

math

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math on bookdown started on 2024/01/28

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2.1 discipline

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 - * UWP = Universal Windows Platform
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4.2 learning map

- [W3School](#)
- [SoloLearn](#)
- [Codecademy](#)

Chapter 5

machine learning

Part II

by date

Chapter 6

A Minimal Book Example

6.1 About

This is a *sample* book written in **Markdown**. You can use anything that Pandoc’s Markdown supports; for example, a math equation $a^2 + b^2 = c^2$.

6.1.1 Usage

Each **bookdown** chapter is an .Rmd file, and each .Rmd file can contain one (and only one) chapter. A chapter *must* start with a first-level heading: `# A good chapter`, and can contain one (and only one) first-level heading.

Use second-level and higher headings within chapters like: `## A short section` or `### An even shorter section`.

The `index.Rmd` file is required, and is also your first book chapter. It will be the homepage when you render the book.

6.1.2 Render book

You can render the HTML version of this example book without changing anything:

1. Find the **Build** pane in the RStudio IDE, and
2. Click on **Build Book**, then select your output format, or select “All formats” if you’d like to use multiple formats from the same book source files.

Or build the book from the R console:

```
bookdown::render_book()
```

To render this example to PDF as a `bookdown::pdf_book`, you’ll need to install XeLaTeX. You are recommended to install TinyTeX (which includes XeLaTeX): <https://yihui.org/tinytex/>.

6.1.3 Preview book

As you work, you may start a local server to live preview this HTML book. This preview will update as you edit the book when you save individual .Rmd files. You can start the server in a work session by using the RStudio add-in “Preview book”, or from the R console:

```
bookdown::serve_book()
```

6.2 Hello bookdown

All chapters start with a first-level heading followed by your chapter title, like the line above. There should be only one first-level heading (#) per .Rmd file.

6.2.1 A section

All chapter sections start with a second-level (##) or higher heading followed by your section title, like the sections above and below here. You can have as many as you want within a chapter.

An unnumbered section

Chapters and sections are numbered by default. To un-number a heading, add a `{.unnumbered}` or the shorter `{-}` at the end of the heading, like in this section.

6.3 Cross-references

Cross-references make it easier for your readers to find and link to elements in your book.

6.3.1 Chapters and sub-chapters

There are two steps to cross-reference any heading:

1. Label the heading: `# Hello world #{nice-label}`.
 - Leave the label off if you like the automated heading generated based on your heading title: for example, `# Hello world = # Hello world #{hello-world}`.
 - To label an un-numbered heading, use: `# Hello world {-#nice-label}` or `{# Hello world .unnumbered}`.
2. Next, reference the labeled heading anywhere in the text using `\@ref(nice-label)`; for example, please see Chapter ??.
 - If you prefer text as the link instead of a numbered reference use: any text you want can go here.

6.3.2 Captioned figures and tables

Figures and tables *with captions* can also be cross-referenced from elsewhere in your book using `\@ref(fig:chunk-label)` and `\@ref(tab:chunk-label)`, respectively.

See Figure ??.

```
par(mar = c(4, 4, .1, .1))
plot(pressure, type = 'b', pch = 19)
```

