted Earlier Sample

You can incorporate information from last years results, weighted by a factor (Derks, Swart, Batenburg, et al., 2021), into the prior distribution using `method = 'factor'` in combination with `x` and `n`. For example, the command below incorporates the information from a last years results (a sample of 58 items in which 0 misstatements were found), weighted by a factor 0.7, into a beta prior distribution.

**i** This method requires the poisson, binomial or hypergeometric likelihood.

```
auditPrior(method = "factor", likelihood = "binomial", x = 0, n =
  ↪ 58, factor = 0.7)
#>
#> Prior Distribution for Audit Sampling
#>
#> functional form: beta(0 = 1, 0 = 40.6)
#> parameters obtained via method 'factor'
```

### 4.5.10. Nonparametric Prior

You can base the prior on samples of the prior distribution using `method = 'nonparam'` in combination with `samples`. For example, the command below creates a prior on 1000 samples of a  $\text{beta}(1, 10)$  distribution.

- i** The likelihood argument is not required and will be ignored in this method.

```
auditPrior(method = "nonparam", samples = stats::rbeta(1000, 1,
  ↪ 10))
#>
#> Prior Distribution for Audit Sampling
#>
#> functional form: Nonparametric
#> parameters obtained via method 'nonparam'
```

## 4.6. Practical Examples

This section contains practical examples of how to conduct the planning of statistical audit samples and demonstrates how to set up a prior distribution based on various types of relevant audit information.

### 4.6.1. Audit Risk Model

In our first example, an auditor is performing tests of details on a population of the auditee. For instance, let's say an auditor is performing an audit on a company's accounts payable transactions. The company has a total of  $N = 1000$  accounts payable transactions for the year. Rather than testing all 1000 transactions, the auditor can choose to test a sample of the transactions. The performance materiality for the payable transactions account is set to  $\theta_{max} = 3\%$ , and the audit risk is set to  $\alpha = 0.05$ , or 5%. Based on the results of last years audit, where the most likely estimate of the misstatement was 1%, the auditor wants to tolerate 1% misstatements in the sample before giving an unqualified opinion on the population.

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```
ar          <- 0.05 # Audit risk
materiality <- 0.03 # Performance materiality
expected    <- 0.01 # Tolerable deviation rate
```

Before tests of details, the auditor has assessed risk of material misstatement via the audit risk model. In this example, the auditor has assessed the effectiveness of the company's internal controls, such as its segregation of duties and its risk management processes, and has determined that they are sufficient to prevent or detect material misstatements. Because the internal control systems were effective, the auditor assesses the control risk as medium. The auditor's firm defines the risk categories low, medium, and high respectively as 50%, 60%, and 100%. According to the Audit Risk Model, the detection risk can be calculated as a function of the audit risk, the inherent risk and the control risk.

```
ir <- 1           # Inherent risk
cr <- 0.6         # Control risk
dr <- ar / (ir * cr) # Detection risk
dr
#> [1] 0.08333333
```

By using the detection risk of 8.33% as the sampling risk for this population, the auditor can plan for a sample while taking into account the risk-reducing information. The required minimum sample size is 174 in this case.

```
planning(materiality = 0.03, expected = expected, conf.level = 1 -
          ~ dr)
#>
#> Classical Audit Sample Planning
#>
#> minimum sample size = 174
#> sample size obtained in 175 iterations via method 'poisson'
```

The example above is a frequentist one. However, the auditor is free to apply a Bayesian philosophy in planning the sample. For example, the risk assessments from the ARM can be incorporated into a prior distribution. This can be done using method = "arm" in the auditPrior() function, which takes the values of the inherent risk probability ir and the control risk probability cr. Hence, the prior distribution in this example can be constructed using the following command:

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```
prior <- auditPrior(method = "arm", materiality = 0.03, expected =
  ↵  expected, ir = ir, cr = cr)
```

The `summary()` function can be used to obtain relevant information about the prior distribution.

```
summary(prior)
#>
#> Prior Distribution Summary
#>
#> Options:
#>   Likelihood:           poisson
#>   Specifics:          ir = 1; cr = 0.6; dr = 0.0833333
#>
#> Results:
#>   Functional form:     gamma(k = 1.46, n = 46)
#>   Mode:                0.01
#>   Mean:                0.031739
#>   Median:              0.024859
#>   Variance:             0.00069
#>   Skewness:             1.6552
#>   Information entropy (nat): -2.4894
#>   95 percent upper bound: 0.08343
#>   Precision:            0.07343
```

Furthermore, the prior distribution can be visualized with a call to the `plot()` function.

```
plot(prior)
```

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By using the prior distribution to incorporate the assessments of the inherent risk and the control risk, the auditor can plan a sample while taking into account the risk-reducing information. The required minimum sample size is also 174 in this case.

```
planning(materiality = 0.03, expected = expected, conf.level = 1 -  
  ↪ ar, prior = prior)  
#>  
#> Bayesian Audit Sample Planning  
#>  
#> minimum sample size = 174  
#> sample size obtained in 175 iterations via method 'poisson' +  
  ↪ 'prior'
```

### 4.6.2. Benchmark Analysis

The auditor may incorporate information obtained through analytical procedures (Derks, Swart, Batenburg, et al., 2021), such as a benchmark analysis, into the prior distribution for  $\theta$ . While we have previously discussed methods for constructing a prior distribution based on existing knowledge, there is no set procedure for incorporating information obtained through analytical procedures, as these procedures can vary significantly depending on the type of information being incorporated into the prior distribution. Therefore, it is important to thoroughly substantiate the data and assumptions used in this approach and to carefully consider how these assumptions are incorporated into the prior distribution.

One way to construct a prior distribution on the basis of data is through the use of regression models, such as benchmarking the relationship between sales and costs of sales within the auditee's specific industry sector. The **jfa** package includes a data set benchmark that can be used for this example.

```
data(benchmark)
head(benchmark)
#>   sales costofsales
#> 1 186273256 140755372
#> 2 336491541 248675452
#> 3 222693077 164299866
#> 4 364905221 285768790
#> 5 382140185 280187371
#> 6 113666950 101552955
```

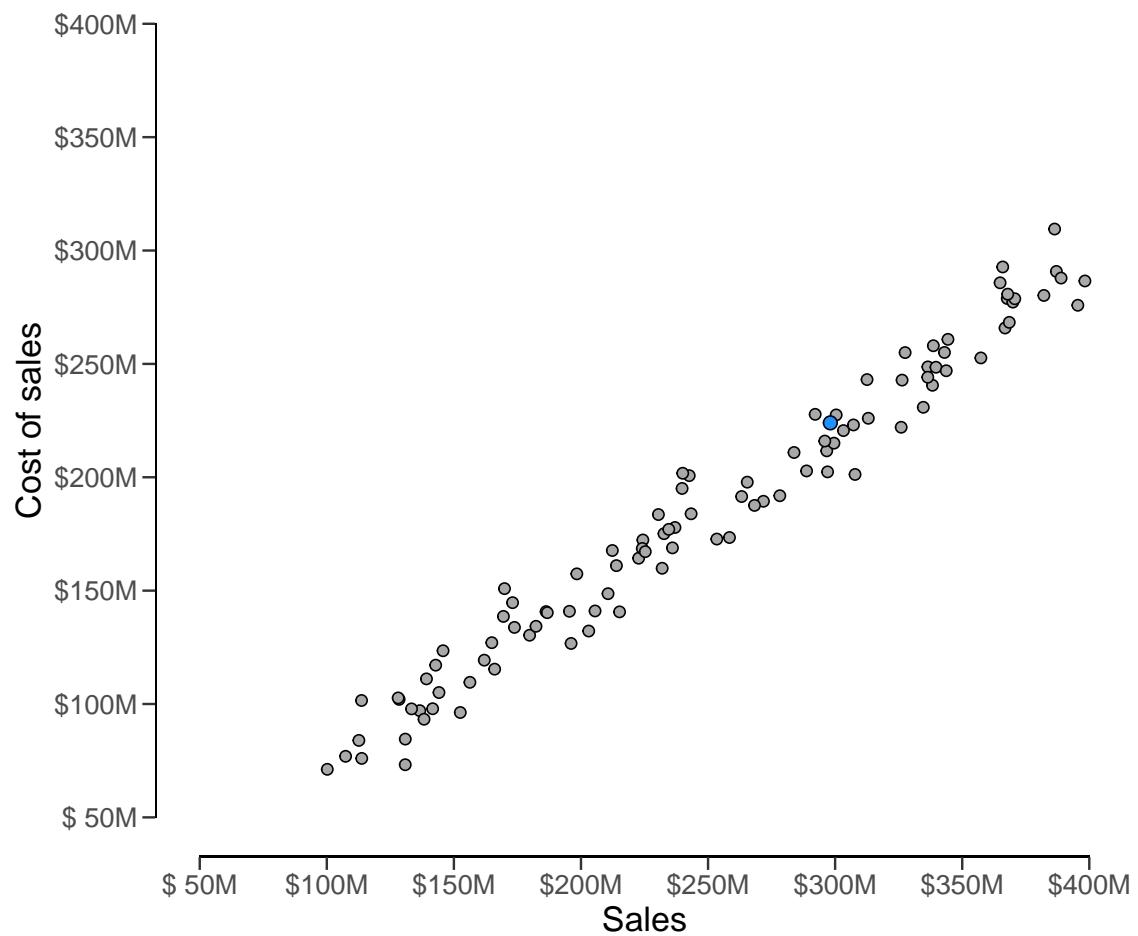
The auditee's the sum of the sales is \$298,112,312 and the sum of the booked costs of sales is \$223,994,405, respectively. This is indicated by a blue dot in the figure below, which visualizes the industry sales versus the cost of sales.

```
C_real <- 223994405
```

The relationship between the sales  $S$  and the cost of sales  $C$  can be modelled by a linear equation:

$$C = \beta_0 + \beta_1 \cdot S + \epsilon. \quad (4.27)$$

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In practice, this relationship is often more complex than is presented above, and the auditor must carefully construct and evaluate the applied regression model. However, for ease of understanding we will continue our example with this toy model. The auditor can estimate the regression model using the following command:

```
fit <- lm(costofsales ~ 1 + sales, data = benchmark)
summary(fit)
#>
#> Call:
#> lm(formula = costofsales ~ 1 + sales, data = benchmark)
#>
#> Residuals:
#>      Min       1Q   Median       3Q      Max
#> -25736696 -7052141 -226945  6857840 25498106
#>
#> Coefficients:
#>             Estimate Std. Error t value Pr(>|t|)
#> (Intercept) 2.413e+05 3.455e+06    0.07    0.944
#> sales       7.366e-01 1.310e-02   56.21  <2e-16 ***
#> ---
#> Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
#>
#> Residual standard error: 11150000 on 98 degrees of freedom
#> Multiple R-squared:  0.9699, Adjusted R-squared:  0.9696
#> F-statistic: 3160 on 1 and 98 DF,  p-value: < 2.2e-16
```

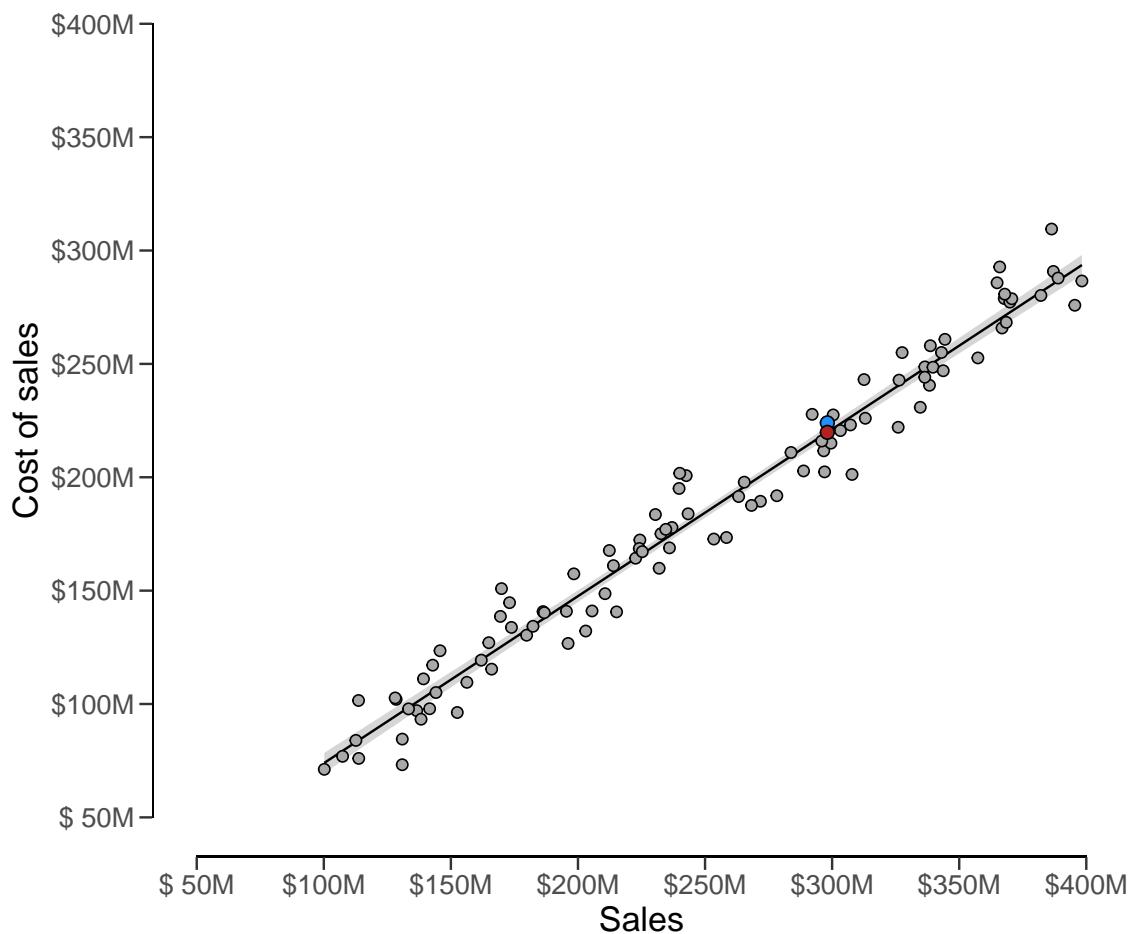
The predicted cost of sales for the auditee, based on the industry benchmark, can be computed as follows:

```
C_pred <- predict(fit, newdata = data.frame(sales = 298112312),
  ↵ interval = "prediction", level = 0.90)[1]
C_pred
#> [1] 219817866
```

The fitted regression line and the predicted cost of sales (red dot) are visualized in the figure below:

The prior distribution can be justified by the data and the auditee's numerical prediction of the cost of sales. In this analytical procedure, the prior distribution on  $\theta$  can utilize

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## 4.6. Practical Examples

the relative error distribution from the linear regression. This relative error distribution, which is a  $\text{Normal}(\mu, \sigma)$  distribution, captures the uncertainty of the prediction of the cost of sales through the use of linear regression, scaled to be a percentage of the total cost of sales. The mean  $\mu$  of the prior distribution is determined by the relative deviation of the auditee's booked cost of sales when compared to the predicted cost of sales according to the benchmark data  $\frac{C - \hat{C}}{C}$ .

```
mu <- (c_real - c_pred) / c_real
mu
#> [1] 0.01864573
```

The standard deviation of the prior distribution is expressed through the standard deviation of the distribution of  $\epsilon$ :

```
stdev <- sd(fit$residuals) / c_real
stdev
#> [1] 0.04951199
```

The  $\text{Normal}(0.019, 0.05)$  prior distribution can be constructed through a call to `auditPrior()`, where the likelihood of the prior is specified as `normal`. We call the function with `method = "param"` to manually specify the parameters of the prior distribution.

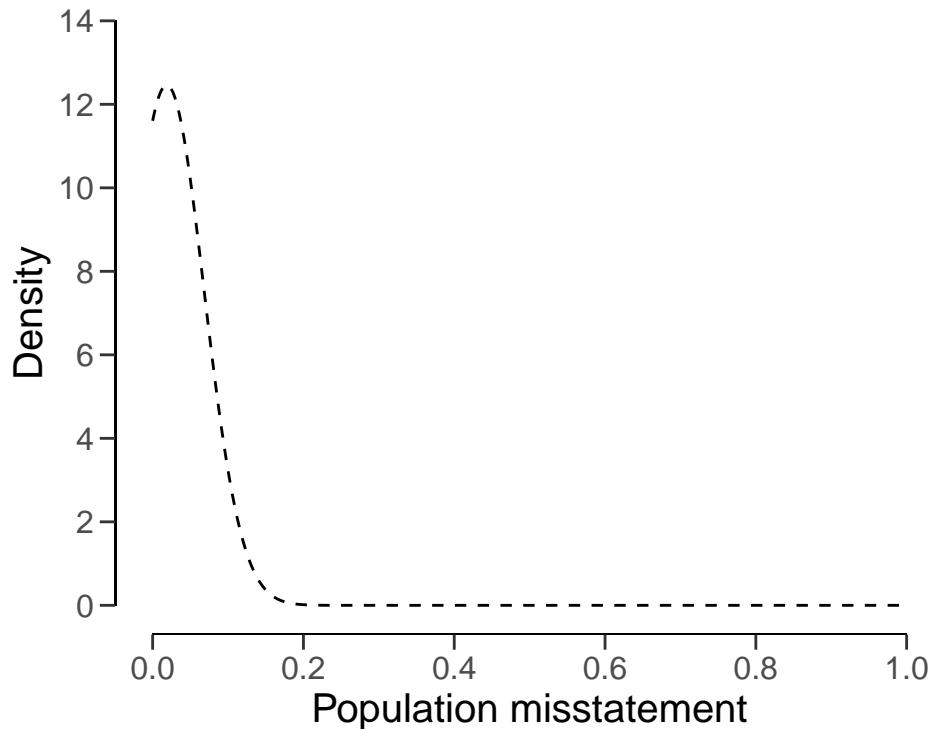
```
prior <- auditPrior(method = "param", likelihood = "normal", alpha
                     = mu, beta = stdev)
summary(prior)
#>
#> Prior Distribution Summary
#>
#> Options:
#> Likelihood:                  normal
#> Specifics:                 mu = 0.0186457; sigma = 0.049512
#>
#> Results:
#> Functional form:            normal(mu = 0.019, sigma = 0.05)T[0,1]
#> Mode:                      0.018646
#> Mean:                       0.047096
#> Median:                     0.041335
```

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```
#> Variance:          0.0011116
#> Skewness:          NA
#> Information entropy (nat): -2.1306
#> 95 percent upper bound:   0.11012
#> Precision:          0.091473
```

The specified prior distribution can be visualized using the `plot()` function.

