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Box Plots: An Introduction to the Visual EDA Wonder

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Abstract

A box plot, also known as a box-and-whisker plot, is a widely used statistical graphic that provides a concise summary of the distribution of numerical data. By displaying key descriptive measures such as the median, quartiles, interquartile range (IQR), minimum and maximum values, and potential outliers, box plots allow researchers to quickly understand the spread and central tendency of a dataset. They are especially useful when comparing distributions across multiple groups, as differences in location, variability, and skewness can be identified easily. This paper discusses the construction and interpretation of box plots, emphasizing the significance of their main components. The median indicates the central value of the data, while the quartiles divide the dataset into four equal parts. The interquartile range measures the spread of the middle 50% of observations and helps detect unusual values. Whiskers extend from the box to represent the range of non-outlying observations, whereas outliers are displayed separately to highlight extreme data points. In addition to the traditional box plot, several enhanced versions have been developed to provide further insights into data distributions. Notched box plots incorporate confidence intervals around the median, enabling visual comparison between groups, while violin plots combine box plot features with density estimation to reveal the underlying shape of the distribution. The paper also demonstrates how box plots can be created and customized using the ggplot2 package in R. Through its flexibility and effectiveness, ggplot2 facilitates clear and informative data visualization. Overall, box plots remain an essential tool for exploratory data analysis in statistics, economics, business, and many scientific disciplines.

Keywords: Box plot, quartiles, interquartile range (IQR), outliers, data visualization, ggplot2, r programming, notched box plot, violin plot, exploratory data analysis (EDA)

INTRODUCTION

Box plots are great visualization tools. They are graphs drawn to scale. A box plot summarizes the distribution of quantitative data and is particularly useful for comparing variations and trends among several groups. It is a graphical EDA (Exploratory Data Analysis) technique used to highlight the centre and extremes of a data set. Being an EDA technique, box plots are more data centric and display differences between populations without making much prior assumptions unlike the Classic DA techniques. Box plots make it easy to compare distributions, as they clearly show the data's centre, spread, and overall range at a glance.

This type of graphical representation is useful in knowing

- Distribution shape
- Central value
- Variability

A box plot represents the data by visualizing a five number summary as graph. Those are:

i. the smallest observation which is the sample minimum

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ii. Q_1, the lower quartile which represents the median of the lower half of the data
iii. The second quartile (Q_2), also known as the median, represents the middle value of the dataset and serves as a measure of central tendency.
iv. Q_3, the upper quartile representing the median of the upper half of the data
v. The largest observation which is the sample maximum

A box plot can be constructed both vertically as well as horizontally. The vertical box plot is a useful construction while comparing data set and the horizontal box plot is aesthetical while studying a single data ser.

Vertical box plots are formed with, random variables in the vertical axis and the factor of interest in the horizontal axis when constructed vertically and vice-versa for the horizontal box plots [1].

Construction of a Box Plot

1. Sort the data values from the smallest to the largest.
2. Calculate the first quartile (Q1), second quartile (Q2), and third quartile (Q3).
3. The lower edge of the box represents the first quartile (Q1), also called the lower hinge.
4. The upper edge of the box represents the third quartile (Q3), also known as the upper hinge.
5. The line drawn inside the box indicates the second quartile (Q2), or the median.
6. A line extending from the point corresponding to the smallest observation to the first quartile bottom hinge is drawn as such meeting its mid-point. This line is known as the lower whisker.
7. A line extending from the point corresponding to the largest observation to the third quartile top hinge is drawn as such meeting its mid-point known as the upper whisker. Hence the box plot is also called as box-and-whisker plot [2, 3].

Box Plot - an Illustration

Let us examine the construction of box plot through an illustration. Let us consider the following data of 37 computers whose speed were examined in seconds through a benchmarking game. The observations were compared for 16 Intel processors and 21 AMD processors. The observations are given as follows in Table 1 and 2:

Components of a Box Plot

Now let us look at the various components and terminologies associated with a box plot [4].

The Upper and Lower Hinges

The lower hinge corresponds to the first quartile (Q1), while the upper hinge corresponds to the third quartile (Q3).

For the illustration discussed above, the values of upper and lower hinges are 21 and 17 for the AMD processors whereas for the Intel processors they are 25 and 19 respectively shown in Figure 1.

When we plot the values calculated above with the observations (time in seconds) in the y-axis and the factor of interest in x-axis, we arrive at the following box plot in Table 3 [5].