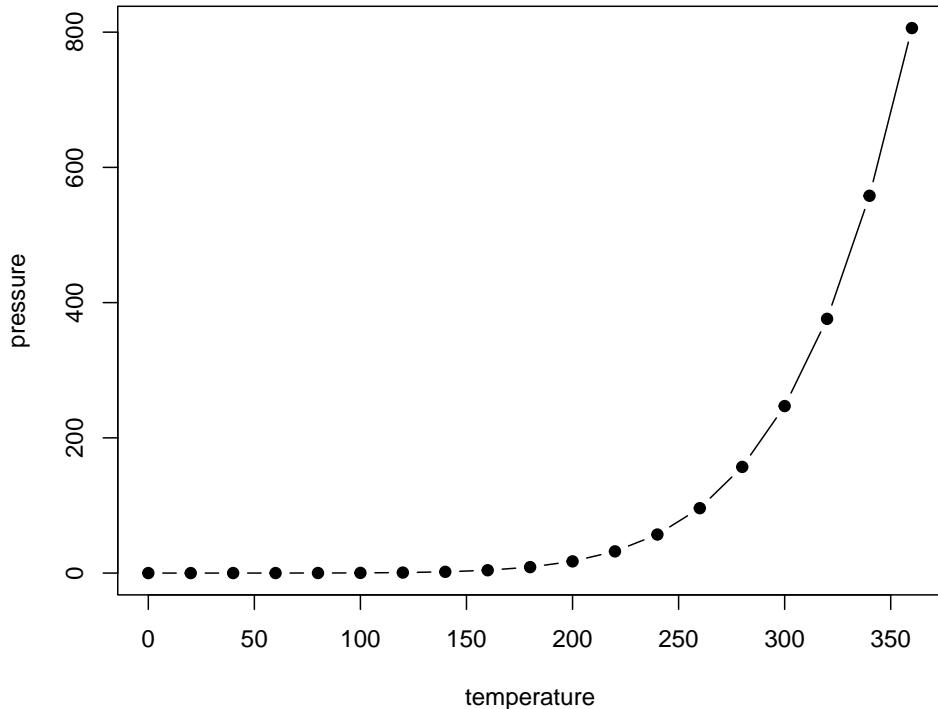


Figure 6.1: Here is a nice figure!

Don't miss Table ??.

```
knitr:::kable(
  head(pressure, 10), caption = 'Here is a nice table!',
  booktabs = TRUE
)
```

6.4 Parts

You can add parts to organize one or more book chapters together. Parts can be inserted at the top of an .Rmd file, before the first-level chapter heading in that same file.

Add a numbered part: # (PART) Act one {-} (followed by # A chapter)

Add an unnumbered part: # (PART*) Act one {-} (followed by # A chapter)

Table 6.1: Here is a nice table!

temperature	pressure
0	0.0002
20	0.0012
40	0.0060
60	0.0300
80	0.0900
100	0.2700
120	0.7500
140	1.8500
160	4.2000
180	8.8000

Add an appendix as a special kind of un-numbered part: `# (APPENDIX) Other stuff {-}` (followed by `# A chapter`). Chapters in an appendix are prepended with letters instead of numbers.

6.5 Footnotes and citations

6.5.1 Footnotes

Footnotes are put inside the square brackets after a caret `^[]`. Like this one ¹.

6.5.2 Citations

Reference items in your bibliography file(s) using `@key`.

For example, we are using the `bookdown` package² (check out the last code chunk in index.Rmd to see how this citation key was added) in this sample book, which was built on top of R Markdown and `knitr`³ (this citation was added manually in an external file book.bib). Note that the `.bib` files need to be listed in the index.Rmd with the YAML `bibliography` key.

The RStudio Visual Markdown Editor can also make it easier to insert citations: <https://rstudio.github.io/visual-markdown-editing/#/citations>

6.6 Blocks

6.6.1 Equations

Here is an equation.

$$f(k) = \binom{n}{k} p^k (1-p)^{n-k} \tag{6.1}$$

You may refer to using `\@ref(eq:binom)`, like see Equation (??).

¹This is a footnote.

6.6.2 Theorems and proofs

Labeled theorems can be referenced in text using `\@ref(thm:tri)`, for example, check out this smart theorem ??.

Theorem 6.1. *For a right triangle, if c denotes the length of the hypotenuse and a and b denote the lengths of the **other** two sides, we have*

$$a^2 + b^2 = c^2$$

Read more here <https://bookdown.org/yihui/bookdown/markdown-extensions-by-bookdown.html>.

6.6.3 Callout blocks

The R Markdown Cookbook provides more help on how to use custom blocks to design your own callouts: <https://bookdown.org/yihui/rmarkdown-cookbook/custom-blocks.html>

6.7 Sharing your book

6.7.1 Publishing

HTML books can be published online, see: <https://bookdown.org/yihui/bookdown/publishing.html>

6.7.2 404 pages

By default, users will be directed to a 404 page if they try to access a webpage that cannot be found. If you'd like to customize your 404 page instead of using the default, you may add either a `_404.Rmd` or `_404.md` file to your project root and use code and/or Markdown syntax.

6.7.3 Metadata for sharing

Bookdown HTML books will provide HTML metadata for social sharing on platforms like Twitter, Facebook, and LinkedIn, using information you provide in the `index.Rmd` YAML. To setup, set the `url` for your book and the path to your `cover-image` file. Your book's `title` and `description` are also used.

This `gitbook` uses the same social sharing data across all chapters in your book- all links shared will look the same.