```
plot(prior)
```



The performance materiality for this example is set to  $\theta_{max} = 5\%$ , and the audit risk is set to  $\alpha = 0.05$ , or 5%. By using this prior distribution, the required minimum sample size is 50.

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```
plan <- planning(materiality = 0.05, conf.level = 0.95, likelihood
  ↵ = "binomial", prior = prior)
plan
#>
#> Bayesian Audit Sample Planning
#>
#> minimum sample size = 50
#> sample size obtained in 51 iterations via method 'binomial' +
  ↵ 'prior'
```

You can inspect how the prior distribution compares to the expected posterior distribution by using the `plot()` function.

```
plot(plan)
```



By using a frequentist approach, the required minimum sample size is 50. Thus, by per-

#### 4. Planning

forming the analytical procedure and incorporating this information into the prior distribution, the auditor has achieved a reduction in sample size of 9 items.

```
plan <- planning(materiality = 0.05, conf.level = 0.95, likelihood
  ↵   = "binomial")
plan
#>
#> Classical Audit Sample Planning
#>
#> minimum sample size = 59
#> sample size obtained in 60 iterations via method 'binomial'
```

#### 4.6.3. Predictive Modeling

As a final example, we consider an example where the auditor incorporates information about the probability of misstatement obtained through a predictive analysis into the prior distribution for  $\theta$ . In this example, the auditor is conducting an audit on a long-term client that they have been working with for fifteen years. Hence, the auditor has access to a historical data set called `history`, which contains the samples from all of the previous audits that have been conducted on this auditee over the past fifteen years.

```
history <-
  ↵  read.csv("https://github.com/koenderks/sasr/raw/master/data/ch3_history.csv",
  ↵  ↵  colClasses = c("factor", "numeric", "numeric"))
head(history)
#>   k  ftes days
#> 1 0  2.09 1.83
#> 2 0 17.51 5.02
#> 3 0 17.29 8.47
#> 4 0 23.88 8.31
#> 5 0 15.31 8.25
#> 6 0 18.28 4.47
```

It should be noted that for all historical sample items, there are three known characteristics: whether they contained a misstatement (designated as `k`), the number of full-time equivalent employees (FTEs) who had access to that item within the internal computer systems of the auditee (designated as `ftes`), and the number of days that the item was

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outstanding (designated as days). Additionally, the ftes and days characteristics are also known for all items in the current year's population. Of course, it is unknown if any misstatements exist within the population of the current year.

```
population <-
  ↳ read.csv("https://github.com/koenderks/sasr/raw/master/data/ch3_population.csv")
head(population)
#>      ID bookValue ftes days
#> 1 82884    242.61   14    4
#> 2 25064    642.99   11    4
#> 3 81235    628.53    8    3
#> 4 71769    431.87   11    3
#> 5 55080    620.88   12    3
#> 6 93224    501.76   12    5
```

The objective of this analytical procedure is to forecast potential misstatements within the population of the current year. In order for the information obtained through this procedure to serve as prior knowledge in a Bayesian analysis, the procedure must yield a distribution of the probability of misstatement. Therefore, the auditor employs a machine learning technique known as Random Forest (Hastie et al., 2009) to learn the relationship between misstatements, the number of full-time equivalent employees, and the number of outstanding days in the historical data set.

```
set.seed(1)
fit <- randomForest::randomForest(formula = k ~ ftes + days, data =
  ↳ history)
```

The auditor specifically uses the random forest technique due to its ability to provide a distribution of the misstatement probabilities. The probabilistic predictions for the unseen misstatements in the population data can be obtained by calling the predict() function with the argument type = "prob".

```
predictions <- predict(object = fit, newdata = population, type =
  ↳ "prob")
```

These predictions come in a probabilistic format, which means that for each item in the population of the current year there is a predicted probability that that item is misstated. These probabilities are stored in the second column of the predictions data frame.

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```
head(predictions)
#>      0      1
#> 1 0.974 0.026
#> 2 0.966 0.034
#> 3 0.992 0.008
#> 4 0.928 0.072
#> 5 0.776 0.224
#> 6 0.982 0.018
```

The prior distribution for  $\theta$  will be based on the distribution of probabilities that each item in the population is misstated. In contrast to the previous example, this distribution is not a parametric distribution, which means we are unable to utilize any parametric priors from **jfa**. However, by providing samples of the prior distribution, **jfa** is able to construct a nonparametric prior distribution internally via the density of the samples.

The nonparametric prior distribution can be constructed through a call to `auditPrior()`, where the method to construct of the prior is specified as `nonparam`. The samples of the prior distribution can be provided through the `samples` argument. We use the second column of the `predictions` object for this.

```
prior <- auditPrior(method = "nonparam", samples = predictions[, 
  ↴ 2])
```

The nonparametric prior distribution can be visualized using the `plot()` function.

```
plot(prior)
```



The performance materiality for this example is set to  $\theta_{max} = 1\%$ , and the audit risk is set to  $\alpha = 0.05$ , or 5%. The minimum sample size can be calculated with the command below and is 108.

```
plan <- planning(materiality = 0.01, conf.level = 0.95, likelihood
  ↵ = "binomial", prior = prior)
plan
#>
#> Bayesian Audit Sample Planning
#>
#> minimum sample size = 108
#> sample size obtained in 109 iterations via method 'binomial' +
  ↵ 'prior'
```

You can inspect how the prior distribution compares to the expected posterior distribution by using the `plot()` function.

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```
plot(plan)
```



By using a frequentist approach, the required minimum sample size is 299. Thus, by performing the analytical procedure and incorporating this information into the prior distribution, the auditor has achieved a reduction in sample size of  $299 - 108 = 191$  items.

```
plan <- planning(materiality = 0.01, conf.level = 0.95, likelihood
                   = "binomial")
plan
#>
#> Classical Audit Sample Planning
#>
#> minimum sample size = 299
#> sample size obtained in 300 iterations via method 'binomial'
```

## 4.7. Exercises

1. Use the classical approach with the hypergeometric likelihood to compute the minimum required sample size for a population of  $N = 100$  when applying a performance materiality of 3% and a sampling risk of 5%. Tolerate no misstatements in the sample.

[Click to reveal answer](#)

```
planning(materiality = 0.03, likelihood = "hypergeometric", N.units
         ← = 100)
#>
#> Classical Audit Sample Planning
#>
#> minimum sample size = 63
#> sample size obtained in 64 iterations via method
         ← 'hypergeometric'
```

2. Recompute the previous sample size with the Bayesian approach using a default prior.

[Click to reveal answer](#)

```
planning(materiality = 0.03, likelihood = "hypergeometric", N.units
         ← = 100, prior = TRUE)
#>
#> Bayesian Audit Sample Planning
#>
#> minimum sample size = 63
#> sample size obtained in 64 iterations via method
         ← 'hypergeometric' + 'prior'
```

3. Use the classical approach with the binomial likelihood to compute the minimum required sample size for a performance materiality of 4.4% and a sampling risk of 5%. Tolerate one misstatement in the sample.

[Click to reveal answer](#)

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```
planning(materiality = 0.044, likelihood = "binomial", expected =
  ↵  1)
#>
#> Classical Audit Sample Planning
#>
#> minimum sample size = 106
#> sample size obtained in 105 iterations via method 'binomial'
```

4. Recompute the previous sample size with the Bayesian approach using a default prior.

Click to reveal answer

```
planning(materiality = 0.044, likelihood = "binomial", expected =
  ↵  1, prior = TRUE)
#>
#> Bayesian Audit Sample Planning
#>
#> minimum sample size = 105
#> sample size obtained in 104 iterations via method 'binomial' +
  ↵  'prior'
```

5. Use the classical approach with the Poisson likelihood to compute the minimum required sample size for a performance materiality of 2% and a sampling risk of 5%. Use an expected misstatement rate of 0.5%.

Click to reveal answer

```
planning(materiality = 0.02, expected = 0.005)
#>
#> Classical Audit Sample Planning
#>
#> minimum sample size = 262
#> sample size obtained in 263 iterations via method 'poisson'
```

6. Recompute the previous sample size with the Bayesian approach using a default prior.

Click to reveal answer

```
planning(materiality = 0.02, expected = 0.005, prior = TRUE)
#>
#> Bayesian Audit Sample Planning
#>
#> minimum sample size = 261
#> sample size obtained in 262 iterations via method 'poisson' +
#> 'prior'
```

7. Compute the sampling risk according to the Audit Risk Model for an audit risk percentage of 5%, an inherent risk percentage of 50% and an internal control risk percentage of 80%. Next, use the classical approach with the binomial likelihood to compute the minimum sample size for a performance materiality of 5% and the new sampling risk. Tolerate no misstatements in the sample.

Click to reveal answer

```
dr <- 0.05 / (0.5 * 0.8)
planning(materiality = 0.05, conf.level = 1 - dr)
#>
#> Classical Audit Sample Planning
#>
#> minimum sample size = 42
#> sample size obtained in 43 iterations via method 'poisson'
```

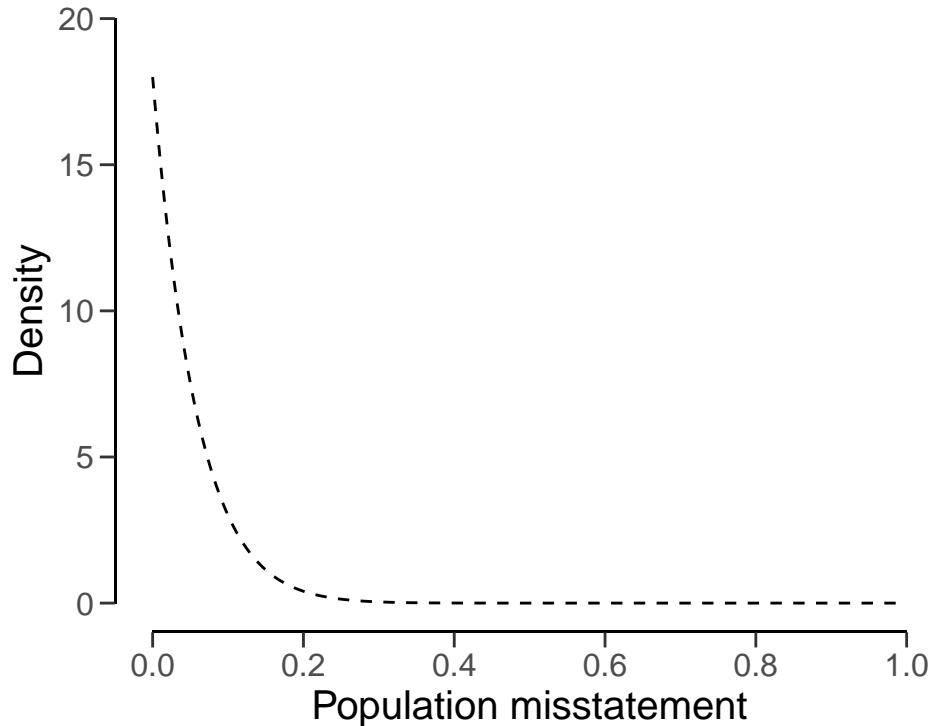
8. Construct a prior distribution on the basis of the information in exercise 7. Use this prior distribution to recompute the previous sample size with the Bayesian approach.

Click to reveal answer

```
prior <- auditPrior(method = "arm", likelihood = "binomial",
#> materiality = 0.05, ir = 0.5, cr = 0.8)
plot(prior)
planning(materiality = 0.05, prior = prior)
#>
#> Bayesian Audit Sample Planning
```

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```
#>  
#> minimum sample size = 41  
#> sample size obtained in 42 iterations via method 'binomial' +  
#> 'prior'
```



9. Construct a prior distribution on the basis of the assumption that tolerable misstatement is equally likely as intolerable misstatement before seeing the sample data. Use the binomial likelihood and assume a performance materiality of 2.5%.

Click to reveal answer

```
prior <- auditPrior(method = "impartial", likelihood = "binomial",  
#> materiality = 0.05)  
plot(prior)
```





# 5. Selection

- i** You are reading the work-in-progress first edition of Statistical Auditing with R. This chapter is currently a dumping ground of ideas, and it is incomplete.

Auditors must often evaluate balances or populations that include a large quantity of items. As it is not possible to individually examine all of these items, they must select a subset, or sample, from the total population to make a statement about a specific characteristic of the population. Several selection methodologies, which are widely accepted in the audit context, are available for this purpose. This chapter discusses the most frequently used sampling methodology for audit sampling and demonstrates how to select a sample using these methods in R.

## 5.1. Sampling Units

Selecting a subset from the population requires knowledge of the sampling units; physical representations of the population that needs to be audited. Generally, the auditor has to choose between two types of sampling units: individual items in the population or individual monetary units in the population. In order to perform statistical selection, the population must be divided into individual sampling units that can be assigned a probability to be included in the sample. The total collection of all sampling units which have been assigned a selection probability is called the sampling frame.

### 5.1.1. Items

A sampling unit for record (i.e., attributes) sampling is generally a characteristic of an item in the population. For example, suppose that you inspect a population of receipts. A possible sampling unit for record sampling can be the date of payment of the receipt. When a sampling unit (e.g., date of payment) is selected by the sampling method, the population item that corresponds to the sampled unit is included in the sample.

## 5. Selection

### 5.1.2. Monetary Units

A sampling unit for monetary unit sampling is different than a sampling unit for record sampling in that it is an individual monetary unit within an item or transaction, like an individual dollar. For example, a single sampling unit can be the 10<sup>th</sup> dollar from a specific receipt in the population. When a sampling unit (e.g., individual dollar) is selected by the sampling method, the population item that includes the sampling unit is included in the sample.

## 5.2. Sampling Methods

This section discusses four sampling methods that are commonly used in audit sampling. The methods that will be discussed are:

- Random sampling
- Fixed interval sampling
- Cell sampling
- Modified sieve sampling

First, let's get some notation out of the way. As discussed in Chapter 2, the population size  $N$  is defined as the total set of individual sampling units (denoted by  $x_i$ ).

$$N = \{x_1, x_2, \dots, x_N\}. \quad (5.1)$$

In statistical sampling, every sampling unit  $x_i$  in the population should receive a selection probability  $p(x_i)$ . The purpose of the sampling method is to provide a framework to assign selection probabilities to each of the sampling units, and subsequently draw sampling units from the population until a set of size  $n$  has been created.

To illustrate how the resulting sample differs for various sampling methods, we will use the `BuildIt` data set included in the `jfa` package. These data can be loaded into R using the code below. For simplicity, we will use a sample size of  $n = 10$  for all examples.

```
data(BuildIt)
n <- 10
```

### 5.2.1. Random Sampling

Random sampling is the most simple and straight-forward selection method. The random sampling method provides a method that allows every sampling unit in the population an equal chance of being selected, meaning that every combination of sampling units has the same probability of being selected as every other combination of the same number of sampling units. Simply put, the algorithm draws a random selection of size  $n$  of the sampling units. Therefore, the selection probability for each sampling unit is defined as:

$$p(x) = \frac{1}{N}. \quad (5.2)$$

To make this procedure visually intuitive, the figure below provides an illustration of the random sampling method.

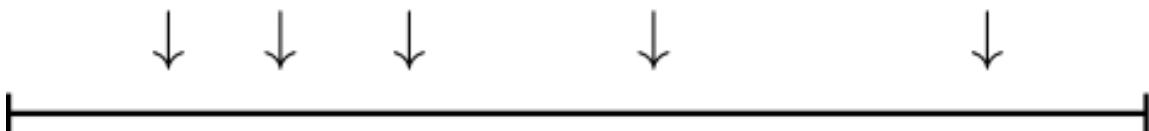


Figure 5.1.: Illustration of random sampling

- **Advantage(s):** The random sampling method yields an optimal random selection, with the additional advantage that the sample can be easily extended by applying the same method again.
- **Disadvantages:** Because the selection probabilities are equal for all sampling units there is no guarantee that items with a large monetary value in the population will be included in the sample.

#### 5.2.1.1. Record Sampling

Random sampling can easily be coded in base R. First, we have to get a vector of the possible items (rows) in the population that can be selected. When we are performing record sampling, we can simply use R's built-in `sample()` function to draw a random sample from a vector `1:nrow(BuildIt)` representing the row indices of the items and store the result in a variable `items`.

## 5. Selection

```
set.seed(1)
items <- sample(1:nrow(BuildIt), size = n, replace = FALSE)
items
#> [1] 1017 679 2177 930 1533 471 2347 270 1211 3379
```

You can then select the sample from the population using the selected indices stored in `items`.

```
BuildIt[items, ]
#>      ID bookValue auditValue
#> 1017 50755    618.24    618.24
#> 679 20237    669.75    669.75
#> 2177 9517     454.02    454.02
#> 930 85674    257.82    257.82
#> 1533 31051    308.53    308.53
#> 471 84375    824.66    824.66
#> 2347 75616    623.70    623.70
#> 270 82033    352.75    352.75
#> 1211 12877     52.89    52.89
#> 3379 85322    330.24    330.24
```

The sample can be reproduced in **jfa** via the `selection()` function. This function takes as input the population data, the sample size, and the characteristics of the sampling method. The argument `units` allows you to specify that you want to use record sampling (`units = "items"`), while the `method` argument enables you to specify that you are performing random sampling (`method = 'random'`).

```
set.seed(1)
result <- selection(data = BuildIt, size = n, units = "items",
                     method = "random")
result$sample
#>   row times     ID bookValue auditValue
#> 1 1017     1 50755    618.24    618.24
#> 2 679      1 20237    669.75    669.75
#> 3 2177     1 9517     454.02    454.02
#> 4 930      1 85674    257.82    257.82
#> 5 1533     1 31051    308.53    308.53
```

## 5.2. Sampling Methods

```
#> 6    471      1 84375    824.66    824.66  
#> 7   2347     1 75616    623.70    623.70  
#> 8    270     1 82033    352.75    352.75  
#> 9   1211     1 12877    52.89     52.89  
#> 10  3379     1 85322    330.24    330.24
```

An alternative to specifying the desired sample size through the `size` argument is to provide an object generated by the `planning()` function to the `selection()` function. For instance, the following code utilizes the `planning()` function to plan a sample size based on a performance materiality of 3% and a sampling risk of 5%, which can be passed directly to `selection()` to select the sample from the `BuildIt` population.

```
plan <- planning(materiality = 0.03)  
result <- selection(data = BuildIt, size = plan, units = "items",  
                     method = "random")
```

The ability of one function to accept input from another function allows for the implementation of a workflow in which the `planning()` function and the `selection()` function are sequentially linked. Additionally, the use of R's native pipe operator `|>` further simplifies this process.

```
result <- planning(materiality = 0.03) |>  
       selection(data = BuildIt, units = "items", method =  
                  "random")
```

The `selection()` function has three additional arguments which you can use to pre-process your population before selection. These arguments are `order`, `decreasing` and `randomize`.

The `order` argument takes as input a column name in `data` which determines the order of the population. For example, you can order the population from lowest book value to highest book value before engaging in the selection. In this case, you should use the `decreasing = FALSE` (its default value) argument.