Table 1. Construction of box plot through an illustration

Intel Processors	Time (in seconds)
Intel Processors	18, 19, 20, 22, 24, 25, 26, 16, 17, 19, 25, 27, 28, 23, 23, 31
AMD Processors	15, 17, 18, 19, 20, 21, 23, 14, 17, 18, 19, 20, 21, 24, 19, 16, 17, 18, 20, 22, 28

Table 2. Constructing the box plots, let us arrange the given data in ascending order.

Processors	Time (in seconds)
Intel	16, 17, 18, 19, 19, 20, 22, 22, 23, 23, 24, 25, 25, 27, 28, 31
AMD	14, 15, 16, 17, 17, 17, 18, 18, 18, 19, 19, 19, 20, 20, 20, 21, 21, 22, 23, 24, 28

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Table 3. Steps for construction:

General Steps:	Intel Calculation	AMD Calculation
The lowest or smallest observation, X_s	16	14
$Q_1 = ¼ (n + 1)^{th}$ item, where n is the number of observations	$= ¼ (16 + 1) = 4.25^{th}$ item $= 4^{th}$ item + 0.25 (5^{th} item – 4^{th} item) =19 + 0.25 (19-19) = 19	$= ¼ (21 + 1) = 5.5^{th}$ item $= 5^{th}$ item + 0.5 (6^{th} item – 5^{th} item) =17 + 0.5 (17-17) = 17
$Q_2 = ½ (n+1)^{th}$ item, where n is the number of observations	$= ½ (16 + 1) = 8.5^{th}$ item = mean of 8^{th} and 9^{th} item = ½ (22 + 23) = 22.5	$= ½ (21 + 1) = 11^{th}$ item = 19
$Q_3 = ¾ (n+1)^{th}$ item, where n is the number of observations	$= ¾ (16+1) = 12.75^{th}$ item $= 12^{th}$ item + 0.75 (13^{th} item – 12^{th} item) = 25 + 0.75 (25 – 25) = 25	$= ¾ (21+1) = 16.5^{th}$ item = mean of 16^{th} and 17^{th} item) = ½ (21 + 21) = 21
The largest observation, X_l	31	28

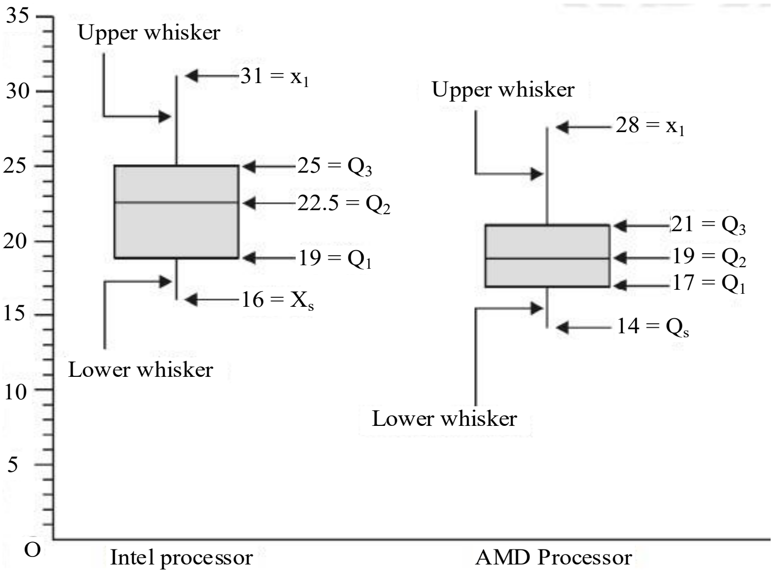

Figure 1. Box plots of Intel and AMD processor performance.

H-Spread

This value is determined by subtracting the lower hinge from the upper hinge. The H-Spread shows the spread of the elements of the data between the first quartile and third quartile showing the horizontal spread of the data. It is also known as the Inter Quartile Range.

For the data related to Intel in the example discussed above, the H-spread is 25–19 = 6 whereas for AMD it is 21–17 = 4 [6].

Whiskers

The lines extending above and below the box are called whiskers. Lower whisker extends from the point corresponding to the smallest observation to Q_1 and the upper whisker extends from Q_3 to the largest observation.

The maximum length whiskers can be extended is till the upper and lower fences [7].