Specify your book's source repository on GitHub using the `edit` key under the configuration options in the `_output.yml` file, which allows users to suggest an edit by linking to a chapter's source file.

Read more about the features of this output format here:

<https://pkgs.rstudio.com/bookdown/reference/gitbook.html>

Or use:

```
?bookdown::gitbook
```


Chapter 7

test

<https://bookdown.org/yihui/rmarkdown-cookbook/verbatim-code-chunks.html>

7.1 RStudio

7.1.1 writer options

<https://rstudio.github.io/visual-markdown-editing/markdown.html#writer-options>

7.1.1.1 line wrapping

<https://rstudio.github.io/visual-markdown-editing/markdown.html#line-wrapping>

7.1.1.2 ensuring the same markdown between source / visual mode

<https://stackoverflow.com/questions/71775027/rstudio-switch-markdown-editing-mode-between-source-and-visual-changes-special>

canonical mode

<https://rstudio.github.io/visual-markdown-editing/markdown.html#canonical-mode>

```
---
```

```
title: "My Document"
editor_options:
  markdown:
    wrap: 72
    references:
      location: block
    canonical: true
---
```

7.1.2 Rtools

Rtools43 for Windows <https://cran.r-project.org/bin/windows/Rtools/rtools43/rtools.html>

7.1.3 addins

<https://github.com/rstudio/addinexamples>

```
if (!requireNamespace("devtools", quietly = TRUE))
  install.packages("devtools")
```

```
devtools::install_github("rstudio/htmltools")
devtools::install_github("rstudio/shiny")
devtools::install_github("rstudio/minUI")
```

7.1.4 Git

commit: filename or extension is too long

<https://stackoverflow.com/questions/22575662/filename-too-long-in-git-for-windows>

<https://stackoverflow.com/questions/55327408/how-to-fix-git-for-windows-error-could-not-lock-config-file-c-file-path-to-g>

7.2 RMarkdown

R Markdown <https://cosname.github.io/rmarkdown-guide/index.html>

<https://www.rstudio.com/wp-content/uploads/2015/02/rmarkdown-cheatsheet.pdf>

<https://slides.yihui.org/2020-taipei-satrday-rmarkdown.html#1>

7.2.1 Pandoc link

<https://pandoc.org/chunkedhtml-demo/8.16-links-1.html>

<https://stackoverflow.com/questions/39281266/use-internal-links-in-rmarkdown-html-output>

<https://community.rstudio.com/t/how-to-hyperlink-between-different-rmd-files-in-rmarkdown/62289>

7.2.2 URL

<https://stackoverflow.com/questions/29787850/how-do-i-add-a-url-to-r-markdown>

[I'm an inline-style link] (<https://www.google.com>)

[I'm an inline-style link with title] (<https://www.google.com> "Google's Homepage")

[I'm a reference-style link] [Arbitrary case-insensitive reference text]

[I'm a relative reference to a repository file](../blob/master/LICENSE)

[You can use numbers for reference-style link definitions][1]

Or leave it empty and use the [link text itself]

Some text to show that the reference links can follow later.

[arbitrary case-insensitive reference text]: <https://www.mozilla.org>

[1]: <http://slashdot.org>

[link text itself]: <http://www.reddit.com>

7.2.3 arrow

<https://reimbar.org/dev/arrows/>

Up arrow: ↑

Down arrow: ↓

Left arrow: ←

Right arrow: →

Double headed arrow: ↔

7.2.4 superscript and subscript

script^{superscript}_{subscript}

script^{superscript}[^]

script^{superscript}_{subscript}

~subscript~

script_{subscript}

7.2.4.1 LaTeX

<https://tex.stackexchange.com/questions/580824/subscript-not-distinguished-enough>

<https://tex.stackexchange.com/questions/262295/make-subscript-size-smaller-always>

7.2.5 equation

<https://stackoverflow.com/questions/26049762/erroneous-nesting-of-equation-structures-in-using-align-in-a-multi-l>

7.2.5.1 proof QED

<https://math.meta.stackexchange.com/questions/3582/qed-for-mathjax-here-on-stackexchange>

```
\tag*{$\Box$}
```

$$a^2 + b^2 = c^2$$

□

```
\tag*{$\blacksquare$}
```

$$a^2 + b^2 = c^2$$

■

7.2.6 image

<https://stackoverflow.com/questions/25166624/insert-picture-table-in-r-markdown>

7.2.6.1 DiagrammeR / mermaid flowchart

Error: Functions that produce HTML output found in document targeting latex output.
Please change the output type of this document to HTML.