## 5. Selection

```
set.seed(1)
result <- selection(data = BuildIt, size = n, units = "items",
                     method = "random", order = "bookValue")
result$sample
#>      row times     ID bookValue auditValue
#> 1    29     1 58849   274.26   274.26
#> 2   3297    1 24279   229.95   229.95
#> 3    931     1 28025   429.14   429.14
#> 4    756     1 11563   263.08   105.23
#> 5   3375    1 58981   335.39   335.39
#> 6   1624     1 97783   197.19   197.19
#> 7   2534     1 95715   457.42   457.42
#> 8   1798     1 95520   157.54   157.54
#> 9   3448     1 12959   296.82   296.82
#> 10  450      1 39908   831.31   831.31
```

The randomize argument can be used to randomly shuffle the items in the population before selection. For example, you can randomly shuffle the population before engaging in the selection using randomize = TRUE.

```
set.seed(1)
result <- selection(data = BuildIt, size = n, units = "items",
                     method = "random", randomize = TRUE)
result$sample
#>      row times     ID bookValue auditValue
#> 1   1264     1 85424   406.81   406.81
#> 2   923      1 12566   287.61   287.61
#> 3   776      1 92923   247.89   247.89
#> 4   127      1 71325   306.78   306.78
#> 5   1611     1 10019   191.18   191.18
#> 6   3087     1 87887   666.13   666.13
#> 7   1729     1 78779   608.02   608.02
#> 8   2037     1 74155   347.18   347.18
#> 9   2769     1 26010   240.10   240.10
#> 10  2276     1 80154   282.91   282.91
```

### 5.2.1.2. Monetary Unit Sampling

When we are performing record sampling, we have to consider that each item in the population consists of multiple smaller items (i.e., the monetary units), which means that items with a higher book value should get a higher probability of being selected. The `sample()` function facilitates weighted selection via the `prob` argument, which takes a vector of values and, using normalization, computes the weights for selection. The call below is similar to before, but in this case we use the book values in the column `bookValues` of the data set to weigh the items and store the result in a variable `items`.

```
set.seed(1)
items <- sample(1:nrow(BuildIt), size = n, replace = FALSE, prob =
  ~ BuildIt$bookValue)
items
#> [1] 2174 2928 1627 700 147 3056 3118 2045 1311 716
```

You can then select the sample from the population using the selected indices stored in `items`.

```
BuildIt[items, ]
#>      ID bookValue auditValue
#> 2174 90260     625.98    625.98
#> 2928 68595     548.21    548.21
#> 1627 98301     429.07    429.07
#> 700  29683     239.26    239.26
#> 147  72906     677.62    677.62
#> 3056 86317     246.22    246.22
#> 3118 14548     204.63    204.63
#> 2045 45416     381.05    381.05
#> 1311 91955     398.96    398.96
#> 716  12815     873.43    873.43
```

The sample can be reproduced in **jfa** via the `selection()` function. The argument `units` allows you to specify that you want to use monetary unit sampling (`units = "values"`), while the `method` argument enables you to specify that you are performing random sampling (`method = 'random'`). Note that you should provide the name of the column in the data that contains the monetary units via the `values` argument.

## 5. Selection

```
set.seed(1)
result <- selection(data = BuildIt, size = n, units = "values",
                     method = "random", values = "bookValue")
result$sample
#>      row times     ID bookValue auditValue
#> 1  2174      1 90260    625.98    625.98
#> 2  2928      1 68595    548.21    548.21
#> 3  1627      1 98301    429.07    429.07
#> 4   700      1 29683    239.26    239.26
#> 5   147      1 72906    677.62    677.62
#> 6  3056      1 86317    246.22    246.22
#> 7  3118      1 14548    204.63    204.63
#> 8  2045      1 45416    381.05    381.05
#> 9  1311      1 91955    398.96    398.96
#> 10  716      1 12815    873.43    873.43
```

### 5.2.2. Fixed Interval Sampling

Fixed interval sampling is a method designed for yielding representative samples from monetary populations. The algorithm determines a uniform interval on the (optionally ranked) sampling units. Next, a starting point is handpicked or randomly selected in the first interval and a sampling unit is selected throughout the population at each of the uniform intervals from the starting point. For example, if the interval has a width of 10 sampling units and sampling unit number 5 is chosen as the starting point, the sampling units 5, 15, 25, etc. are selected to be included in the sample.

The number of required intervals  $I$  can be determined by dividing the number of sampling units in the population by the required sample size:

$$I = \frac{N}{n}, \quad (5.3)$$

in which  $n$  is the required sample size and  $N$  is the total number of sampling units in the population.

If the space between the selected sampling units is equal, the selection probability for each sampling unit is theoretically defined as:

$$p(x) = \frac{1}{I}, \quad (5.4)$$

with the property that the space between selected units  $i$  is the same as the interval  $I$ , see the figure below. However, in practice the selection is deterministic and completely depends on the chosen starting points (using start).

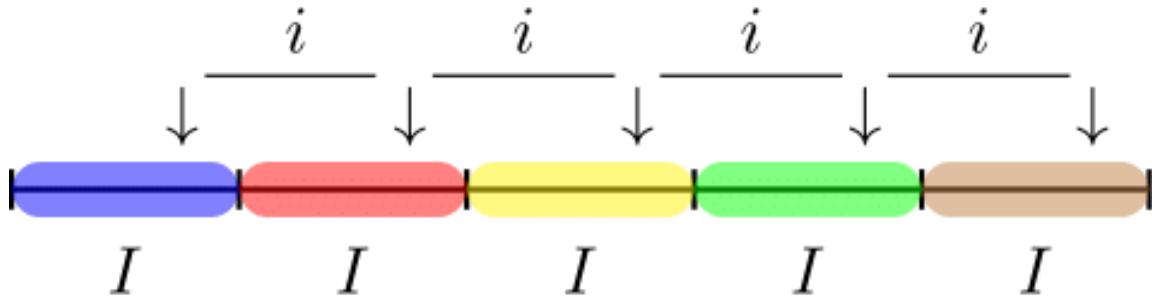


Figure 5.2.: Illustration of fixed interval sampling

The fixed interval method yields a sample that allows every sampling unit in the population an equal chance of being selected. However, the fixed interval method has the property that all items in the population with a monetary value larger than the interval  $I$  have an selection probability of one because one of these items' sampling units are always selected from the interval. Note that, if the population is arranged randomly with respect to its deviation pattern, fixed interval sampling is equivalent to random selection.

- **Advantage(s):** The advantage of the fixed interval sampling method is that it is often simple to understand and fast to perform. Another advantage is that, in monetary unit sampling, all items that are greater than the calculated interval will be included in the sample. In record sampling, since units can be ranked on the basis of value, there is also a guarantee that some large items will be in the sample.
- **Disadvantage(s):** A pattern in the population can coincide with the selected interval, rendering the sample less representative. What is sometimes seen as an added complication for this method is that the sample is hard to extend after drawing the initial sample. This is due to the chance of selecting the same sampling unit. However, by removing the already selected sampling units from the population and redrawing the intervals this problem can be efficiently solved.

## 5. Selection

### 5.2.2.1. Record Sampling

To code fixed interval sampling in a record sampling context, we first have to compute the size of the interval we are working with. This is computed by dividing the number of items in the population by the desired sample size  $n$ . Suppose the auditor wants to select a sample of 10 items, then the interval is computed by:

```
interval <- nrow(BuildIt) / n
```

Next, we have to determine the starting point. We are going to take the fifth unit in each interval in this case.

```
start <- 5
```

To find which rows are part of the sample, we execute the following code:

```
items <- floor(start + interval * 0:(n - 1))
```

You can then select the sample from the population using the selected indices stored in `items`.

```
BuildIt[items, ]  
#>      ID bookValue auditValue  
#> 5    55080    620.88    620.88  
#> 355  27934    749.38    749.38  
#> 705  21900    919.00    919.00  
#> 1055 66675    384.27    384.27  
#> 1405 13472    360.05    360.05  
#> 1755 61607    389.75    389.75  
#> 2105 68519    354.71    354.71  
#> 2455 91983    467.72    467.72  
#> 2805 25646    420.80    420.80  
#> 3155 94955    248.77    248.77
```

The sample can be reproduced in `jfa` via the `selection()` function. The argument `units` allows you to specify that you want to use record sampling (`units = "items"`), while the `method` argument enables you to specify that you are performing fixed interval sampling (`method = 'interval'`). Note that, by default, the first sampling unit from each interval

is selected. However, this can be changed by setting the argument `start` to a different value.

```
result <- selection(data = BuildIt, size = n, units = "items",
  ↵ method = "interval", start = start)
result$sample
#>      row times     ID bookValue auditValue
#> 1      5      1 55080    620.88    620.88
#> 2    355      1 27934    749.38    749.38
#> 3    705      1 21900    919.00    919.00
#> 4   1055      1 66675    384.27    384.27
#> 5   1405      1 13472    360.05    360.05
#> 6   1755      1 61607    389.75    389.75
#> 7   2105      1 68519    354.71    354.71
#> 8   2455      1 91983    467.72    467.72
#> 9   2805      1 25646    420.80    420.80
#> 10  3155      1 94955    248.77    248.77
```

### 5.2.2.2. Monetary Unit Sampling

In monetary unit sampling, the only difference is that we are computing the interval on the basis of the booked values in the column `bookValue` of the data set. In this case, the starting point `start = 5` determines which monetary unit from each interval is selected.

```
interval <- sum(BuildIt$bookValue) / n
```

To find which units are part of the sample, we execute the following code:

```
units <- floor(start + interval * 0:(n - 1))
```

To obtain which items are part of the sample, we can run the following for loop. Note that this does not take into account whether the book values contain negative values, which should not be included in the cumulative sum below.

## 5. Selection

```
all_units <- ifelse(BuildIt$bookValue < 0, 0, BuildIt$bookValue)
all_items <- 1:nrow(BuildIt)
items <- numeric(n)
for (i in 1:n) {
  item <- which(units[i] <= cumsum(all_units))[1]
  items[i] <- all_items[item]
}
```

You can then select the sample from the population using the selected indices stored in `items`.

```
BuildIt[items, ]
#>      ID bookValue auditValue
#> 1  82884   242.61   242.61
#> 358 20711   610.88   610.88
#> 715 99012   313.75   313.75
#> 1081 65319   502.54   201.02
#> 1421 88454   856.28   856.28
#> 1774 87258   157.68   157.68
#> 2103 48652   497.21   497.21
#> 2435 37248  1041.44  1041.44
#> 2787 10925   377.10   377.10
#> 3152 71832  1001.82  1001.82
```

The sample can be reproduced in **jfa** via the `selection()` function. The argument `units` allows you to specify that you want to use monetary unit sampling (`units = "values"`), while the `method` argument enables you to specify that you are performing fixed interval sampling (`method = 'interval'`). Note that you should provide the name of the column in the data that contains the monetary units via the `values` argument.

```
result <- selection(data = BuildIt, size = n, units = "values",
                     method = "interval", values = "bookValue", start = start)
result$sample
#>      row times      ID bookValue auditValue
#> 1      1     1  82884    242.61   242.61
#> 2     358     1 20711    610.88   610.88
#> 3      715     1 99012    313.75   313.75
```

```
#> 4 1081     1 65319    502.54    201.02
#> 5 1421     1 88454    856.28    856.28
#> 6 1774     1 87258    157.68    157.68
#> 7 2103     1 48652    497.21    497.21
#> 8 2435     1 37248    1041.44   1041.44
#> 9 2787     1 10925    377.10    377.10
#> 10 3152    1 71832    1001.82   1001.82
```

### 5.2.3. Cell Sampling

The cell sampling method divides the (optionally ranked) population into a set of intervals  $I$  that are computed through the previously given equations. Within each interval, a sampling unit is selected by randomly drawing a number between 1 and the interval range  $I$ . This causes the space  $i$  between the sampling units to vary.

Like in the fixed interval sampling method, the selection probability for each sampling unit is defined as:

$$p(x) = \frac{1}{I}. \quad (5.5)$$



Figure 5.3.: Illustration of cell sampling

The cell sampling method has the property that all items in the population with a monetary value larger than twice the interval  $I$  have a selection probability of one.

- **Advantage(s):** More sets of samples are possible than in fixed interval sampling, as there is no systematic interval  $i$  to determine the selections. It is argued that the

## 5. Selection

cell sampling algorithm offers a solution to the pattern problem in fixed interval sampling.

- **Disadvantage(s):** A disadvantage of this sampling method is that not all items in the population with a monetary value larger than the interval have a selection probability of one. Besides, population items can be in two adjacent cells, thereby creating the possibility that an item is included in the sample twice.

### 5.2.3.1. Record Sampling

To code cell sampling in a record sampling context, we again have to compute the size of the interval we are working with:

```
interval <- nrow(BuildIt) / n
```

Next, we have to randomly determine which items are going to be selected in each interval.

```
set.seed(1)
starts <- floor(runif(n, 0, interval))
```

To find which rows are part of the sample, we execute the following code:

```
items <- floor(starts + interval * 0:(n - 1))
```

You can then select the sample from the population using the selected indices stored in `items`.

```
BuildIt[items, ]
#>      ID bookValue auditValue
#> 92    75133    355.16    355.16
#> 480   81037    456.27    456.27
#> 900   1730     449.87    449.87
#> 1367  36587    282.32    282.32
#> 1470  10305    648.70    648.70
#> 2064  96344    268.94    268.94
#> 2430  60885    493.77    493.77
```

## 5.2. Sampling Methods

```
#> 2681 60935      312.98      312.98  
#> 3020 8716      450.76      450.76  
#> 3171 61036      387.67      387.67
```

The sample can be reproduced in **jfa** via the `selection()` function. The argument `units` allows you to specify that you want to use record sampling (`units = "items"`), while the `method` argument enables you to specify that you are performing cell sampling (`method = 'cell'`).

```
set.seed(1)  
result <- selection(data = BuildIt, size = n, units = "items",  
                     method = "cell")  
result$sample  
#>      row times     ID bookValue auditValue  
#> 1    92      1 75133   355.16   355.16  
#> 2    480     1 81037   456.27   456.27  
#> 3    900     1 1730    449.87   449.87  
#> 4   1367     1 36587   282.32   282.32  
#> 5   1470     1 10305   648.70   648.70  
#> 6   2064     1 96344   268.94   268.94  
#> 7   2430     1 60885   493.77   493.77  
#> 8   2681     1 60935   312.98   312.98  
#> 9   3020     1 8716    450.76   450.76  
#> 10  3171     1 61036   387.67   387.67
```

### 5.2.3.2. Monetary Unit Sampling

In monetary unit sampling, the only difference is that we are computing the interval on the basis of the booked values in the column `bookValue` of the data set. In this case, the starting points `start` determines which monetary unit from each interval is selected.

```
interval <- sum(BuildIt$bookValue) / n
```

To obtain which items are part of the sample, we can run the following for loop. Note that this does not take into account whether the book values contain negative values, which should not be included in the cumulative sum below.

## 5. Selection

```
set.seed(1)
all_units <- ifelse(BuildIt$bookValue < 0, 0, BuildIt$bookValue)
all_items <- 1:nrow(BuildIt)
intervals <- 0:n * interval
items <- numeric(n)
for (i in 1:n) {
  unit <- stats::runif(1, intervals[i], intervals[i + 1])
  item <- which(unit <= cumsum(all_units))[1]
  items[i] <- all_items[item]
}
```

You can then select the sample from the population using the selected indices stored in `items`.

```
BuildIt[items, ]
#>           ID bookValue auditValue
#> 95    15009    415.60   415.60
#> 486   79093    635.85   635.85
#> 931   28025    429.14   429.14
#> 1387  56444    296.37   296.37
#> 1492  81443    543.80   543.80
#> 2074  14196    270.45   270.45
#> 2418  87743    347.99   347.99
#> 2660  23927    454.81   454.81
#> 3024  78925    251.44   251.44
#> 3172  18286    450.57   450.57
```

The sample can be reproduced in **jfa** via the `selection()` function. The argument `units` allows you to specify that you want to use monetary unit sampling (`units = "values"`), while the `method` argument enables you to specify that you are performing cell sampling (`method = 'cell'`). Note that you should provide the name of the column in the data that contains the monetary units via the `values` argument.

```
set.seed(1)
result <- selection(data = BuildIt, size = n, units = "values",
                     method = "cell", values = "bookValue")
result$sample
```

```
#>      row times     ID bookValue auditValue
#> 1      95     1 15009    415.60    415.60
#> 2     486     1 79093    635.85    635.85
#> 3     931     1 28025    429.14    429.14
#> 4    1387     1 56444    296.37    296.37
#> 5    1492     1 81443    543.80    543.80
#> 6    2074     1 14196    270.45    270.45
#> 7    2418     1 87743    347.99    347.99
#> 8    2660     1 23927    454.81    454.81
#> 9    3024     1 78925    251.44    251.44
#> 10   3172     1 18286    450.57    450.57
```

### 5.2.4. Modified Sieve Sampling

The fourth option for the sampling method is modified sieve sampling (Hoogduin, Hall, & Tsay, 2010). The algorithm starts by selecting a standard uniform random number  $R_i$  between 0 and 1 for each item in the population. Next, the sieve ratio:

$$S_i = \frac{Y_i}{R_i} \quad (5.6)$$

is computed for each item by dividing the book value of that item by the random number. Lastly, the items in the population are sorted by their sieve ratio  $S$  (in decreasing order) and the top  $n$  items are selected for inspection. In contrast to the classical sieve sampling method (Rietveld, 1978), the modified sieve sampling method provides precise control over sample sizes.

#### 5.2.4.1. Monetary Unit Sampling

```
set.seed(1)
all_units <- ifelse(BuildIt$bookValue < 0, 0, BuildIt$bookValue)
all_items <- 1:nrow(BuildIt)
ri <- all_units / stats::runif(length(all_items), 0, 1)
items <- all_items[order(-ri)]
items <- items[1:n]
```

## 5. Selection

You can then select the sample from the population using the selected indices stored in `items`.

```
BuildIt[items, ]  
#>           ID bookValue auditValue  
#> 2329 29919     681.10    681.10  
#> 2883 59402     279.29    279.29  
#> 1949 56012     581.22    581.22  
#> 3065 47482     621.73    621.73  
#> 1072 79901     789.97    789.97  
#> 488  50811     651.35    651.35  
#> 1916 53565     266.37    266.37  
#> 463  65768     480.89    480.89  
#> 1311 91955     398.96    398.96  
#> 2895 8688      492.02    492.02
```

The sample can be reproduced in `jfa` via the `selection()` function. The argument `units` allows you to specify that you want to use monetary unit sampling (`units = "values"`), while the `method` argument enables you to specify that you are performing modified sieve sampling (`method = 'sieve'`). Note that you should provide the name of the column in the data that contains the monetary units via the `values` argument.

```
set.seed(1)  
result <- selection(data = BuildIt, size = n, units = "values",  
                     method = "sieve", values = "bookValue")  
result$sample  
#>   row times   ID bookValue auditValue  
#> 1  2329     1 29919    681.10    681.10  
#> 2  2883     1 59402    279.29    279.29  
#> 3  1949     1 56012    581.22    581.22  
#> 4  3065     1 47482    621.73    621.73  
#> 5  1072     1 79901    789.97    789.97  
#> 6  488      1 50811    651.35    651.35  
#> 7  1916     1 53565    266.37    266.37  
#> 8  463      1 65768    480.89    480.89  
#> 9  1311     1 91955    398.96    398.96  
#> 10 2895     1 8688     492.02    492.02
```

### 5.3. Exercises

1. Select a random sample of 120 items from the BuildIt data set.

Click to reveal answer

```
selec <- selection(data = BuildIt, size = 120, method = "random",
  ↵ units = "items")
head(selec$sample, 5)
#>   row times     ID bookValue auditValue
#> 1 2453      1 95755    295.58    295.58
#> 2 2914      1 86541    470.99    470.99
#> 3 301       1 61726    588.81    588.81
#> 4 2632      1 3335     237.32    237.32
#> 5 1579      1 62317    309.74    309.74
```

2. Select a sample of 240 monetary units from the BuildIt data set using a fixed interval selection method. Use a starting point of 12.