Step

The step is calculated by multiplying the H-spread by 1.5.

For the data in the illustration above, the value of 1 step is 1.5 x 6 = 9 for Intel processors and 1.5 x 4 = 6 for AMD processors.

Upper and Lower Inner Fences

The upper and lower inner fences are calculated by adding one step to the upper hinge and subtracting one step from the lower hinge respectively. In other words, upper inner fence is equal to 1 step ahead of the upper hinge and lower inner fence is equal to 1 step before the lower hinge.

For the data in the illustration, for Intel processors upper inner fence is 25 + 9 = 34 and the lower inner fence is 19 – 9 = 10 [8].

Upper and Lower Outer Fences

Like the inner fences but calculated at an interval of two steps.

In the illustration, for the Intel processors its 25 + 2(9) = 43 for upper outer fence and 19 – 2(9) = 1 for lower outer fence.

Upper and Lower Adjacent

The upper and lower adjacent are used to represent the largest and the smallest observations of the data.

For the data of Intel processors in the example discussed above upper and lower adjacent are 31 and 16 respectively [9].

Outside Value

A data point that lies outside the inner fence but remains within the outer fence is referred to as an outside value. These values indicate observations that are somewhat distant from the main body of the data. In a box plot, outside values are typically represented using circles [10].

Far-out Value

The far-out value is a value which is beyond the upper outer fence or lower outer fence. To represent these values, the asterisks are used.

Box-plot Showing all the Components for the Data of Intel Processors

The data of Intel processors does not contain any outside or far-out values. Therefore, there are no extreme observations to be represented separately in the box plot. All the observations lie within the acceptable range defined by the inner and outer fences.

Box-plots with Outliers and + Sign

Outliers, Small 'o'

Outside value(s) and far out value(s) are known as extreme observations. If the extreme observations are present in the data, then those observations may be represented in box plot with an individual mark. The extreme observations are described as outliers when they are represented in box plots in Figure 2. [11, 12]

The outside value is a value which is beyond an inner fence but not beyond an outer fence and is denoted by a small 'o' whereas the far-out value is a value which is beyond the lower and upper outer fences denoted by an asterisk or small 'o'. The individual marks for extreme values can be plotted above and below to the whiskers in box plot. Especially, outside values are indicated by small 'o'.

In the data of AMD processors in the above given example 28 is only far out value.

Mean, + Sign

One more component which can be included in box plots are the value of some important parameters like, mean, mode etc. In a box plot, the mean value of a dataset is often represented by a '+' symbol. This gives more idea about the central tendency of the data which enables us to understand mor about the symmetry of the distribution in Figure 4.

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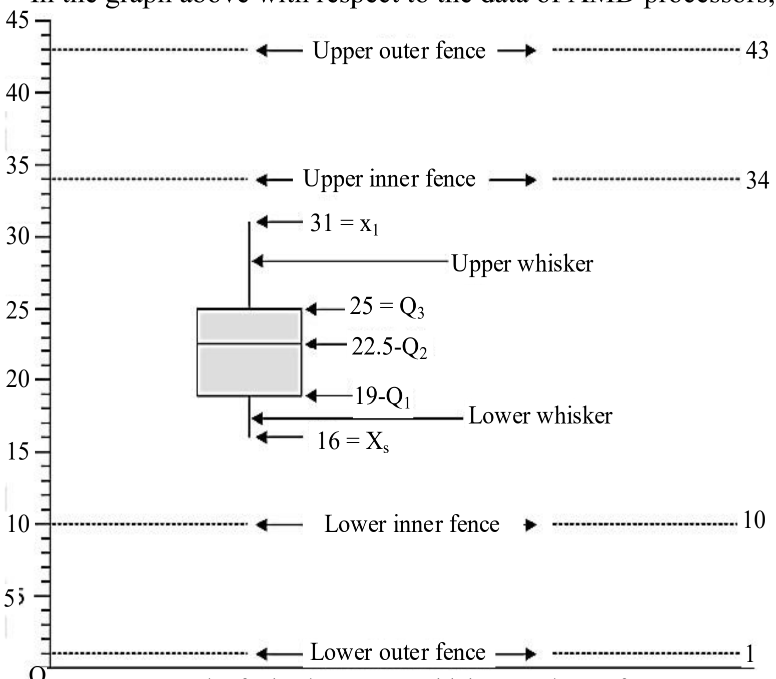
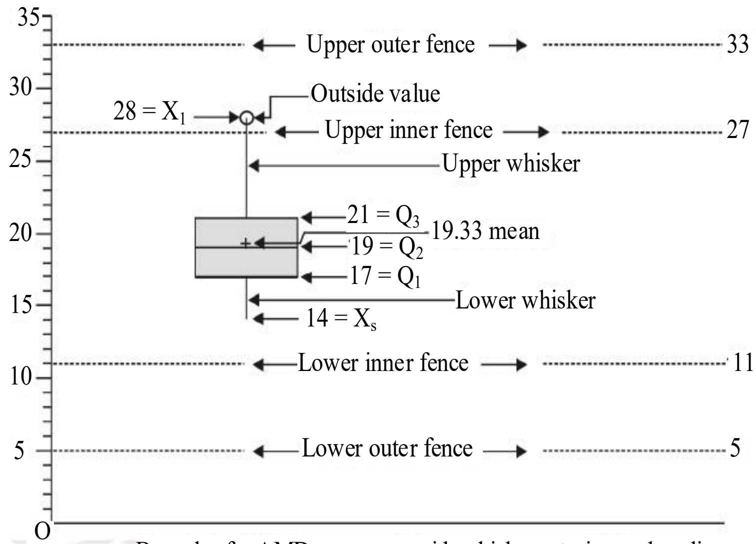
In the graph above with respect to the data of AMD processors, mean is shown by a + sign [13, 14].