If you're aiming to have some HTML widgets shown in non-HTML format as a screenshot,
please install webshot or webshot2 R package for knitr to do the screenshot.

Alternatively, you can allow HTML output in non-HTML formats
by adding this option to the YAML front-matter of
your rmarkdown file:

```
always_allow_html: true
```

Note however that the HTML output will not be visible in non-HTML formats.

<https://bookdown.org/yihui/rmarkdown-cookbook/diagrams.html#diagrams>

<https://stackoverflow.com/questions/40803017/how-to-include-diagrammer-mermaid-flowchart-in-a-rmarkdown-file>

```
{r}
library(DiagrammeR)
mermaid("
graph LR
A-->B
",
width = 100
)
```

<https://github.com/rich-iannone/DiagrammeR/issues/364>

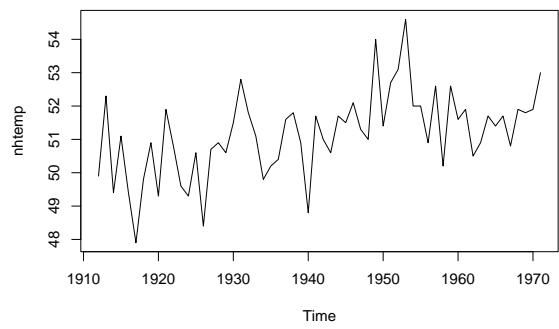
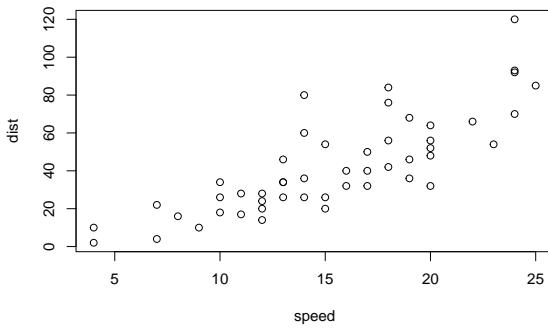
<https://stackoverflow.com/questions/55994210/how-to-solve-diagrammer-waste-of-space-issue-in-rmarkdown>

7.2.6.2 multiple images / figures in the same line

<https://cosname.github.io/rmarkdown-guide/rmarkdown-base.html#element-figure>

```
{r, fig.show = "hold", out.width = "50%"}  
plot(cars)  
plot(nhtemp)
```