Click to reveal answer

```
selec <- selection(data = BuildIt, size = 240, method = "interval",
  ↵ units = "values", values = "bookValue", start = 12)
head(selec$sample, 5)
#>   row times     ID bookValue auditValue
#> 1    1      1 82884    242.61    242.61
#> 2   15      1 76073    469.93    469.93
#> 3   31      1 83557    507.34    507.34
#> 4   47      1 53784    325.19    325.19
#> 5   63      1 51272    248.40    248.40
```



## 6. Evaluation

**i** You are reading the work-in-progress first edition of Statistical Auditing with R. This chapter is currently a dumping ground of ideas, and it is incomplete.

Evaluating a sample is the final stage in the audit sampling workflow and the bread and butter of statistical audit sampling. In this stage, the auditor weighs the audit evidence obtained from the sample together with the audit evidence obtained in earlier stages of the audit to determine their opinion about the population.

Like planning a sample, evaluating a sample requires knowledge of the conditions that lead to acceptance or rejection of the population (i.e., the sampling objectives). A quick reminder: Sampling objectives can be classified into one of the following two categories:

- **Hypothesis testing:** The goal of the sample is to obtain evidence for or against the claim that the misstatement in the population is lower than a given value (i.e., the performance materiality).
- **Estimation:** The goal of the sample is to obtain an accurate estimate of the misstatement in the population (with a minimum precision).

A non-stratified audit sample does not involve dividing the population into subgroups. Here, the auditor selects a random sample from the entire population without considering any specific characteristics of the population.

For example, in an audit of a company's inventory, the auditor may simply select a random sample of items from the entire inventory without dividing it into subgroups based on characteristics such as location or type of item. Another example of such a situation would be where the auditor is auditing the general ledger of a small business.

Naturally, non-stratified sampling is simpler than stratified sampling and can be used when the population is considered homogenous or the auditor does not need to consider differences between subgroups (e.g., strata).

## 6. Evaluation



Figure 6.1.: When evaluating a sample with respect to a specific hypothesis, the auditor must consider the evidence in favour as well as the evidence against that hypothesis. Image available under a CC-BY-NC 4.0 license.

### 6.1. Classical Evaluation

Classical hypothesis testing uses the  $p$ -value to make a decision about whether to reject the hypothesis  $H_0$  or not. As an example, consider that an auditor wants to verify whether the population contains less than 5 percent misstatement, implying the hypotheses  $H_1 : \theta < 0.05$  and  $H_0 : \theta \geq 0.05$ . They have taken a sample of 100 items, of which 1 contained an error. They set the significance level for the  $p$ -value to 0.05, implying that  $p < 0.05$  will be enough to reject the hypothesis  $H_0$ . The call below evaluates the sample using a classical non-stratified evaluation procedure.

```
evaluation(materiality = 0.05, x = 1, n = 100)
#>
#> Classical Audit Sample Evaluation
#>
#> data: 1 and 100
#> number of errors = 1, number of samples = 100, taint = 1,
#>   p-value =
```

```
#> 0.040428
#> alternative hypothesis: true misstatement rate is less than 0.05
#> 95 percent confidence interval:
#> 0.0000000 0.04743865
#> most likely estimate:
#> 0.01
#> results obtained via method 'poisson'
```

The output shows that the most likely error in the population is estimated to be  $1 / 100 = 1\%$  and that the 95% (one-sided) confidence interval ranges from 0% to 4.74%. The output also shows that the  $p$ -value is lower than 0.05 implying that the hypothesis  $H_0$  can be rejected. Hence, the auditor is able to conclude that the sample provides sufficient evidence to state with reasonable assurance that the population does not contain material misstatement.

## 6.2. Bayesian Evaluation

Bayesian hypothesis testing uses the Bayes factor,  $BF_{10}$  or  $BF_{01}$ , to make a statement about the evidence provided by the sample in support for one of the two hypotheses  $H_1$  or  $H_0$ . As an example of how to interpret the Bayes factor, the value of  $BF_{10} = 10$  (provided by the `evaluation()` function) can be interpreted as: *the data are 10 times more likely to have occurred under the hypothesis  $H_1$  than under the hypothesis  $H_0$* .  $BF_{10} > 1$  indicates evidence in favor of  $H_1$  and against  $H_0$ , while  $BF_{10} < 1$  indicates evidence in favor of  $H_0$  and against  $H_1$ . The `evaluation()` function returns the value for  $BF_{10}$ , but  $BF_{01}$  can be computed as  $\frac{1}{BF_{10}}$ .

Consider the previous example of an auditor who wants to verify whether the population contains less than 5 percent misstatement, implying the hypotheses  $H_1 : \theta < 0.05$  and  $H_0 : \theta \geq 0.05$ . They have taken a sample of 100 items, of which 1 was found to contain a misstatement. The prior distribution is assumed to be a default  $beta(1,1)$  prior. The call below evaluates the sample using a Bayesian non-stratified evaluation procedure.

```
prior <- auditPrior(materiality = 0.05, method = "default",
  ↵ likelihood = "binomial")
evaluation(materiality = 0.05, x = 1, n = 100, prior = prior)
#>
```

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```
#> Bayesian Audit Sample Evaluation
#>
#> data: 1 and 100
#> number of errors = 1, number of samples = 100, taint = 1, BF10 =
#> 515.86
#> alternative hypothesis: true misstatement rate is less than 0.05
#> 95 percent credible interval:
#> 0.00000000 0.04610735
#> most likely estimate:
#> 0.01
#> results obtained via method 'binomial' + 'prior'
```

The output shows that the most likely error in the population is estimated to be  $1 / 100 = 1\%$  and that the 95% (one-sided) credible interval ranges from 0% to 4.61%. The small difference between the classical and default Bayesian results is due to the prior distribution, which must be proper in order to calculate a Bayes factor (classical results can be emulated by constructing a prior with `method = "strict"` in the `auditPrior()` function). The Bayes factor in this case is shown to be  $BF_{10} = 515$ , meaning that the data from the sample are about 515 times more likely to occur under the hypothesis of tolerable misstatement than under the hypothesis of material misstatement.

The prior distribution and posterior distribution can be used to directly calculate the Bayes factor in favor of (in)tolerable misstatement. To begin, we compute the prior probability of the hypothesis of tolerable misstatement.

```
prior.prob.h1 <- pbeta(0.05, shape1 = 1, shape2 = 1)
prior.prob.h1
#> [1] 0.05
```

Since the hypothesis of intolerable misstatement is the complement of the hypothesis of tolerable misstatement, its probability is simply one minus the prior probability of the hypothesis of tolerable misstatement.

```
prior.prob.h0 <- 1 - prior.prob.h1
prior.prob.h0
#> [1] 0.95
```

The prior odds is the ratio of the prior probabilities.

## 6.2. Bayesian Evaluation

```
prior.odds.h1 <- prior.prob.h1 / prior.prob.h0  
prior.odds.h1  
#> [1] 0.05263158
```

Next, the posterior probability of the hypothesis of tolerable misstatement can be computed using the posterior distribution.

```
post.prob.h1 <- pbeta(0.05, shape1 = 1 + 1, shape2 = 1 + 100 - 1)  
post.prob.h1  
#> [1] 0.9644768
```

The posterior probability of the hypothesis of intolerable misstatement is one minus the posterior probability of the hypothesis of tolerable misstatement.

```
post.prob.h0 <- 1 - post.prob.h1  
post.prob.h0  
#> [1] 0.03552318
```

The posterior odds is the ratio of the posterior probabilities.

```
post.odds.h1 <- post.prob.h1 / post.prob.h0  
post.odds.h1  
#> [1] 27.15064
```

The Bayes factor is the ratio of posterior odds and prior odds and equals 515.86.

```
bf10 <- post.odds.h1 / prior.odds.h1  
bf10  
#> [1] 515.8621
```

Note that this is a very high Bayes factor for the little data that is observed. That is because the Bayes factor is dependent on the prior distribution for the model parameters (in this case  $\theta$ ). As a rule of thumb, when the prior distribution is highly conservative (as with `method = 'default'`) with respect to the hypothesis of tolerable misstatement, the Bayes factor tends to over quantify the evidence in favor of this hypothesis. You can mitigate this dependency by using a prior distribution that is impartial with respect to the hypotheses via `method = "impartial"` in the `auditPrior()` function (Derks et al.,

## 6. Evaluation

2022a).

```
prior <- auditPrior(materiality = 0.05, method = "impartial",
  ↪ likelihood = "binomial")
evaluation(materiality = 0.05, x = 1, n = 100, prior = prior)
#>
#> Bayesian Audit Sample Evaluation
#>
#> data: 1 and 100
#> number of errors = 1, number of samples = 100, taint = 1, BF10 =
#> 47.435
#> alternative hypothesis: true misstatement rate is less than 0.05
#> 95 percent credible interval:
#> 0.00000000 0.04110834
#> most likely estimate:
#> 0.0088878
#> results obtained via method 'binomial' + 'prior'
```

The output shows that  $BF_{10} = 47$ , implying that under the assumption of impartiality there is strong evidence for  $H_1$ , the hypothesis that the population contains misstatements lower than 5 percent of the population (tolerable misstatement). Since the two prior distributions both resulted in convincing Bayes factors, the results can be considered robust to the choice of prior distribution. Hence, the auditor is able to conclude that the sample provides convincing evidence to state that the population does not contain material misstatement.

### 6.3. Evaluation using Data

For this example, we take the allowances that set that comes with the package. This data set contains 3500 financial statement line items, each with a booked value `bookValue` and, for illustrative purposes, and audited (true) value `auditValue`. Since the focus of this vignette is the evaluation stage in the audit, the sample is already indicated in the data set. The performance materiality in this example is set to 5%.

```
data(allowances)
head(allowances)
```

```
#>   item branch bookValue auditValue times
#> 1     1      12       1600      1600    1
#> 2     2      12       1625        NA    0
#> 3     3      12       1775        NA    0
#> 4     4      12       1250      1250    1
#> 5     5      12       1400        NA    0
#> 6     6      12       1190        NA    0
```

Evaluating a non-stratified sample using data requires specification of the data, values and values.audit arguments. The input for these arguments is the name of the specific column in data.

### 6.3.1. Classical Evaluation

The call below evaluates the allowances sample using a classical non-stratified evaluation procedure.

```
x <- evaluation(materiality = 0.05, data = allowances, values =
  "bookValue", values.audit = "auditValue", times = "times")
summary(x)
#>
#> Classical Audit Sample Evaluation Summary
#>
#> Options:
#> Confidence level:                  0.95
#> Materiality:                      0.05
#> Hypotheses:                        H0 :  $\bar{x} \geq 0.05$  vs. H1 :  $\bar{x} < 0.05$ 
#> Method:                            poisson
#>
#> Data:
#> Sample size:                       1604
#> Number of errors:                 401
#> Sum of taints:                    252.9281046
#>
#> Results:
#> Most likely error:                0.15769
```

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```
#> 95 percent confidence interval: [0, 0.175]
#> Precision: 0.017311
#> p-value: 1
```

In this case, the output shows that the estimate of the misstatement in the population is 15.77%, with the 95% (one-sided) confidence interval ranging from 0% to 17.5%.

### 6.3.2. Bayesian evaluation

The call below evaluates the allowances sample using a Bayesian non-stratified evaluation procedure.

```
x <- evaluation(materiality = 0.05, data = allowances, prior =
  TRUE, values = "bookValue", values.audit = "auditValue", times
  = "times")
summary(x)
#>
#> Bayesian Audit Sample Evaluation Summary
#>
#> Options:
#> Confidence level: 0.95
#> Materiality: 0.05
#> Hypotheses: H0:  $\bar{x} > 0.05$  vs. H1:  $\bar{x} < 0.05$ 
#> Method: poisson
#> Prior distribution: gamma( $\alpha = 1$ ,  $\beta = 1$ )
#>
#> Data:
#> Sample size: 1604
#> Number of errors: 401
#> Sum of taints: 252.9281046
#>
#> Results:
#> Posterior distribution: gamma( $\alpha = 253.928$ ,  $\beta = 1605$ )
#> Most likely error: 0.15759
#> 95 percent credible interval: [0, 0.17489]
#> Precision: 0.0173
```

```
#>     BF1|0 : 0
```

The output shows that the estimate of the misstatement in the population is 15.76%, with the 95% (one-sided) credible interval ranging from 0% to 17.49%.

## 6.4. Exercises

1. Evaluate a sample of  $n = 30$  items containing  $k = 2$  misstatement. Use the classical approach.

Click to reveal answer

```
evaluation(n = 30, x = 2, method = "binomial")
#>
#> Classical Audit Sample Evaluation
#>
#> data: 2 and 30
#> number of errors = 2, number of samples = 30, taint = 2
#> 95 percent confidence interval:
#>  0.000000 0.195326
#> most likely estimate:
#>  0.066667
#> results obtained via method 'binomial'
```



## 7. Stratified Evaluation

**i** You are reading the work-in-progress first edition of Statistical Auditing with R. This chapter is currently a dumping ground of ideas, and it is incomplete.

In an audit context, stratified sampling can be used to select a sample of transactions from different departments, locations, or business units to ensure that the sample is representative of the population. This means that there is a hierarchical structure in the data (strata are nested in the population) and the statistical model should ideally reflect this.

In general, there are three approaches to evaluating a stratified sample: no pooling, complete pooling, and partial pooling. No pooling assumes no similarities between strata, which means that all strata are analyzed independently. Complete pooling assumes no difference between strata, which means that all data is aggregated and analyzed as a whole. Finally, partial pooling assumes differences and similarities between strata, which means that information can be shared between strata. Partial pooling (i.e., hierarchical modeling) is a powerful technique that can result in more efficient population and stratum estimates.

For example, if you want to audit the expense claims of a large organization, you can stratify the population based on the department, location, or business unit to ensure that all departments are represented accordingly in the sample. Another example of such a situation would be a group audit where the audited organization consists of different components or branches. Stratification is relevant for the group auditor if they must form an opinion on the group as a whole because they must aggregate the samples taken by the component auditors.

As a data example, consider the `retailer` data set that comes with the package. The organization in question consists of 20 branches across the country. In each of the 20 strata, a component auditor has taken a statistical sample and reported the outcomes to the group auditor.

## 7. Stratified Evaluation



Figure 7.1.: There are three approaches to evaluating a stratified audit sample: no pooling, complete pooling and partial pooling. Image available under a CC-BY-NC 4.0 license.

```
data(retailer)
head(retailer)
#>   stratum items samples errors
#> 1      1 5000     300     21
#> 2      2 5000     300     16
#> 3      3 5000     300     15
#> 4      4 5000     300     14
#> 5      5 5000     300     16
#> 6      6 5000     150      5
```

The number of units per stratum in the population can be provided with `N.units` to weigh the stratum estimates to determine population estimate. This is called poststratification. If `N.units` is not specified, each stratum is assumed to be equally represented in the population.

## 7.1. No pooling

No pooling (pooling = "none", default) assumes no similarities between strata. This means that the prior distribution specified through prior is applied independently for each stratum. This allows for independent estimates for the misstatement in each stratum but also results in a relatively high uncertainty in the population estimate. The call below evaluates the sample using a Bayesian stratified evaluation procedure, in which the stratum estimates are poststratified to arrive at the population estimate.

```
set.seed(1) # Important because the posterior distribution is
#> determined via sampling
result_np <- evaluation( materiality = 0.05, method = "binomial",
#> prior = TRUE, n = retailer$samples, x = retailer$errors, N.units
#> = retailer$items, alternative = "two.sided", pooling = "none")
summary(result_np)
#>
#> Bayesian Audit Sample Evaluation Summary
#>
#> Options:
#>   Confidence level:           0.95
#>   Population size:          144000
#>   Materiality:              0.05
#>   Hypotheses:                H0: ̘ = 0.05 vs. H1: ̘ ≠ 0.05
#>   Method:                    binomial
#>   Prior distribution:        Nonparametric
#>
#> Data:
#>   Sample size:               2575
#>   Number of errors:          115
#>   Sum of taints:             115
#>
#> Results:
#>   Posterior distribution:    Nonparametric
#>   Most likely error:         0.0598
#>   95 percent credible interval: [0.042763, 0.082201]
#>   Precision:                 0.022401
#>   BF1:0:                   0
```

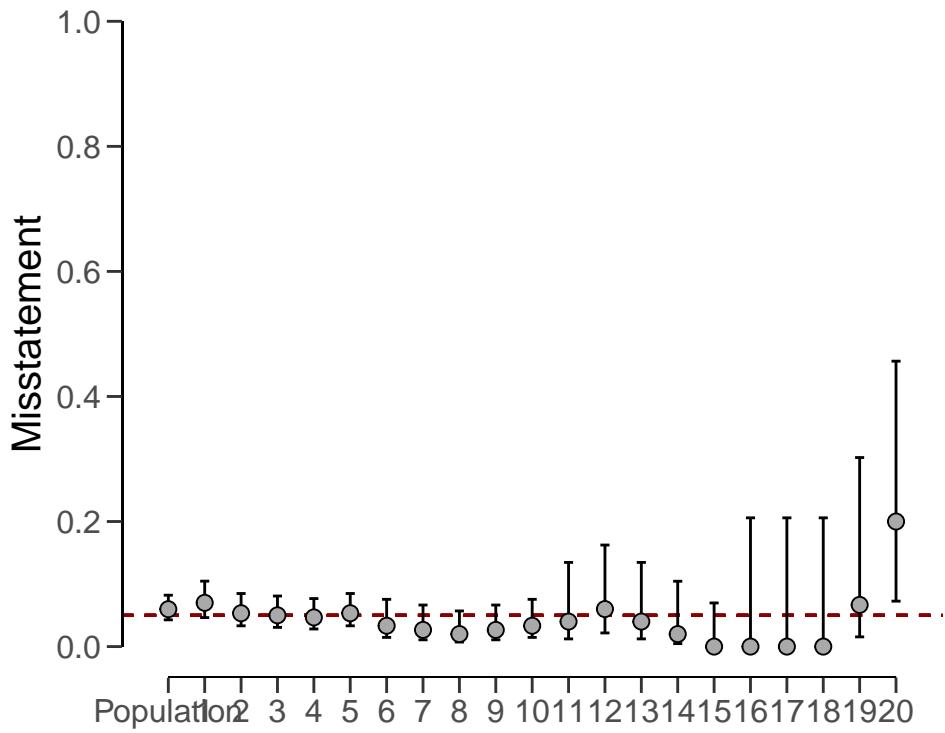
## 7. Stratified Evaluation

```
#>
#> Strata (20):
#>      N   n   x   t     mle      lb      ub precision
#> 1  5000 300 21 21 0.07000 0.04637 0.10467  0.03467
#> 2  5000 300 16 16 0.05333 0.03324 0.08489  0.03156
#> 3  5000 300 15 15 0.05000 0.03069 0.08086  0.03086
#> 4  5000 300 14 14 0.04667 0.02816 0.07681  0.03014
#> 5  5000 300 16 16 0.05333 0.03324 0.08489  0.03156
#> 6  5000 150  5  5 0.03333 0.01472 0.07558  0.04225
#> 7  5000 150  4  4 0.02667 0.01084 0.06643  0.03977
#> 8  5000 150  3  3 0.02000 0.00726 0.05696  0.03696
#> 9  5000 150  4  4 0.02667 0.01084 0.06643  0.03977
#> 10 5000 150  5  5 0.03333 0.01472 0.07558  0.04225
#> 11 10000  50  2  2 0.04000 0.01230 0.13459  0.09459
#> 12 10000  50  3  3 0.06000 0.02178 0.16242  0.10242
#> 13 10000  50  2  2 0.04000 0.01230 0.13459  0.09459
#> 14 10000  50  1  1 0.02000 0.00478 0.10447  0.08447
#> 15 10000  50  0  0 0.00000 0.00050 0.06978  0.06978
#> 16 10000  15  0  0 0.00000 0.00158 0.20591  0.20591
#> 17 10000  15  0  0 0.00000 0.00158 0.20591  0.20591
#> 18 10000  15  0  0 0.00000 0.00158 0.20591  0.20591
#> 19 10000  15  1  1 0.06667 0.01551 0.30232  0.23565
#> 20 4000   15  3  3 0.20000 0.07266 0.45646  0.25646
```