Box-plot for intel processor with inner and outer fences

Figure 2. Box plot of Intel processor benchmarking times showing the inner and outer fences.



Box-plot for AMD processor with whiskers, + sign and outliers

Figure 3. Box plot of AMD processor benchmarking times showing whiskers, mean (+), and an outside value.

Box Plot Distribution vs. Frequency Distribution

The distribution of a box plot can explain how tightly the data is grouped, how the data is skewed and about the symmetry of the data.

In a normal distribution (Bell Curve), then the inter-quartile range (IQR), which is defined as Q3 − Q1, is equal to SD × 1.35 and mean = median. Shown in Figure 4.

Therefore

Q1 = mean − (0.5 × IQR)
Q3 = mean + (0.5 × IQR)
For simply:
Q1 = mean − (0.675 × SD)
Q3 = mean + (0.675 × SD)

a. If the median is positioned near the center of the box and the whiskers extend approximately the same distance on both sides, the distribution is considered symmetric in Figure 5.
b. If the median lies closer to the first quartile (Q1) and the lower whisker is shorter than the upper whisker, the distribution is positively skewed (right-skewed).
c. If the median is located closer to the third quartile (Q3) and the upper whisker is shorter than the lower whisker, the distribution is negatively skewed (left-skewed) [15].

Width of the Box plot

While the length of the box plot represents the IQR representing the 50% of the distribution of the data, inquisitively, the width of the box plot can also be used in some cases.

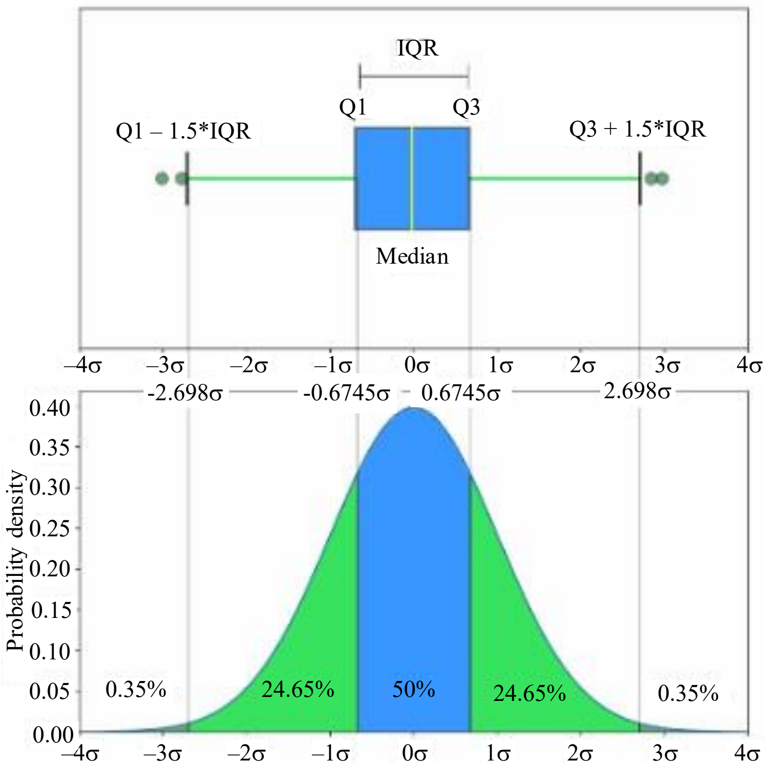


Figure 4. Relationship between the box plot and the normal distribution.