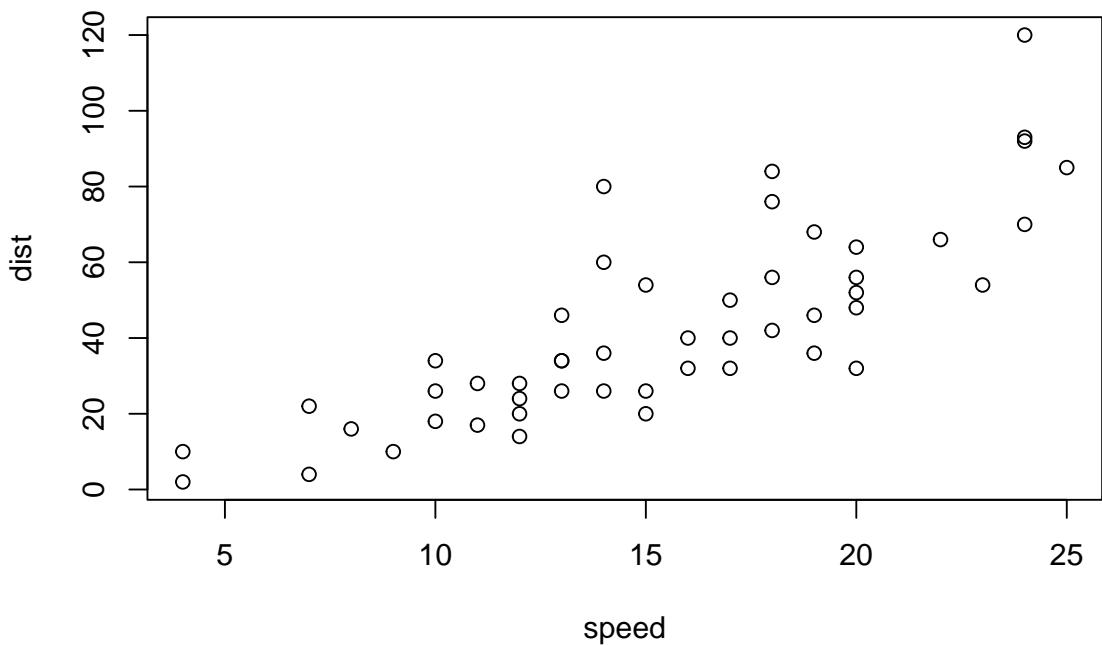
```
plot(cars)  
plot(nhtemp)
```



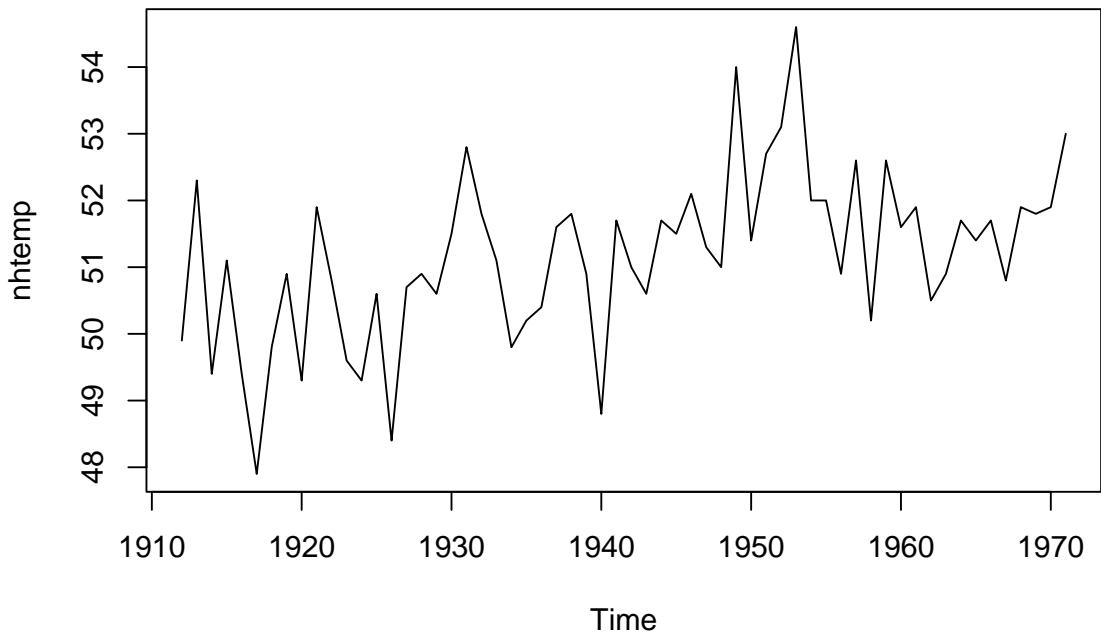
cf.

```
{r}  
plot(cars)  
plot(nhtemp)
```

```
plot(cars)
```



```
plot(nhtemp)
```



7.2.6.3 figure size

https://sebastiansauer.github.io/figure_sizing_knitr/

YAML in index.Rmd

```
---
```

```
title: "My Document"
output: html_document:
fig_width: 6
fig_height: 4
---
```

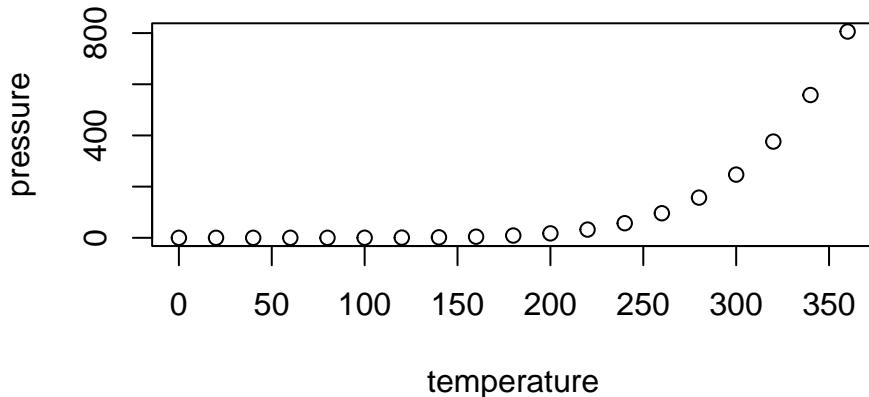
first R-chunk in your RMD document

```
knitr::opts_chunk$set(fig.width=12, fig.height=8)
```