In this case, the output of the `summary()` function shows that the estimate of the misstatement in the population is 5.85%, with the 95% credible interval ranging from 4.28% to 8.22%. The stratum estimates differ substantially from each other but are relatively uncertain.

```
plot(result_np, type = "estimates")
```

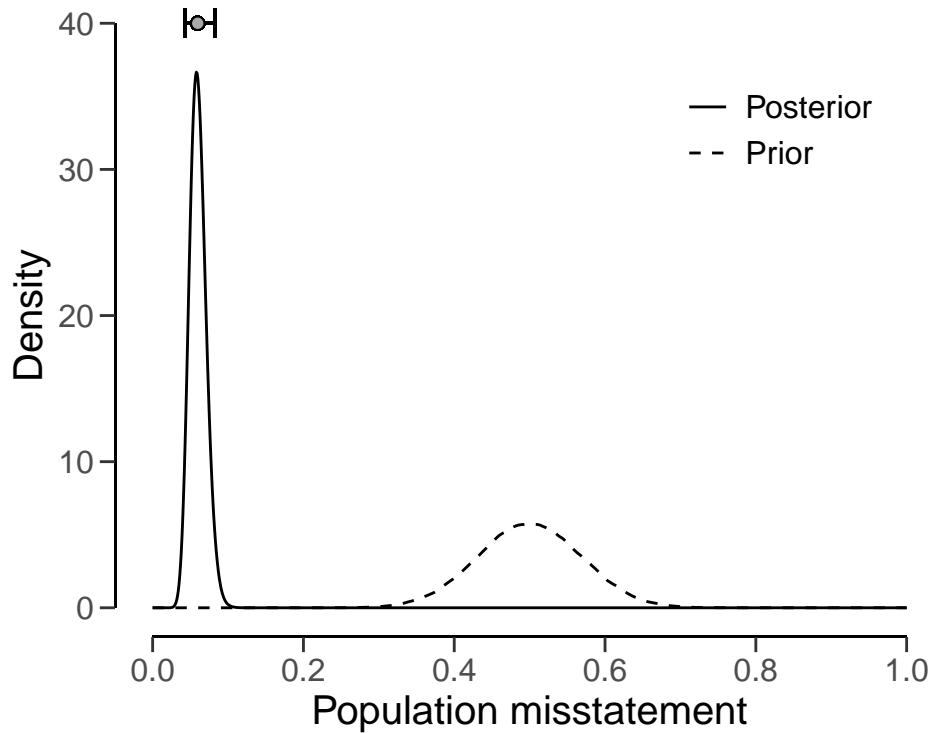
### 7.1. No pooling



The prior and posterior distribution for the population misstatement can be requested via the `plot()` function.

```
plot(result_np, type = "posterior")
```

## 7. Stratified Evaluation



### 7.2. Complete pooling

Complete pooling (pooling = "complete") assumes no differences between strata. This has the advantages that data from all strata can be aggregated, which decreases the uncertainty in the population estimate compared to the no pooling approach. However, the disadvantage of this approach is that it does not facilitate the distinction between between strata, as every stratum receives the same estimate equal to that of the population. The call below evaluates the sample using a Bayesian stratified evaluation procedure, in which the strata are assumed to be the same.

```
result_cp <- evaluation(materiality = 0.05, method = "binomial",
  prior = TRUE, n = retailer$samples, x = retailer$errors,
  N.units = retailer$items, alternative = "two.sided", pooling =
  "complete")
summary(result_cp)
```

## 7.2. Complete pooling

```

#>
#> Bayesian Audit Sample Evaluation Summary
#>
#> Options:
#>   Confidence level:          0.95
#>   Population size:          144000
#>   Materiality:              0.05
#>   Hypotheses:                H0:  $\theta = 0.05$  vs. H1:  $\theta \neq 0.05$ 
#>   Method:                    binomial
#>   Prior distribution:        beta( $\theta = 1$ ,  $\theta = 1$ )
#>
#> Data:
#>   Sample size:               2575
#>   Number of errors:          115
#>   Sum of taints:             115
#>
#> Results:
#>   Posterior distribution:    beta( $\theta = 116$ ,  $\theta = 2461$ )
#>   Most likely error:         0.04466
#>   95 percent credible interval: [0.03735, 0.053345]
#>   Precision:                 0.0086852
#>   BF10:                     0.022725
#>
#> Strata (20):
#>   N   n   x   t     mle      lb      ub precision     bf10
#> 1  5000 300 21 21  0.04466  0.03735  0.05335  0.00869  0.02273
#> 2  5000 300 16 16  0.04466  0.03735  0.05335  0.00869  0.02273
#> 3  5000 300 15 15  0.04466  0.03735  0.05335  0.00869  0.02273
#> 4  5000 300 14 14  0.04466  0.03735  0.05335  0.00869  0.02273
#> 5  5000 300 16 16  0.04466  0.03735  0.05335  0.00869  0.02273
#> 6  5000 150  5  5  0.04466  0.03735  0.05335  0.00869  0.02273
#> 7  5000 150  4  4  0.04466  0.03735  0.05335  0.00869  0.02273
#> 8  5000 150  3  3  0.04466  0.03735  0.05335  0.00869  0.02273
#> 9  5000 150  4  4  0.04466  0.03735  0.05335  0.00869  0.02273
#> 10 5000 150  5  5  0.04466  0.03735  0.05335  0.00869  0.02273
#> 11 10000 50  2  2  0.04466  0.03735  0.05335  0.00869  0.02273
#> 12 10000 50  3  3  0.04466  0.03735  0.05335  0.00869  0.02273

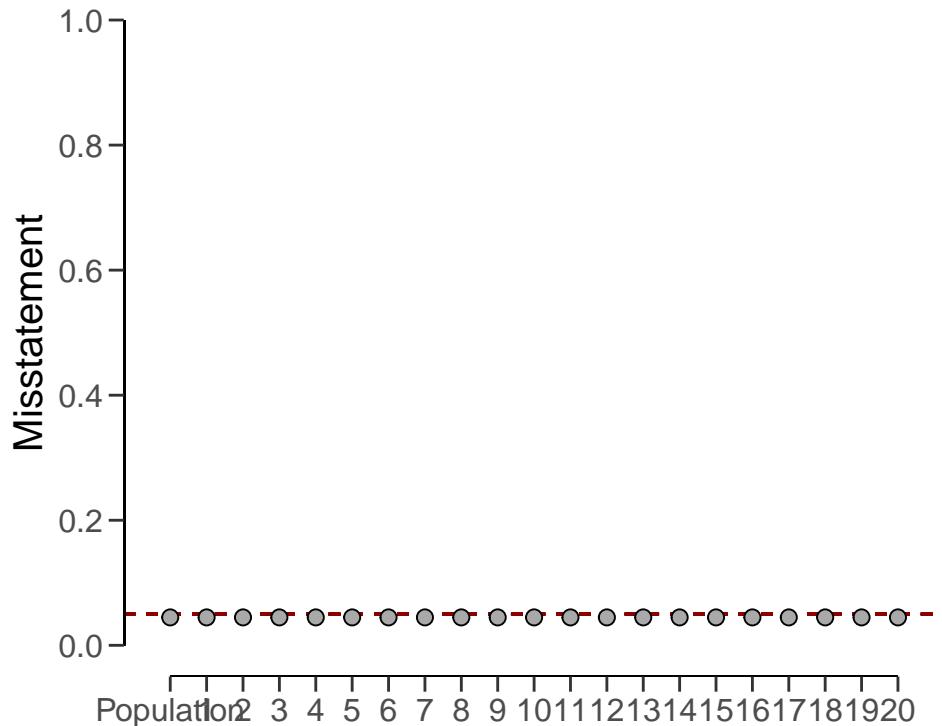
```

## 7. Stratified Evaluation

```
#> 13 10000 50 2 2 0.04466 0.03735 0.05335 0.00869 0.02273
#> 14 10000 50 1 1 0.04466 0.03735 0.05335 0.00869 0.02273
#> 15 10000 50 0 0 0.04466 0.03735 0.05335 0.00869 0.02273
#> 16 10000 15 0 0 0.04466 0.03735 0.05335 0.00869 0.02273
#> 17 10000 15 0 0 0.04466 0.03735 0.05335 0.00869 0.02273
#> 18 10000 15 0 0 0.04466 0.03735 0.05335 0.00869 0.02273
#> 19 10000 15 1 1 0.04466 0.03735 0.05335 0.00869 0.02273
#> 20 4000 15 3 3 0.04466 0.03735 0.05335 0.00869 0.02273
```

For example, the output of the `summary()` function shows that the estimate of the misstatement in the population is 4.47%, with the 95% credible interval ranging from 3.74% to 5.33%. Since the data is aggregated, the stratum estimates contain relatively little uncertainty. However, the probability of misstatement in stratum 20 (many misstatements) under this assumption is the same as that of stratum 15 (few misstatements).

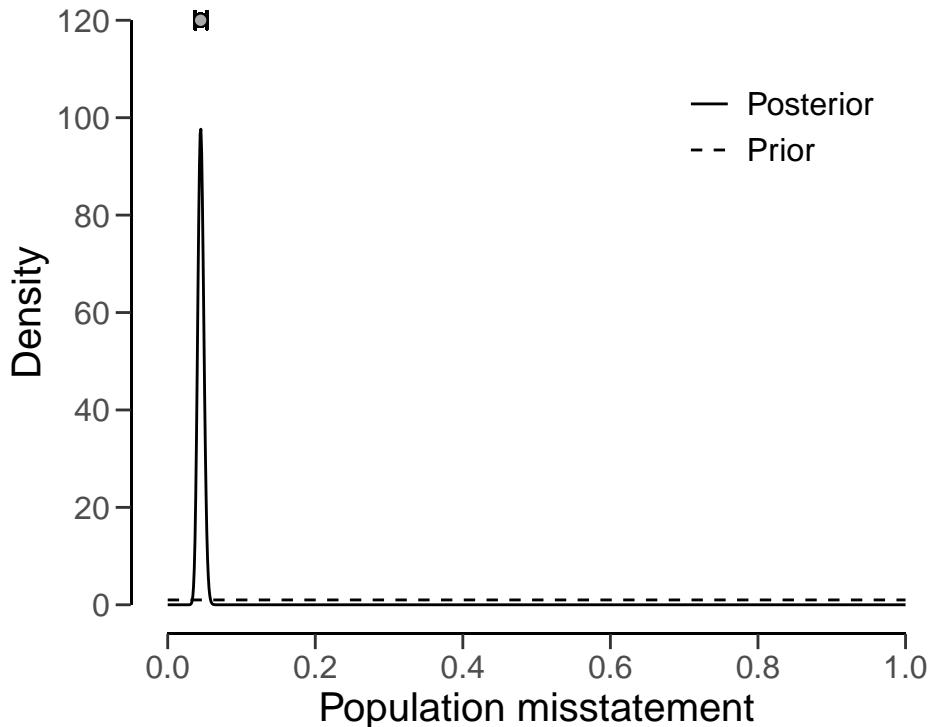
```
plot(result_cp, type = "estimates")
```



### 7.3. Partial pooling

The prior and posterior distribution for the population misstatement can be requested via the `plot()` function.

```
plot(result_cp, type = "posterior")
```



## 7.3. Partial pooling

Finally, partial pooling (`pooling = "partial"`) assumes differences and similarities between strata. This allows the auditor to differentiate between strata, while also sharing information between the strata to reduce uncertainty in the population estimate.

The call below evaluates the sample using a Bayesian stratified evaluation procedure, in which the stratum estimates are poststratified to arrive at the population estimate.

## 7. Stratified Evaluation



Figure 7.2.: Partial pooling takes into account the hierarchical structure in the data. Image available under a CC-BY-NC 4.0 license.

```
set.seed(1) # Important because the posterior distribution is
  ↳ determined via sampling
result_pp <- evaluation( materiality = 0.05, method = "binomial",
  ↳ prior = TRUE, n = retailer$samples, x = retailer$errors,
  ↳ N.units = retailer$items, alternative = "two.sided", pooling =
  ↳ "partial")
summary(result_pp)
#>
#> Bayesian Audit Sample Evaluation Summary
#>
#> Options:
#>   Confidence level:           0.95
#>   Population size:          144000
#>   Materiality:              0.05
#>   Hypotheses:                H0:  $\bar{x} = 0.05$  vs. H1:  $\bar{x} \neq 0.05$ 
#>   Method:                    binomial
#>   Prior distribution:        Nonparametric
#>
```

```

#> Data:
#>   Sample size:           2575
#>   Number of errors:     115
#>   Sum of taints:        115
#>
#> Results:
#>   Posterior distribution: Nonparametric
#>   Most likely error:      0.0432
#>   95 percent credible interval: [0.034575, 0.052994]
#>   Precision:              0.0097941
#>   BF1:0:                 0.02178
#>
#> Strata (20):
#>   N  n  x  t    mle      lb      ub precision
#> 1 5000 300 21 21 0.0467 0.03778 0.07996  0.03326
#> 2 5000 300 16 16 0.0466 0.03335 0.06634  0.01974
#> 3 5000 300 15 15 0.0436 0.03184 0.06439  0.02079
#> 4 5000 300 14 14 0.0437 0.03121 0.06147  0.01777
#> 5 5000 300 16 16 0.0450 0.03328 0.06707  0.02207
#> 6 5000 150  5  5 0.0421 0.02346 0.05876  0.01666
#> 7 5000 150  4  4 0.0402 0.02165 0.05686  0.01666
#> 8 5000 150  3  3 0.0405 0.01807 0.05541  0.01491
#> 9 5000 150  4  4 0.0447 0.02082 0.05651  0.01181
#> 10 5000 150  5  5 0.0429 0.02326 0.05899  0.01609
#> 11 10000 50  2  2 0.0466 0.02271 0.06766  0.02106
#> 12 10000 50  3  3 0.0434 0.02654 0.07291  0.02951
#> 13 10000 50  2  2 0.0429 0.02270 0.06701  0.02411
#> 14 10000 50  1  1 0.0452 0.02022 0.06137  0.01617
#> 15 10000 50  0  0 0.0407 0.01608 0.05795  0.01725
#> 16 10000 15  0  0 0.0422 0.01964 0.06657  0.02437
#> 17 10000 15  0  0 0.0432 0.02023 0.06786  0.02466
#> 18 10000 15  0  0 0.0484 0.01956 0.06639  0.01799
#> 19 10000 15  1  1 0.0433 0.02447 0.07685  0.03355
#> 20 4000 15  3  3 0.0404 0.03031 0.10450  0.06410

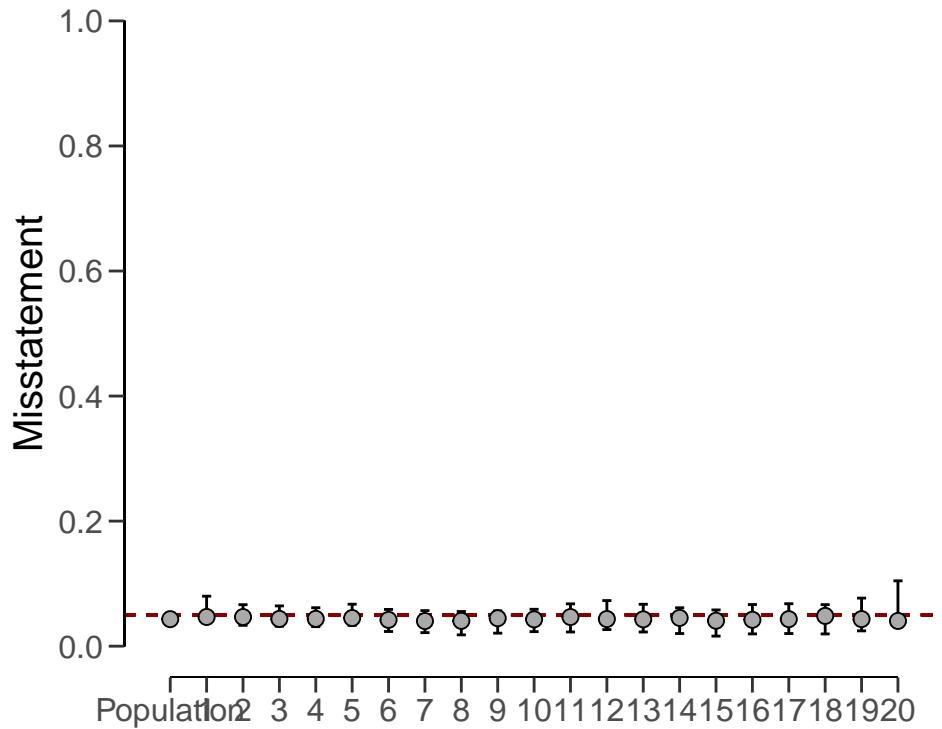
```

In this case, the output shows that the estimate of the misstatement in the population is 4.34%, with the 95% credible interval ranging from 3.45% to 5.33%. Note that this population estimate is substantially less uncertain than that of the no pooling approach. Note