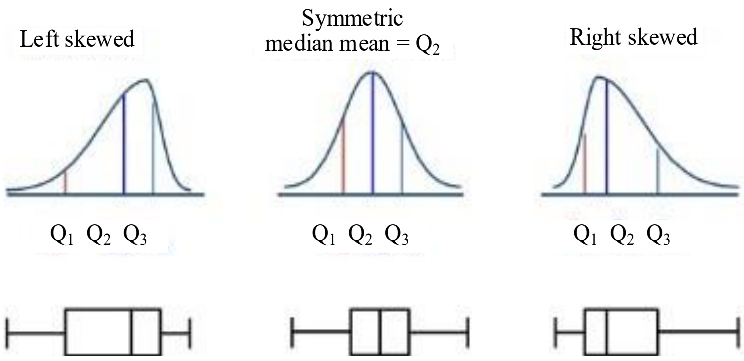


Figure 5. Box plots and corresponding distribution shapes for left-skewed, symmetric, and right-skewed data.

For example, when comparing two groups of data sets which are the outcome of different strengths of the factor of interest as in the case of different doses of the same medicine used for treatment of same disease on different groups; same fertilizer of different ratios used on the same crop etc. [16].

Why Box plot?

Box plots clearly highlight important landmarks of the data.

The box plot can provide answers to the following questions:

i. Is a factor significant?
ii. Does the location differ between subgroups?
iii. Does the variation differ between subgroups?
iv. Are there any outliers?

The box plot is also an effective tool summarizing large quantities of information visually like

- Median as a measure of central tendency
- Range and quartile deviation as measures of dispersion
- Symmetry
- Skewness
- Examining outliers, useful in
  - Identifying strong skew in the distribution
  - Identifying possible data collection or data entry errors
  - Providing insight into interesting properties of the data
- Tight grouping of data
- Quick comparison between groups of data

Box plots in R

R Markdown

This RMD document uses **“ggplot2”** library and the **“diamonds”** data set.

Let us call the library ‘ggplot2’ using the **library ()** function; **data ()** function will load the ‘diamonds’ data set whereas we can inspect the diamonds data set by using the **head ()** function

```
library(ggplot2)
data("diamonds")
head(diamonds)

## # A tibble: 6 x 10
##   carat cut       color clarity depth table price     x     y     z
##   <dbl> <ord>     <ord> <ord>   <dbl> <dbl> <int> <dbl> <dbl> <dbl>
## 1  0.23 Ideal     E     SI2      61.5    55   326  3.95  3.98  2.43
## 2  0.21 Premium   E     SI1      59.8    61   326  3.89  3.84  2.31
## 3  0.23 Good      E     VS1      56.9    65   327  4.05  4.07  2.31
## 4  0.29 Premium   I     VS2      62.4    58   334  4.2   4.23  2.63
## 5  0.31 Good      J     SI2      63.3    58   335  4.34  4.35  2.75
## 6  0.24 Very Good J     VVS2     62.8    57   336  3.94  3.96  2.48
```

Including Box Plots

Now let us construct a simple box plot where we will use the factor **‘carat’** to understand how the distribution of diamonds is based on the attribute ‘carat’. This we are doing using the **boxplot ()** in R shown in Figure 6.

Using ggplot

Now we can use ggplot2 library. It has the versatile **ggplot()** function which can be used to create several graphs. We can create box plots using ggplot() function. Let use the 'cut' attribute of the diamonds to group the diamonds and compare it based on 'carat'. x-axis - 'cut' - factor of interest y-axis - 'carat' - frequency of observations in Figure 7.