width, height and options

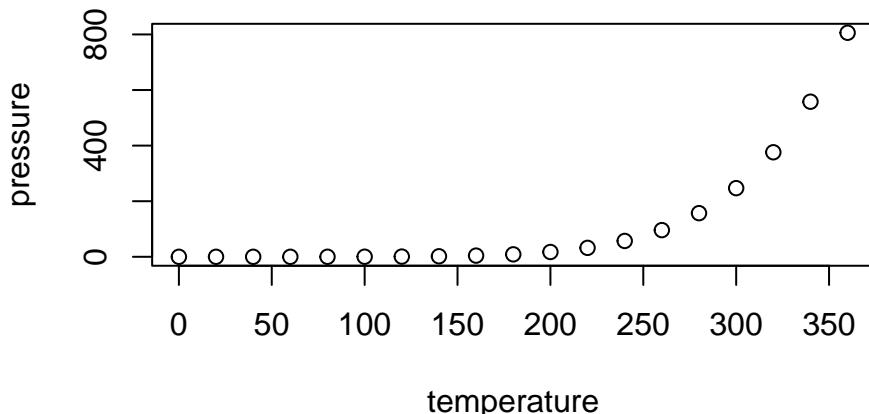
```
```{r fig.height = 3, fig.width = 5
plot(pressure)
```
{r fig.height = 3, fig.width = 5}
```

```
plot(pressure)
```



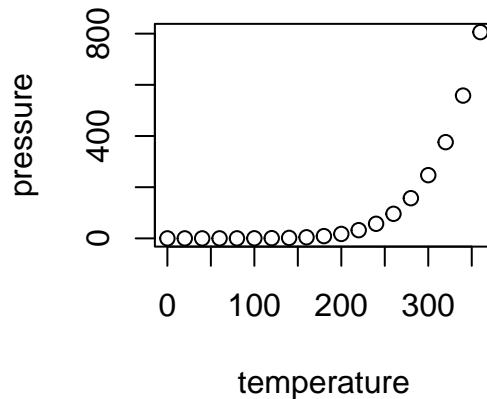
```
{r fig.height = 3, fig.width = 3, fig.align = "center"
```

```
plot(pressure)
```



```
{r fig.width = 5, fig.asp = .62
```

```
plot(pressure)
```

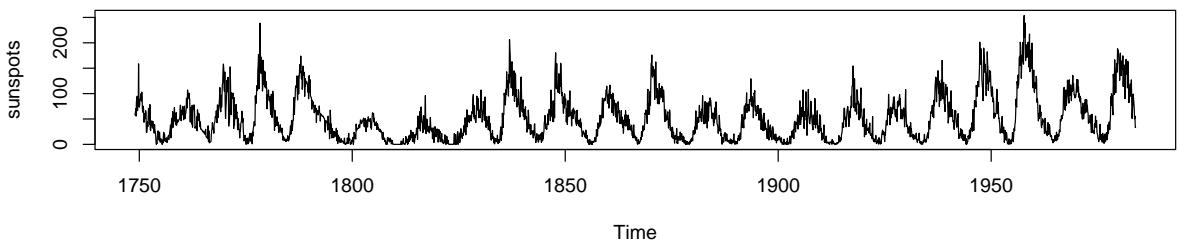


```
<center>
! [] (https://bookdown.org/yihui/rmarkdown-cookbook/images/cover.png){width=20%}
</center>
```