## 7. Stratified Evaluation

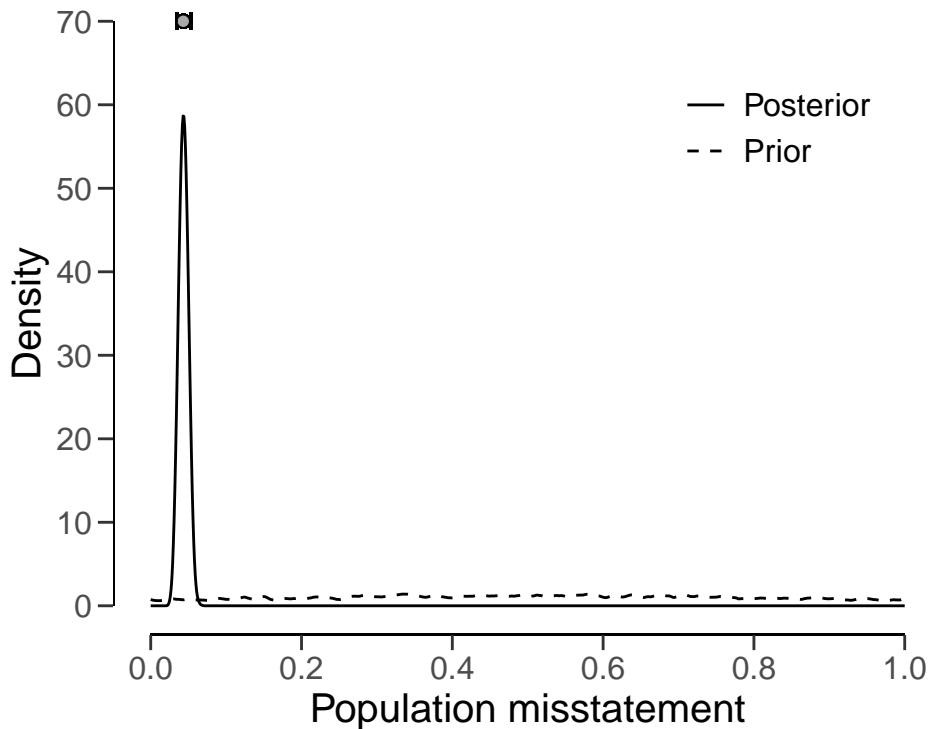
that, like in the no pooling approach, the stratum estimates are different from each other but lie closer together and are less uncertain.

```
plot(result_pp, type = "estimates")
```



The prior and posterior distribution for the population misstatement can be requested via the `plot()` function.

```
plot(result_pp, type = "posterior")
```



## 7.4. Evaluation using data

For this example, we take the `allowances` dataset that comes with the package. This data set contains 3500 financial statement line items, each with a booked value `bookValue` and, for illustrative purposes, and audited (true) value `auditValue`. Since the focus of this chapter is the evaluation stage in the audit, the sample is already indicated in the data set. The performance materiality in this example is set to 5%.

```
data(allowances)
head(allowances)
#>   item branch bookValue auditValue times
#> 1    1      12     1600      1600     1
#> 2    2      12     1625       NA     0
#> 3    3      12     1775       NA     0
#> 4    4      12     1250      1250     1
```

## 7. Stratified Evaluation

```
#> 5      5      12      1400      NA      0
#> 6      6      12      1190      NA      0
```

Evaluating a stratified sample using data requires specification of the data, values, values.audit and strata arguments in the evaluation() function. In this case, the units are monetary and calculated by aggregating the book values of the items in each stratum.

```
N.units <- aggregate(allowances$bookValue, list(allowances$branch),
  ~ sum)$x
```

### 7.4.1. Classical Evaluation

The call below evaluates the allowances sample using a classical stratified evaluation procedure, in which the stratum estimates are poststratified to arrive at the population estimate.

```
x <- evaluation(materiality = 0.05, data = allowances, values =
  ~ "bookValue", values.audit = "auditValue", strata = "branch",
  ~ times = "times", alternative = "two.sided", N.units = N.units)
summary(x)
#>
#> Classical Audit Sample Evaluation Summary
#>
#> Options:
#>   Confidence level:          0.95
#>   Population size:          16772249
#>   Materiality:              0.05
#>   Hypotheses:                H0:  $\bar{x} = 0.05$  vs. H1:  $\bar{x} \neq 0.05$ 
#>   Method:                   poisson
#>
#> Data:
#>   Sample size:               1604
#>   Number of errors:          401
#>   Sum of taints:             252.9281046
```

## 7.4. Evaluation using data

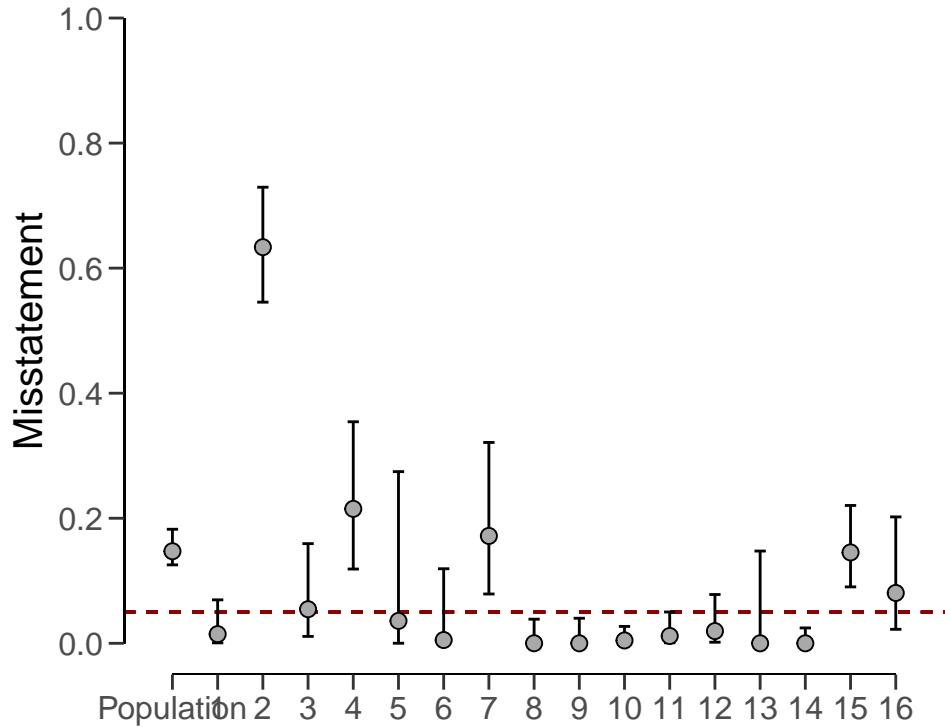
```
#>
#> Results:
#>   Most likely error:          0.14723
#>   95 percent confidence interval: [0.12549, 0.18239]
#>   Precision:                 0.03516
#>   p-value:                   NA
#>
#> Strata (16):
#>      N   n   x       t     mle      lb      ub precision
#>   ← p.value
#> 1 317200.09 87   6   1.27814 0.01469 0.00073 0.06950 0.05481
#>   ← 0.46285
#> 2 2792814.33 305 233 193.23313 0.63355 0.54558 0.72945
#>   ← 0.09590 0.00000
#> 3 1144231.69 55   3   3.00000 0.05455 0.01105 0.15940 0.10486
#>   ← 0.75827
#> 4 414202.89 70   45  15.05094 0.21501 0.11878 0.35434
#>   ← 0.13933 0.00000
#> 5 96660.53 18   1   0.64537 0.03585 0.00015 0.27456 0.23871
#>   ← 0.59343
#> 6 348006.13 34   1   0.17866 0.00525 0.00000 0.11926 0.11401
#>   ← 1.00000
#> 7 2384079.33 55  14   9.44448 0.17172 0.07885 0.32122
#>   ← 0.14950 0.00058
#> 8 1840399.33 96   1   0.00813 0.00008 0.00000 0.03860 0.03852
#>   ← 0.10355
#> 9 563957.70 92   0   0.00000 0.00000 0.00000 0.04010 0.04010
#>   ← 0.01783
#> 10 3198877.73 201   7   0.92023 0.00458 0.00009 0.02703
#>   ← 0.02245 0.00122
#> 11 1983299.06 128   7   1.50034 0.01172 0.00084 0.05013
#>   ← 0.03841 0.10773
#> 12 319144.13 86   5   1.68141 0.01955 0.00174 0.07806 0.05851
#>   ← 0.46069
#> 13 148905.79 25   0   0.00000 0.00000 0.00000 0.14756 0.14756
#>   ← 0.64187
```

## 7. Stratified Evaluation

```
#> 14 513058.76 150 0 0.00000 0.00000 0.00000 0.02459  
  ↳ 0.02459 0.00134  
#> 15 432007.61 150 39 21.80000 0.14533 0.09026 0.22045  
  ↳ 0.07511 0.00001  
#> 16 275403.70 52 39 4.18726 0.08052 0.02237 0.20215  
  ↳ 0.12163 0.12258
```

In this case, the output shows that the estimate of the misstatement in the population is 14.72%, with the 95% confidence interval ranging from 12.55% to 18.26%. The precision of the population estimate is 3.54%. The stratum estimates can be seen in the output of the `summary()` function and are visualized below.

```
plot(x, type = "estimates")
```



### 7.4.2. Bayesian Evaluation

Bayesian inference can improve upon the estimates of the classical approach by pooling information between strata where possible. The call below evaluates the allowances sample using a Bayesian multilevel stratified evaluation procedure, in which the stratum estimates are poststratified to arrive at the population estimate.

```
x <- evaluation(materiality = 0.05, data = allowances, prior =
  TRUE, values = "bookValue", values.audit = "auditValue", strata
  = "branch", times = "times", alternative = "two.sided", N.units
  = N.units, pooling = "partial")
summary(x)
#>
#> Bayesian Audit Sample Evaluation Summary
#>
#> Options:
#>   Confidence level:           0.95
#>   Population size:          16772249
#>   Materiality:              0.05
#>   Hypotheses:                H0:  $\bar{x}$  = 0.05 vs. H1:  $\bar{x}$  ≠ 0.05
#>   Method:                    poisson
#>   Prior distribution:       Nonparametric
#>
#> Data:
#>   Sample size:                 1350
#>   Number of errors:            401
#>   Sum of taints:               224.657517
#>
#> Results:
#>   Posterior distribution:     Nonparametric
#>   Most likely error:          0.1549
#>   95 percent credible interval: [0.14616, 0.17]
#>   Precision:                  0.015096
#>   BF10:                      Inf
#>
#> Strata (16):
#>   N    n    x      t    mle      lb      ub precision
```

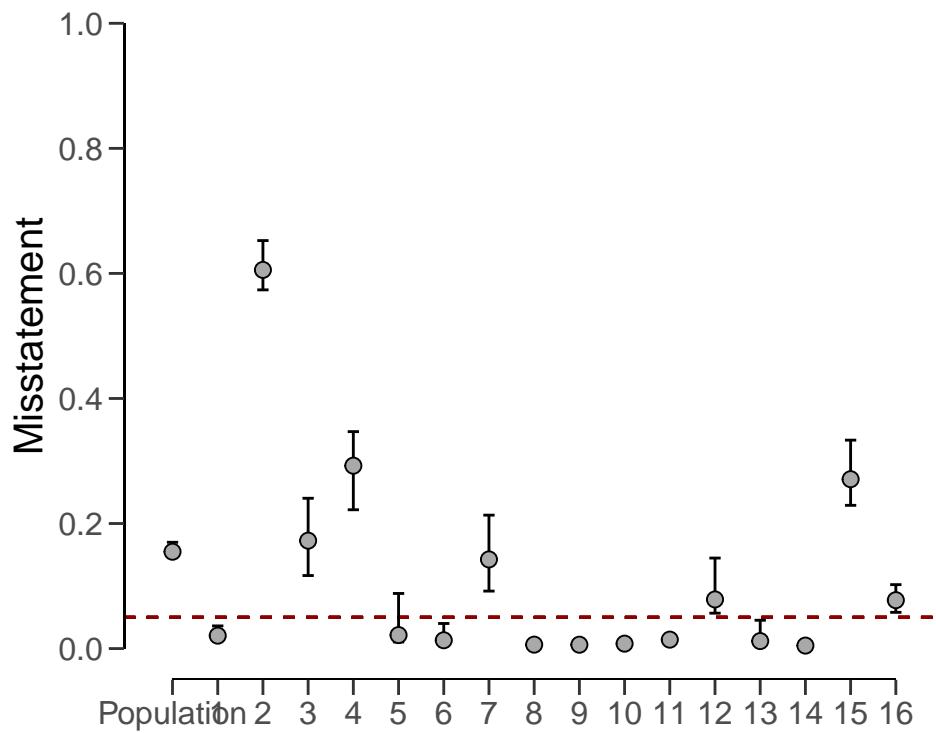
## 7. Stratified Evaluation

```
#> 1 317200.09 62 6 1.07814 0.0207 0.01365 0.03625 0.01555
#> 2 2792814.33 283 233 176.87807 0.6056 0.57370 0.65251 0.04691
#> 3 1144231.69 55 3 3.00000 0.1726 0.11680 0.24039 0.06779
#> 4 414202.89 48 45 11.65094 0.2925 0.22203 0.34698 0.05448
#> 5 96660.53 9 1 0.21512 0.0216 0.01058 0.08814 0.06654
#> 6 348006.13 14 1 0.04467 0.0133 0.00707 0.04013 0.02683
#> 7 2384079.33 44 14 6.65401 0.1426 0.09194 0.21343 0.07083
#> 8 1840399.33 78 1 0.00813 0.0063 0.00467 0.00939 0.00309
#> 9 563957.70 74 0 0.00000 0.0062 0.00460 0.00972 0.00352
#> 10 3198877.73 184 7 0.89982 0.0079 0.00618 0.01055 0.00265
#> 11 1983299.06 111 7 1.35066 0.0143 0.01100 0.02263 0.00833
#> 12 319144.13 56 5 1.19069 0.0786 0.05665 0.14477 0.06617
#> 13 148905.79 10 0 0.00000 0.0120 0.00624 0.04535 0.03335
#> 14 513058.76 150 0 0.00000 0.0048 0.00381 0.00635 0.00155
#> 15 432007.61 128 39 18.30000 0.2709 0.22911 0.33339 0.06249
#> 16 275403.70 44 39 3.38726 0.0774 0.05796 0.10226 0.02486
```

The output shows that the estimate of the misstatement in the population is 15.66%, with the 95% credible interval ranging from 14.59% to 17%. The precision of the population estimate is 1.34%, which is substantially lower than that of the classical approach. The stratum estimates can be seen in the output of the summary() function and are visualized below.

```
plot(x, type = "estimates")
```

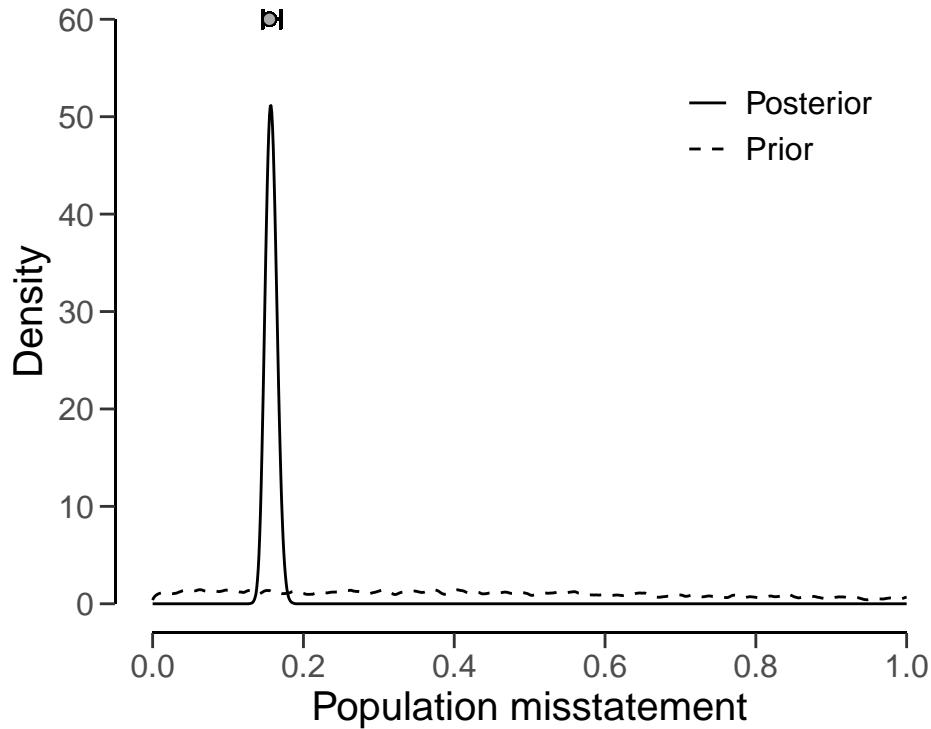
#### 7.4. Evaluation using data



The prior and posterior distribution for the population misstatement can be requested via the `plot()` function.

```
plot(x, type = "posterior")
```

## 7. Stratified Evaluation



## 7.5. Exercises

1. Evaluate a stratified sample of  $n = [30, 40, 50]$  items containing  $k = [0, 1, 2]$  misstatements. Use the classical approach.

Click to reveal answer

```
evaluation(n = c(30, 40, 50), x = c(0, 1, 3), method = "binomial")
#>
#> Classical Audit Sample Evaluation
#>
#> data: 4 and 120
#> number of errors = 4, number of samples = 120, taint = 4
#> 95 percent confidence interval:
#> 0.00000000 0.08898339
```

## 7.5. Exercises

```
#> most likely estimate:  
#> 0.028333  
#> results obtained via method 'binomial' + 'no-pooling'
```



# **Part III.**

# **Software**



## 8. JASP for Audit

- i** You are reading the work-in-progress first edition of Statistical Auditing with R. This chapter is currently a dumping ground of ideas, and it is incomplete.

JASP (JASP Team, 2022), an acronym for Jeffreys's Amazing Statistics Program, is a free and open-source software for statistical analysis developed at the University of Amsterdam. It is intended to be user-friendly and familiar to those who have experience with SPSS. A significant feature of JASP is that it provides most standard statistical analysis procedures in both their classical and Bayesian forms. The program can be downloaded freely from their website <https://jasp-stats.org>. The software is translated into various languages.

JASP for Audit (Derkx, Swart, Wagenmakers, et al., 2021) is an add-on module for JASP based on the **jfa** package, that facilitates statistical audit sampling. The module provides graphical a user interface (GUI) for calculating sample sizes, selecting items according to standard audit sampling techniques, and performing inference about the population misstatement on the basis of a data sample or summary statistics of a sample. The module also features Bayesian equivalents of these analyses that enable the user to easily incorporate prior information into the statistical procedure. In all analyses, the Audit module offers explanatory text that helps the auditor in interpreting, explaining, and reporting the analysis. Since JASP for Audit is an R-based GUI around **jfa**, its functionality can be mapped almost one-on-one to that of the package.

The Audit module in JASP, labeled as "Audit" in the module list, is included by default in the software, but is not initially visible upon starting the program. To access the Audit module, click on the + icon in the top right corner of the JASP welcome screen, and select the module from the list of available options. The Audit module will then be displayed with a blue icon in the ribbon at the top of the screen.