In the code below, ggplot() calls the data set and the aesthetics of the graph; the **geom_boxplot()** the type of graph to be generated.

```
ggplot(diamonds, aes(y=carat, x=cut)) + geom_boxplot()
```

Variants of Box plots

The original restriction of box plot was that it was designed and computed to be drawn by hand since its introduction by John Tukey in 1970. The introduction of computers in the field of statistics has allowed substantially more complex variations of box plot by bringing in the richer distributional summary of the histogram and the density plot. These plots help us in overcoming the box plot such as its failure to display multi-modality.

The first variation of the box plot is the **vase-plot** (Benjamin, 1988), where the box is substituted by a symmetrical display of estimated density for the data in the IQR alone and when the display of density is substituted for all the points, the box plot became the **violin- plot** (Hintze and Nelson, 1998) shown in Figure 8.

```
boxplot(diamonds$carat)
```

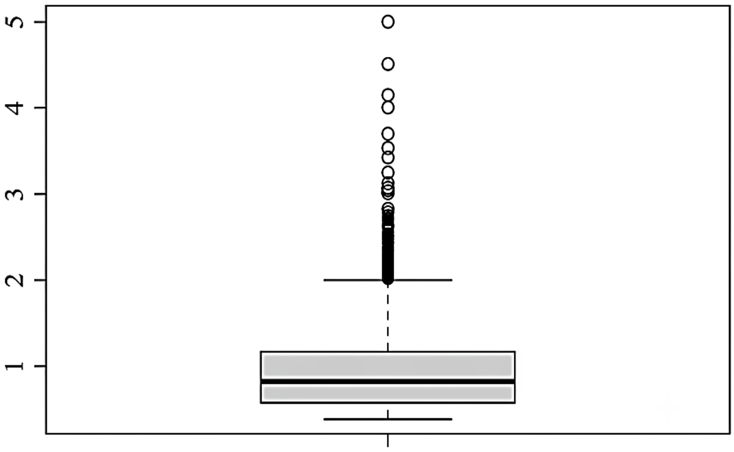


Figure 6. Box plot of diamond carat values showing the distribution and outliers.

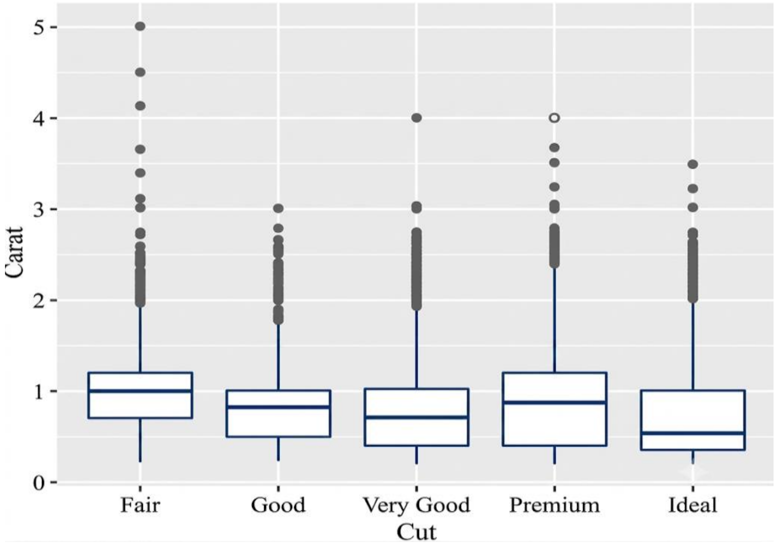


Figure 7. Box plots of diamond carat values across different cut categories using ggplot2.

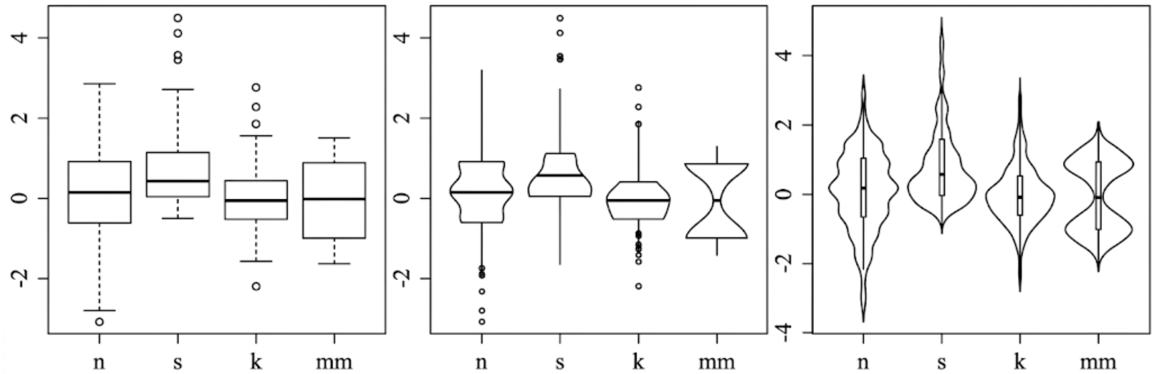
A Comparison of Box Plot and Violin-Plot in R Using the 'Diamonds' Data Set