Upon selecting the Audit module icon, the user can view all of the analyses that the module contains. It is important to note that some of these analyses are grayed out by default and can only be activated once a data set has been loaded into JASP. This means

## 8. JASP for Audit

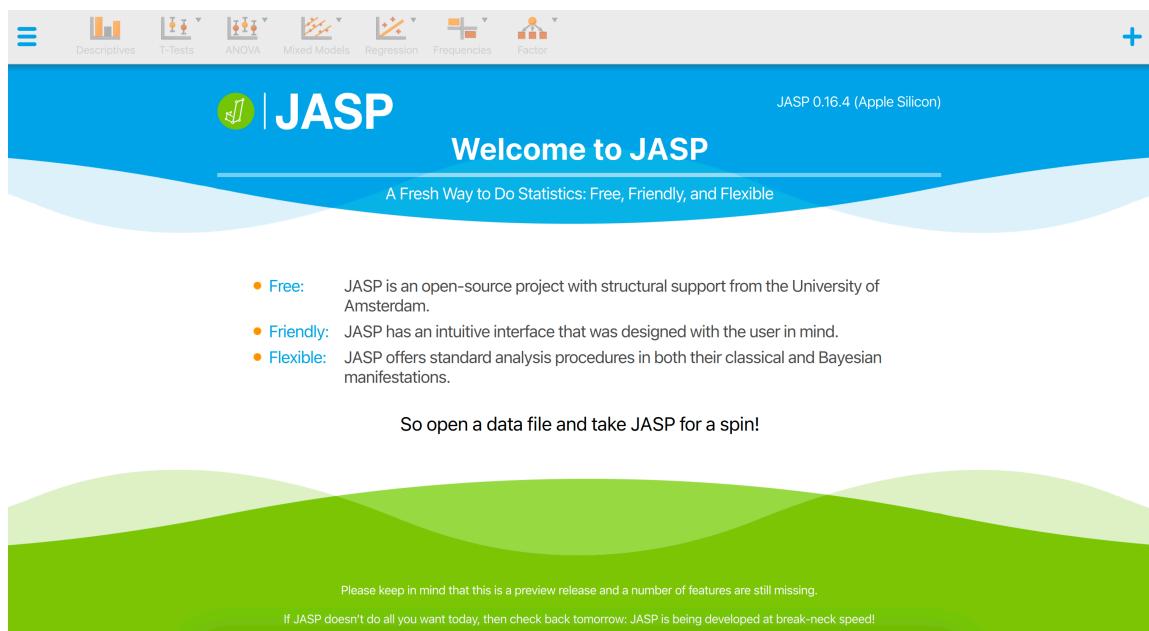


Figure 8.1.: Upon launching JASP, you are presented with the following screen. The icons in the ribbon display a range of statistical analyses. The menu icon located in the top left corner conceals the most crucial user options. The plus icon situated in the top right corner conceals the modules.

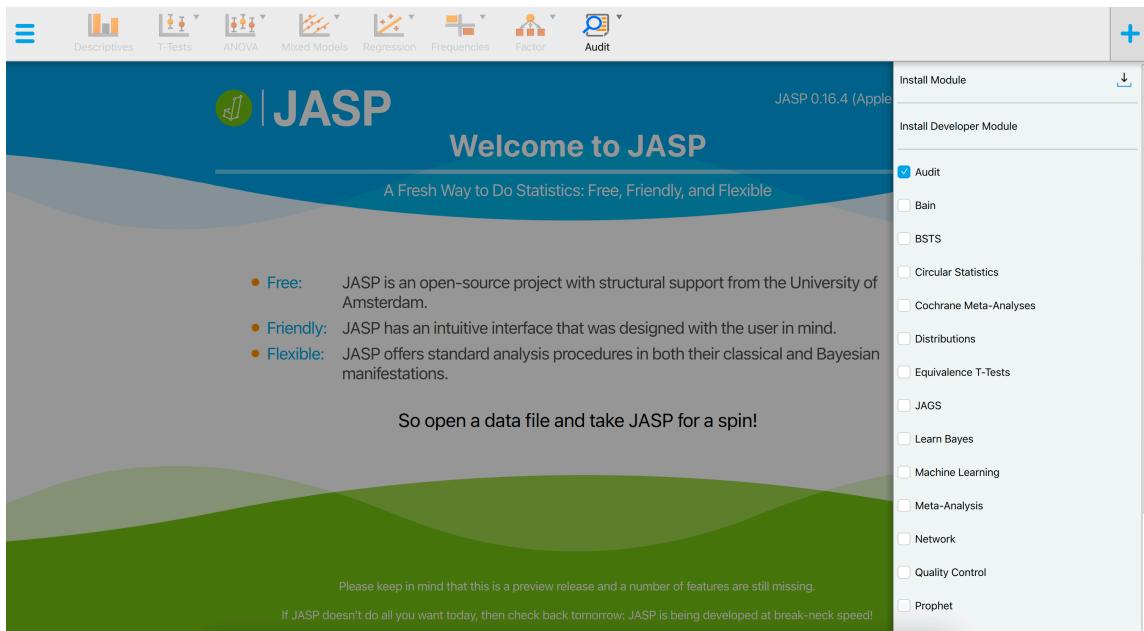


Figure 8.2.: The + icon displays all modules that are currently available in JASP. To activate a module and add it to the ribbon at the top of the screen, click on the checkbox next to it.

## 8. JASP for Audit

that the user must first import a data set in order to access and make use of these specific analyses.

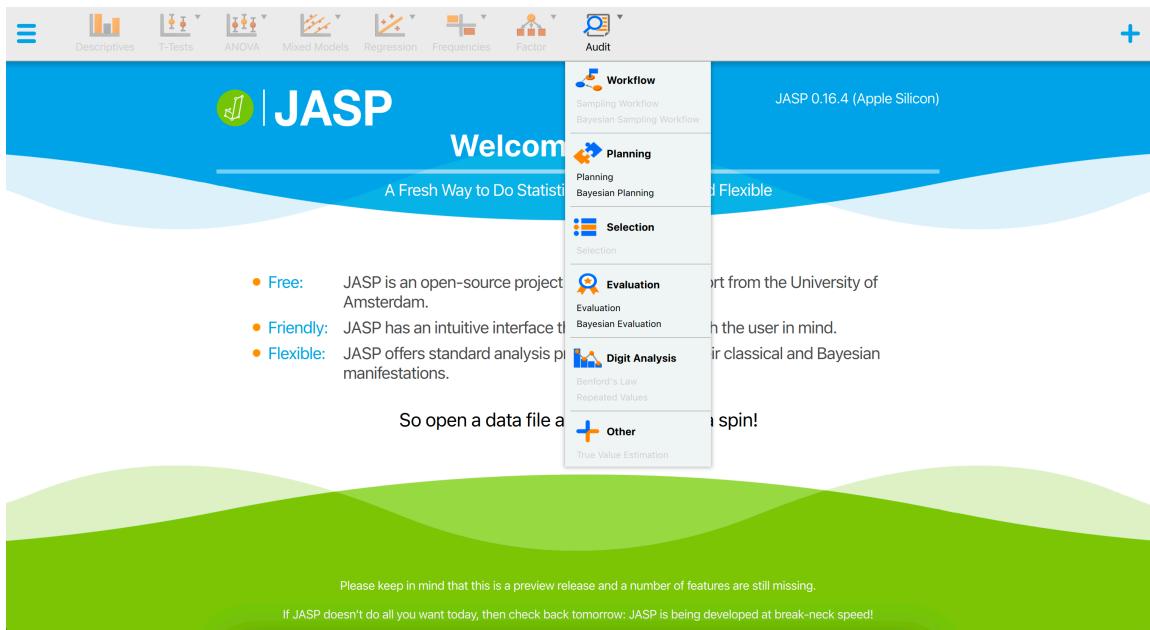


Figure 8.3.: By clicking the Audit module icon in the ribbon, you can view the various analyses that are included in the audit module.

### 8.1. Planning

To plan a sample for an audit using JASP, the procedure is comparable to using **jfa**. This means that both programs involve similar steps and considerations in order to effectively plan an audit sample. Like **jfa**, JASP for Audit offers a classical and a Bayesian approach to planning a sample.

The figure below showcases a snapshot of the classical planning analysis in JASP for Audit. The graphical user interface is displayed on the left side of the screen, while the audit report containing statistical results is displayed on the right side. In the user interface, the auditor can input the known parameters for the sample planning, after which JASP calculates and directly displays the statistical results.

## 8.1. Planning

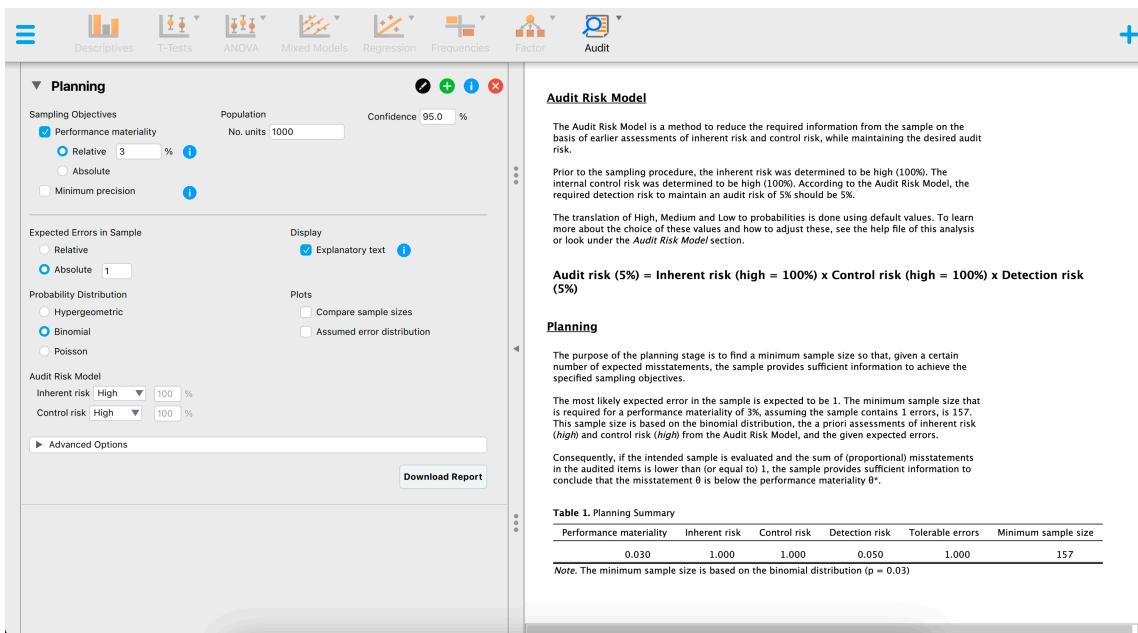


Figure 8.4.: A snapshot of the classical planning analysis in JASP for Audit. In this analysis, the auditor is using the binomial likelihood, a sampling risk of 5%, a performance materiality of 3% and one expected misstatement in the sample. The resulting sample size is 157.

## 8. JASP for Audit

The above screenshot shows an analysis where the auditor is using the binomial distribution, a sampling risk of 5%, a performance materiality of 3% and one expected misstatement in the sample. The resulting sample size is 157.

Using **jfa**, these statistical results can be reproduced by executing the following code:

```
planning(materiality = 0.03, expected = 1, likelihood = "binomial")
#>
#> Classical Audit Sample Planning
#>
#> minimum sample size = 157
#> sample size obtained in 156 iterations via method 'binomial'
```

The figure below showcases a snapshot of the Bayesian planning analysis in JASP. The graphical user interface is largely the same as the interface of the classical planning analysis, with the exception that we can specify a prior distribution with the options under “Prior”.

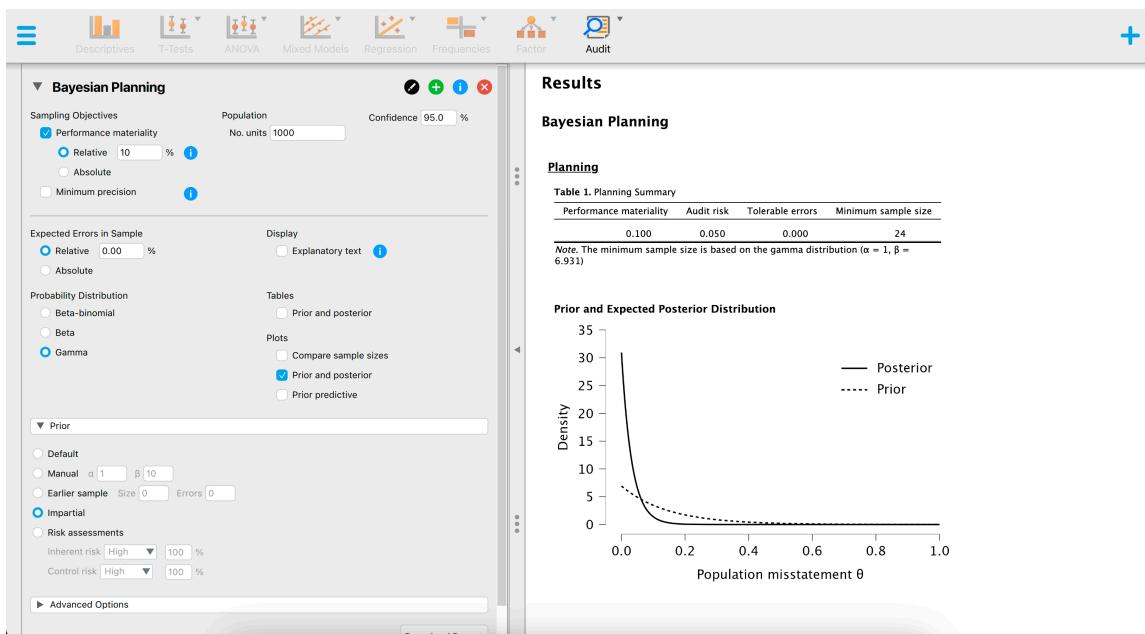


Figure 8.5.: Snapshot of the Bayesian planning analysis in JASP for Audit. In this analysis, the auditor is using the Poisson likelihood with an impartial gamma prior, a sampling risk of 5%, a performance materiality of 10% and no expected misstatements in the sample. The resulting sample size is 24.

The above screenshot shows an analysis where the auditor is using the Poisson likelihood together with an impartial gamma prior, a sampling risk of 5%, a performance materiality of 10% and no expected misstatements in the sample. The resulting sample size is 24.

Using **jfa**, these statistical results can be reproduced by executing the following code:

```
prior <- auditPrior(method = "impartial", materiality = 0.1)
planning(materiality = 0.1, likelihood = "poisson", prior = prior)
#>
#> Bayesian Audit Sample Planning
#>
#> minimum sample size = 24
#> sample size obtained in 25 iterations via method 'poisson' +
#>   'prior'
```

## 8.2. Selection

Selecting a sample in JASP for Audit works similar to how you would do it in **jfa**. The figure below showcases a snapshot of the selection analysis in JASP for Audit. In the user interface, the auditor can input the known parameters for the sample selection, after which JASP calculates and directly displays the statistical results.

The above screenshot shows an analysis where the auditor is using a fixed interval monetary unit sampling method to select a sample of 60 monetary units from the BuildIt population. They use a starting point of 1.

Using **jfa**, these statistical results can be reproduced by executing the following code:

```
set.seed(1)
data(BuildIt)
result <- selection(data = BuildIt, size = 60, units = "values",
#>   method = "interval", start = 1, values = "bookValue")
head(result$sample)
#>   row times     ID bookValue auditValue
#> 1    1      1 82884     242.61     242.61
#> 2    63      1 51272     248.40     248.40
#> 3   123      1 37985     562.09     562.09
```

## 8. JASP for Audit

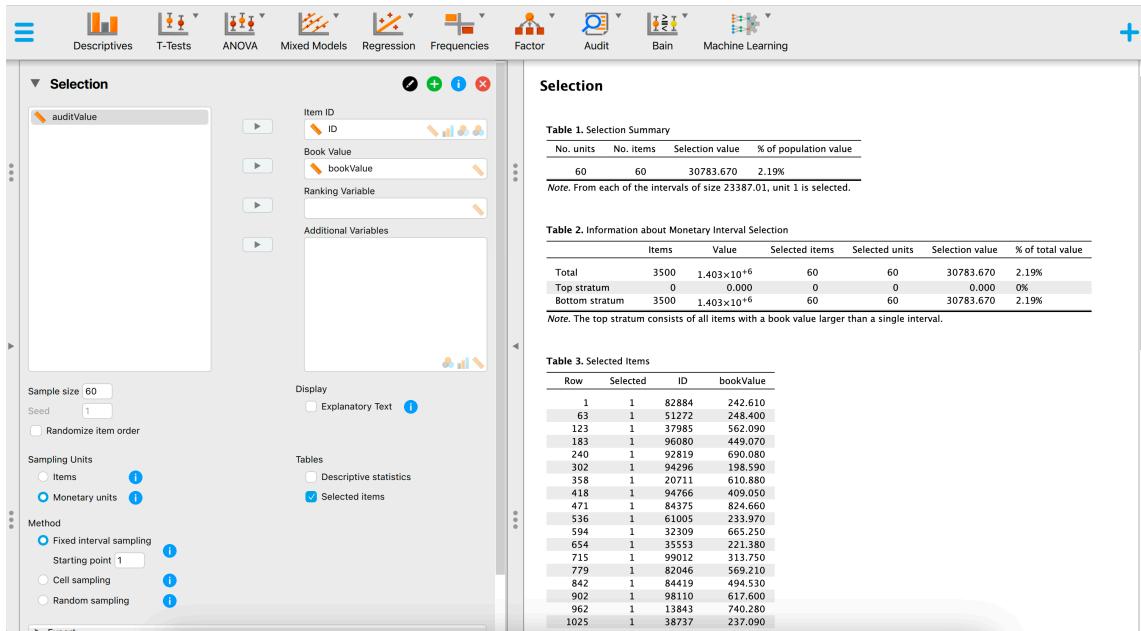


Figure 8.6.: A snapshot of the selection analysis in JASP for Audit. In this analysis, the auditor is using a fixed interval monetary unit sampling method to select a sample of 60 monetary units from a population.

### 8.3. Evaluation

```
#> 4 183      1 96080    449.07    449.07
#> 5 240      1 92819    690.08    690.08
#> 6 302      1 94296    198.59    198.59
```

## 8.3. Evaluation

Finally, evaluating a sample in JASP for Audit works similar to how you would do it in **jfa**. The figure below showcases a snapshot of the evaluation analysis in JASP for Audit. In the user interface, the auditor can input the known parameters for the sample evaluation, after which JASP calculates and directly displays the statistical results.

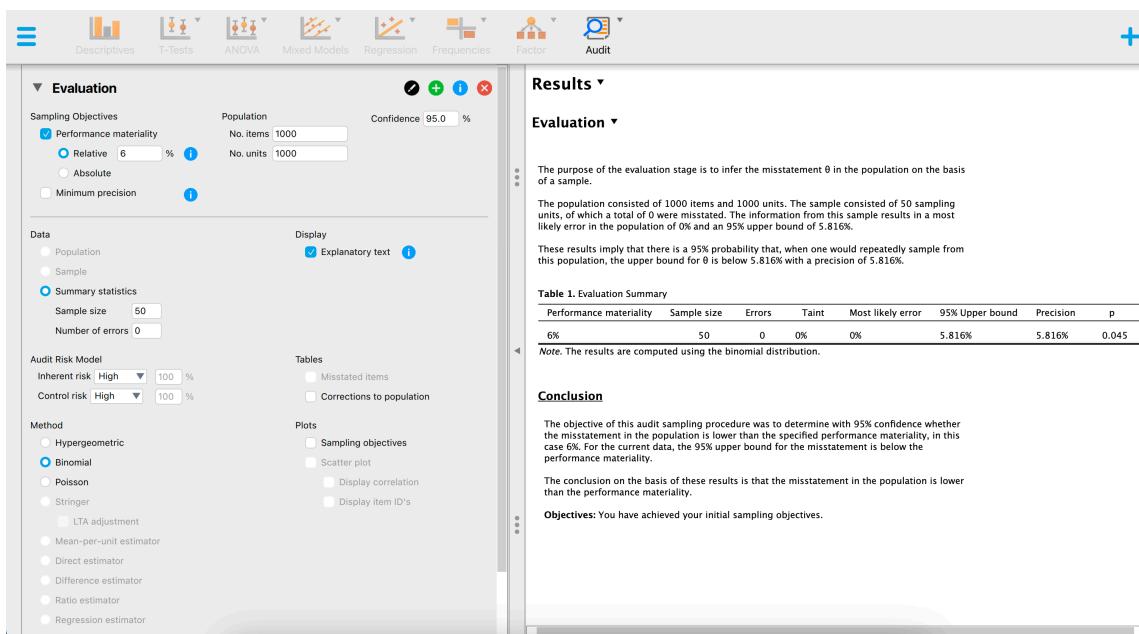


Figure 8.7.: A snapshot of the classical evaluation analysis in JASP for Audit. In this analysis, the auditor is using the binomial likelihood, a sampling risk of 5%, a performance materiality of 6% and evaluates a sample of 50 items of which 0 contained a misstatement. The resulting upper bound is 5.8% and the  $p$ -value is 0.045.