The bean plot is an advanced variation of the box plot introduced by Peter Kampstra in 2008. Its name comes from the visual similarity of the plot to a bean pod. Each bean is created by mirroring a density curve, resulting in a polygon-shaped display. Individual observations are represented by short lines, forming a rug plot within the bean. The outer shape illustrates the data distribution, while the internal lines resemble seeds inside a bean pod. This distinctive appearance inspired the term bean plot. Additionally, a horizontal line is typically included to indicate the overall mean (average) of the data shown in Figure 9 and Figure 10.

A Comparison of Box Plot and bean-plot in R using the 'penguins' data set

(This illustration uses the 'penguins' data set from the palmer penguins library to take advantage of a larger dataset)

A **letter value box plot** (Hoffmann et al 2006) is an enhancement of the box plot designed to overcome the short comings of the box plot for large data. The boxplot displays many outliers and doesn't take advantage of the more reliable estimates of tail behaviour. The letter-value boxplot extends the boxplot with additional letter-values apart from the median (M) and fourths (F): eighths (E), sixteenths (D), ..., until the estimation error becomes too large. Each additional letter-value is displayed with a slightly smaller box. This display just adds extra letter values, and it suffers from the same problems as the original boxplot, multimodality is almost impossible to spot shown in Figure 10 and Figure 12.



Box-plot vs vase-plot vs violin-plot - A comparison.
(Hadley Wickham and Lisa Stryjewski)

Figure 8. Comparison of box plot, vase plot, and violin plot for data distribution visualization.

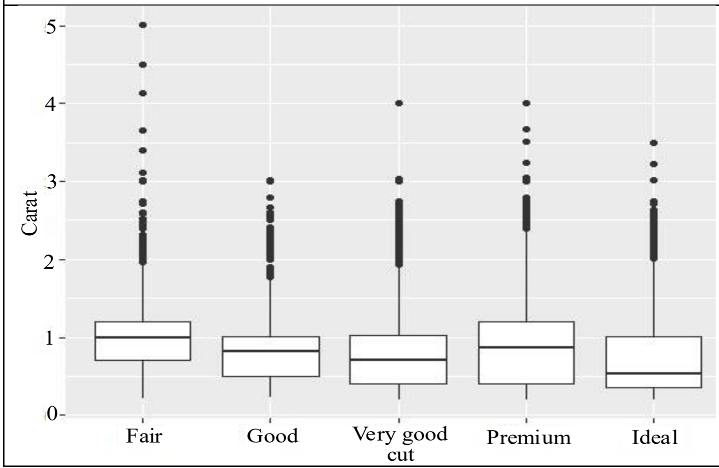
ggplot(diamonds, aes(y=carat, x=cut)) + geom_boxplot()	ggplot(diamonds, aes(y=carat, x=cut)) + geom_violin()
	

Figure 9. Comparative box plots of diamond carat values across different cut categories.

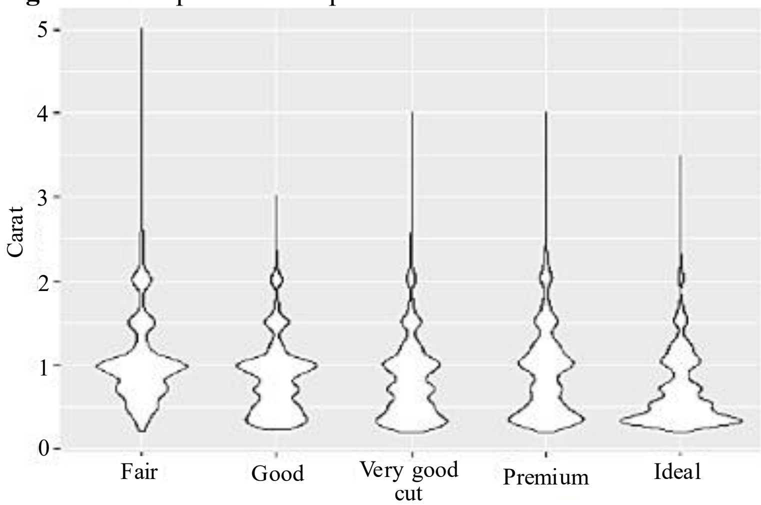


Figure 10. Violin plots of diamond carat values across different cut categories.

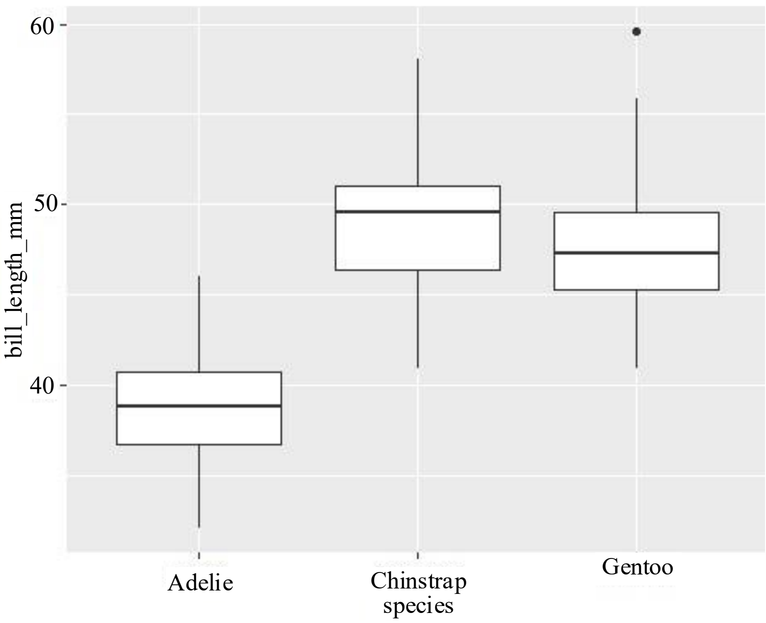


Figure 11. Box plots of penguin bill length across different species.

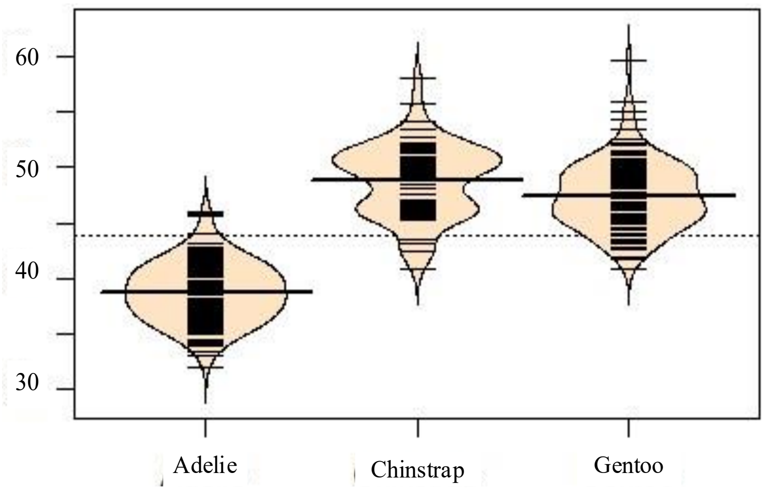


Figure 12. Bean plots of penguin bill length across different species.

CONCLUSION

Box plots are versatile and powerful graphical tools for Exploratory Data Analysis (EDA), providing a concise summary of the distribution, central tendency, variability, skewness, and potential outliers in a dataset. Their simplicity and effectiveness make them valuable for comparing multiple groups and identifying patterns that may not be apparent from numerical summaries alone. Advances in statistical computing have led to several enhanced variants, such as violin plots, vase plots, bean plots, and letter-value box plots, which overcome some limitations of the traditional box plot by providing additional information about the underlying data distribution. These visualization techniques enable researchers to better understand complex datasets and support informed decision-making. With the availability of statistical software such as **R** and the **ggplot2** package, box plots and their variants can be generated efficiently, making them indispensable tools in modern data analysis across statistics, business, economics, medicine, engineering, and many other scientific disciplines.

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