The above screenshot shows an analysis where the auditor is using the binomial likelihood, a sampling risk of 5%, a performance materiality of 6% and evaluates a sample of

## 8. JASP for Audit

$n = 50$  items of which  $k = 0$  contained a misstatement. The resulting 95% upper confidence bound is 5.8% and the  $p$ -value is 0.045, which is lower than the sampling risk of 5%.

Using **jfa**, these statistical results can be reproduced by executing the following code:

```
evaluation(materiality = 0.06, method = "binomial", x = 0, n = 50)
#>
#> Classical Audit Sample Evaluation
#>
#> data: 0 and 50
#> number of errors = 0, number of samples = 50, taint = 0, p-value
#> =
#> 0.045331
#> alternative hypothesis: true misstatement rate is less than 0.06
#> 95 percent confidence interval:
#> 0.00000000 0.05815508
#> most likely estimate:
#> 0
#> results obtained via method 'binomial'
```

The figure below showcases a snapshot of the Bayesian evaluation analysis in JASP. The graphical user interface is fairly similar to that of the classical evaluation analysis, with the exception that we can specify a prior distribution with the options under “Prior”.

The above screenshot shows an analysis where the auditor is using the binomial likelihood together with a beta prior distribution based on an expected error rate of 3% constructed using the audit risk model, a sampling risk of 5%, a performance materiality of 3% and evaluates a sample of  $n = 120$  items of which  $k = 1$  contained a misstatement. The resulting 95% upper credible bound is 3.27% and the Bayes factor in favor of tolerable misstatement is 9.394, indicating that the sample data are about 9 times more likely to occur under the hypothesis of tolerable misstatement than under the hypothesis of intolerable misstatement.

Using **jfa**, these statistical results can be reproduced by executing the following code:

```
prior <- auditPrior(method = "arm", likelihood = "binomial",
#> materiality = 0.03, expected = 0.01, ir = 0.6, cr = 1)
```

### 8.3. Evaluation

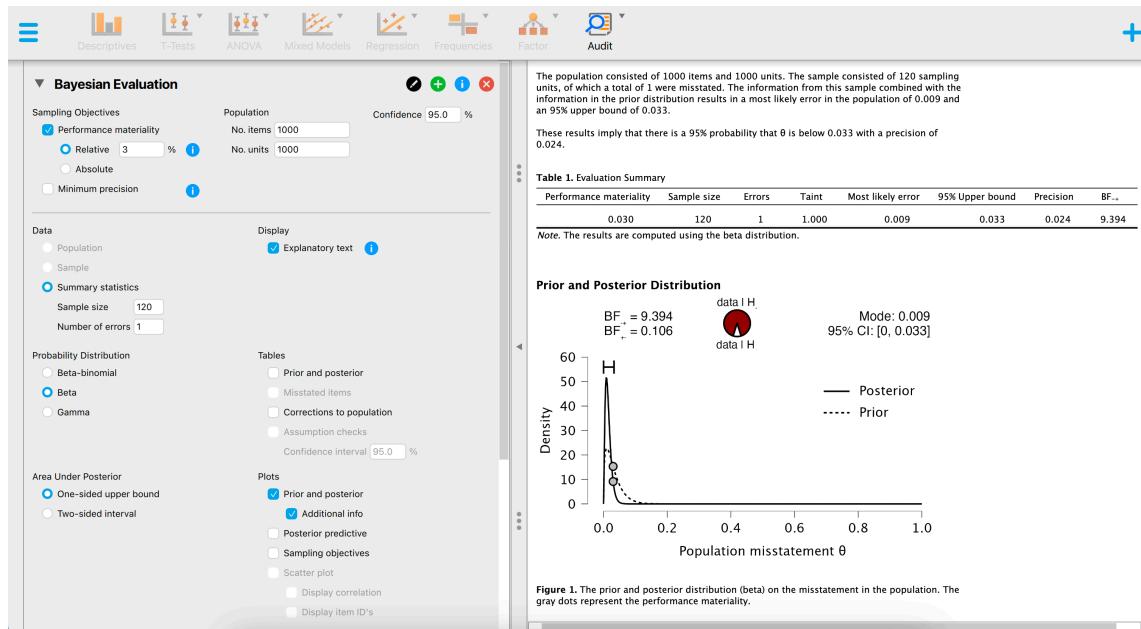


Figure 8.8.: Snapshot of the Bayesian evaluation analysis in JASP for Audit. In this analysis, the auditor is using the binomial likelihood together with a beta prior distribution, a sampling risk of 5%, a performance materiality of 3% and evaluates a sample of 120 items of which 1 contained a misstatement. The resulting upper bound is 3.27% and the Bayes factor in favor of tolerable misstatement is 9.394.

## 8. JASP for Audit

```
evaluation(materiality = 0.03, method = "binomial", x = 1, n = 120,
  ↵ prior = prior)
#>
#> Bayesian Audit Sample Evaluation
#>
#> data: 1 and 120
#> number of errors = 1, number of samples = 120, taint = 1, BF10 =
#> 9.3941
#> alternative hypothesis: true misstatement rate is less than 0.03
#> 95 percent credible interval:
#> 0.00000000 0.03267759
#> most likely estimate:
#> 0.0088415
#> results obtained via method 'binomial' + 'prior'
```

# 9. R Packages

**i** You are reading the work-in-progress first edition of Statistical Auditing with R. This chapter is currently a dumping ground of ideas, and it is incomplete.

This chapter discusses other R packages that implement statistical techniques for audit sampling. Such information may be useful for auditors who wish to explore alternative approaches or simply want to confirm the results obtained through the use of the **jfa** package. By exploring these other packages, auditors can gain a greater understanding of the various options available for audit sample planning, selection and evaluation.

## 9.1. MUS

**MUS** (Prömpers & Guimarães, 2019) is an R package providing sampling and evaluation methods to apply Monetary Unit Sampling during an audit of financial statements. The package is available via CRAN and can be downloaded by running the following code:

```
install.packages("MUS")
```

To show the differences and similarities between the use of the **MUS** package and the **jfa** package, consider a scenario in which an auditor wants to plan a monetary unit sample such that the sampling risk can be reduced below 5%. The population in this example consists of  $N = 1000$  monetary units and the performance materiality is defined as 10% (or 100 monetary units). The auditor plans the sample using an expected misstatement rate of 1% (or 10 monetary units).

To compute this sample size, the **MUS** package provides the **MUS.calc.n.conservative()** function, which takes the performance materiality in monetary units as the **tolerable.error** argument, the expected misstatements in monetary units as the **expected.error** argument, and the total number of unit in the population as the **book.value** argument. The resulting sample size is 37.

## 9. R Packages

```
MUS::MUS.calc.n.conservative(tolerable.error = 100, expected.error
  ↪ = 10, book.value = 1000, confidence.level = 0.95)
#> [1] 37
```

These results can be reproduced in **jfa** using the following command:

```
planning(materiality = 0.1, expected = 0.01, likelihood =
  ↪ "poisson")
#>
#> Classical Audit Sample Planning
#>
#> minimum sample size = 37
#> sample size obtained in 38 iterations via method 'poisson'
```

**i** The **MUS** package provides no functionality for Bayesian audit sampling.

## 9.2. **samplingbook**

**samplingbook** (Manitz et al., 2021) is an R package based on the book **Stichproben: Methoden und praktische Umsetzung mit R** (Kauermann & Kuechenhoff, 2010) that focuses on survey sampling and statistical analysis of these samples. The package is available via CRAN and can be downloaded by running the following code:

```
install.packages("samplingbook")
```

To show the differences and similarities between the use of the **samplingbook** package and the **jfa** package, consider a scenario in which an auditor wants to evaluate a sample of items and is interested in estimating the 95% upper confidence bound. The population in this example consists of  $N = 300$  items and the auditor has inspected a sample of  $n = 100$  items, of which  $k = 3$  contained a misstatement.

To compute the upper bound, the **samplingbook** package provides the `Sprop()` function, which takes the number of found misstatements in the sample as the `m` argument, the sample size as the `n` argument and the population size as the `N` argument. Note that

because this function solely computes a two-sided interval for the population misstatement, the 95% upper bound can be obtained by using an interval of 90% with `level = 0.9`. The resulting upper bound is 0.07.

```
samplingbook::Sprop(m = 3, n = 100, N = 300, level = 0.90)
#>
#> Sprop object: Sample proportion estimate
#> With finite population correction: N = 300
#>
#> Proportion estimate: 0.03
#> Standard error: 0.014
#>
#> 90% approximate confidence interval:
#> proportion: [0.007,0.053]
#> number in population: [3,15]
#> 90% exact hypergeometric confidence interval:
#> proportion: [0.01,0.07]
#> number in population: [3,21]
```

These results can be reproduced in **jfa** using the following command:

```
evaluation(x = 3, n = 100, N.units = 300, method =
  "hypergeometric", alternative = "less", conf.level = 0.95)
#>
#> Classical Audit Sample Evaluation
#>
#> data: 3 and 100
#> number of errors = 3, number of samples = 100, taint = 3
#> 95 percent confidence interval:
#> 0.00000000 0.06666667
#> most likely estimate:
#> 0.03
#> results obtained via method 'hypergeometric'
```

- i** The **samplingbook** package provides limited functionality for auditing as it mainly focuses on survey sampling.

## *9. R Packages*

### **9.3. audit**

**audit** (Meeden, 2021) is an R package based on the paper by Meeden & Sargent (2007) that can be used to find an upper bound for the total amount of overstatement of assets in a set of accounts and estimating the amount of sales tax owed on a collection of transactions. The package is available via CRAN and can be downloaded by running the following code:

```
install.packages("audit")
```

- i** The **audit** package provides limited functionality for evaluating audit samples and has no functionality for planning and selection.

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# R Tutorial

**i** You are reading the work-in-progress first edition of Statistical Auditing with R. This chapter is currently a dumping ground of ideas, and it is incomplete.

R (R Core Team, 2022) is a programming language and software environment for statistical computing and graphics. It is widely used among statisticians and data scientists for data analysis and data visualization. R has a large and active community of users and, as a result, there are many community-made resources available for learning and using R.

In an audit context, R can be used to analyze and visualize large datasets, allowing auditors to identify trends and anomalies in the data. R is particularly useful for performing statistical analysis and testing hypotheses, which can be employed in verifying the accuracy and reliability of financial statements. R can also be used to automate certain audit procedures, reducing the time and effort required to manually review and analyze large amounts of data. Additionally, R allows auditors to easily share their work with others through the use of code and reproducible reports, enabling more efficient and collaborative audit processes. A useful resource that discusses relevant applications of R in the audit can be found in Lin (2021).

This chapter provides a short introduction to working with R but it is not a full programming course in R. If you want to dive deeper into the nooks and crannies of R, the author recommends reading Chang (2022), Wickam & Grolemund (2017), Grolemund (2014) and Wilke (2022). These books are free to read online and discuss various best practices for using R, including examples in code that can be easily reproduced.

## Calculations

One of the basic features of R is its ability to perform calculations. In R, basic calculations work by using the standard arithmetic operators such as + for addition, - for subtraction,



Figure 9.1.: R can be a powerful tool in a business context. Image available under a CC-BY-NC 4.0 license.

\* for multiplication, and / for division. For example, if you want to calculate  $2 + 3$ , you would type in `2 + 3` and R will return the result of 5.

```
2 + 3  
#> [1] 5
```

R also allows for more advanced calculations such as exponentiation using the `^` operator, and square roots using the `sqrt()` function. For example, to calculate the square root of 9, you would type in `sqrt(9)` and R will return the result of 3.

```
sqrt(9)  
#> [1] 3
```

You can also use parentheses to specify the order of operations in your calculations. For example, if you want to calculate  $(2 + 3)^4$ , you would type in `(2 + 3) ^ 4` to get the result of 20.

```
(2 + 3) * 4  
#> [1] 20
```

Overall, basic calculations in R are similar to those in other programming languages and follow the standard order of operations.

## Vectors

In R, vectors are one-dimensional arrays of data that can hold numeric, character, or logical values. Vectors can be created using the `c()` function, which stands for concatenate. For example, to create a numeric vector, you can use the following code:

```
x <- c(1, 2, 3, 4, 5)
```

To create a character vector, you can use quotes around the values:

```
y <- c("apple", "banana", "orange")
```

To create a logical vector, you can use the logical values `TRUE` and `FALSE`:

```
z <- c(TRUE, FALSE, TRUE, TRUE, FALSE)
```

Vectors can be indexed using square brackets and a numeric value. For example, to access the second element of the vector `x`, you can use the following code:

```
x[2]  
#> [1] 2
```

Vectors can also be subsetted using a logical vector. For example, to get all elements of the vector `x` that are greater than 3, you can use the following code:

```
x[x > 3]  
#> [1] 4 5
```

Vectors can also be modified using indexing and assignment. For example, to change the third element of the vector `x` to 6, you can use the following code:

## R Tutorial

```
x[3]  
#> [1] 3  
x[3] <- 6  
x[3]  
#> [1] 6
```

R has many built-in functions for performing mathematical operations on vectors. For example, you can use the `mean()` function to calculate the average of a vector of numbers, or we can use the `length()` function to calculate the number of elements in a vector:

```
mean(x)  
#> [1] 3.6  
length(y)  
#> [1] 3
```

Overall, vectors are a useful data structure in R for storing and manipulating data.

## Matrices

In R, a matrix is a two-dimensional collection of values that are arranged in rows and columns. You can create a matrix using the `matrix()` function. For example:

```
m <- matrix(1:9, nrow = 3, ncol = 3)  
m  
#>      [,1] [,2] [,3]  
#> [1,]    1    4    7  
#> [2,]    2    5    8  
#> [3,]    3    6    9
```

This creates a 3x3 matrix with the values 1, 2, 3 in the first column, 4, 5, 6 in the second column, and 7, 8, 9 in the third column.

You can also create a matrix by combining several vectors using the `cbind()` or `rbind()` functions. For example:

```
v1 <- c(1, 2, 3)
v2 <- c(4, 5, 6)
v3 <- c(7, 8, 9)
m <- cbind(v1, v2, v3)
m
#>      v1  v2  v3
#> [1,]  1  4  7
#> [2,]  2  5  8
#> [3,]  3  6  9
```

This creates a matrix with the same values as before, but the columns are created by binding the vectors together.

You can access the elements of a matrix using the square bracket notation. For example, to access the element in the second row and third column of `m`, you would use the following code:

```
m[2, 3]
#> v3
#> 8
```

You can also use the `dim()` function to get the dimensions of a matrix, and the `colnames()` and `rownames()` functions to get the names of the columns and rows, respectively.

There are many other functions and operations available for working with matrices in R, including mathematical operations such as matrix multiplication and inversion.

## Data Frames

In R, a data frame is a two-dimensional table of data with rows and columns. Each row represents a single observation or record, and each column represents a particular variable or attribute. Data frames are similar to a spreadsheet in Excel or a table in a database. Each column in a data frame can have a different data type, such as numerical, character, or logical. The data in each row must match the data type of the corresponding column.

To create a data frame in R, you can use the `data.frame()` function and pass in the data you want to include in the data frame as arguments. For example:

```
df <- data.frame(x = c(1, 2, 3), y = c(4, 5, 6))
```

This will create a data frame with two columns, x and y, and three rows of data. You can access the data in a data frame using indexing and subsetting. For example, to access the first row of the data frame, you can use the following command:

```
df[1, ]  
#>   x y  
#> 1 1 4
```

To access a specific column, you can use the \$ operator (or the index):

```
df$x  
#> [1] 1 2 3  
df[, 1]  
#> [1] 1 2 3
```

You can also use functions like head() and tail() to view the first or last few rows of a data frame. Data frames also have several built-in functions that allow you to manipulate and analyze the data. For example, you can use the summarize() function to calculate summary statistics for each column, or the group\_by() function to group the data by a specific variable and apply a function to each group.

## Data Sets

When working with data, you will need to load the data file into your R session. How this is done depends on the type of data file that you want to read.

## Built-in Data

Data that is included in an R package can be loaded via the data() function. For example, to load the BuildIt data set that is included in the **jfa** package, you can run the following R code. Note that this requires that the package is loaded in the R session via a call to library().

```
data(BuildIt)
```

## Loading Data from a CSV File

A commonly used data type is a .csv file. You can load this type of files via the `read.csv()` function. For example, if the file `example.csv` is in the current working directory, you can load it by running:

```
read.csv("example.csv")
```

## Loading Data from an Excel File

Another commonly used data type are Excel files. You can load this type of files via the `read_excel()` function from the `readxl` package. For this to work, you should first install this package using the `install.packages()` command and load it into the R session using a call to `library()`. For example, if the file `example.xlsx` is in the current working directory, and the data you want to load is on the first worksheet, you can load it by running:

```
install.packages("readxl")
library(readxl)
read_excel("example.xlsx", sheet = 1)
```

## Exercises

1. Compute the square root of 81 and store the result in a variable called `t1`.

Click to reveal answer

```
t1 <- sqrt(81)
```

2. Compute 81 to the power a half and store the result in a variable called `t2`.

## R Tutorial

Click to reveal answer

```
t2 <- 81^0.5
```

3. Use the `==` operator to check whether the content of `t1` and `t2` is the same.

Click to reveal answer

```
t1 == t2  
#> [1] TRUE
```

4. Use the `c()` function (or `:`) to create the following vector:

```
#> [1] -2 -1 0 1 2 3 4 5 6 7 8
```

Click to reveal answer

```
c(-2, -1, 0, 1, 2, 3, 4, 5, 6, 7, 8)  
#> [1] -2 -1 0 1 2 3 4 5 6 7 8
```

or:

```
-2:8  
#> [1] -2 -1 0 1 2 3 4 5 6 7 8
```

5. Find out the length of the vector created in exercise 4.

Click to reveal answer

```
length(-2:8)  
#> [1] 11
```

6. Find out the mean of the vector created in exercise 4.

Click to reveal answer

```
mean(-2:8)  
#> [1] 3
```