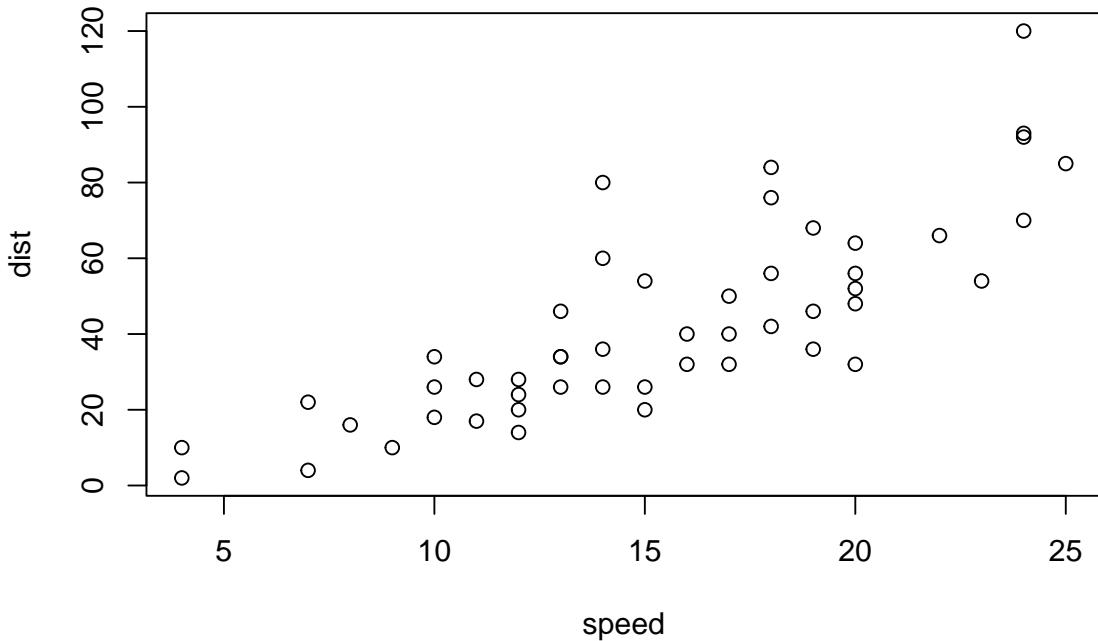
7.2.6.3.1 knitr <https://yihui.org/knitr/options/>

<https://bookdown.org/yihui/rmarkdown/tufte-figures.html>

```
par(mar = c(4, 4, .1, .2)); plot(sunspots)
```



```
plot(cars)
```



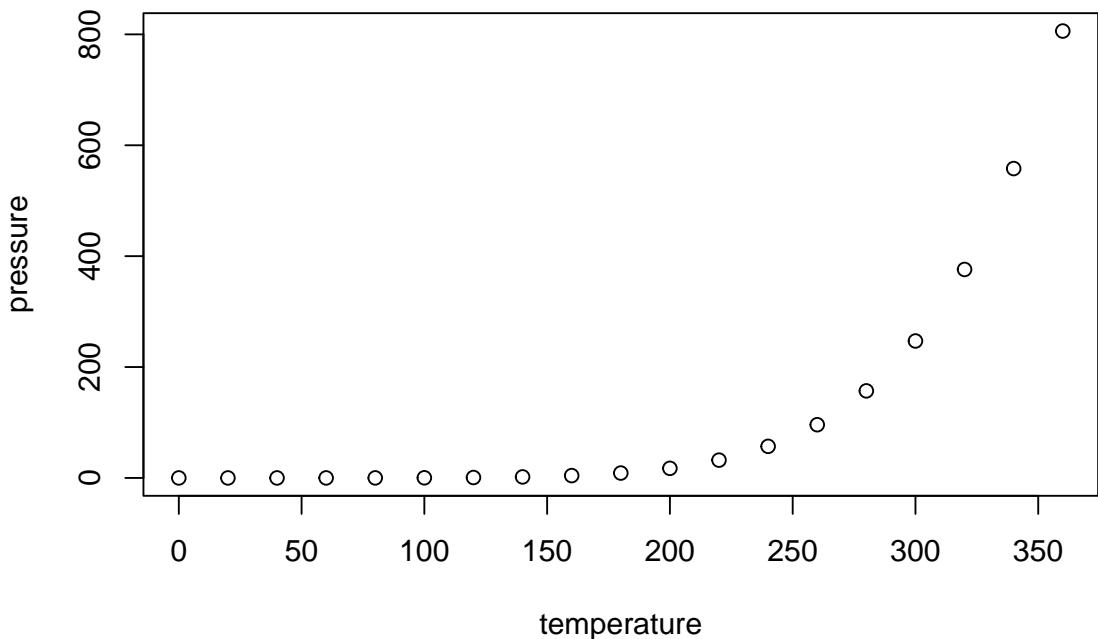
We know from _the first fundamental theorem of calculus_ that
for x in $[a, b]$:

$$\frac{d}{dx} \left(\int_a^x f(u) du \right) = f(x).$$

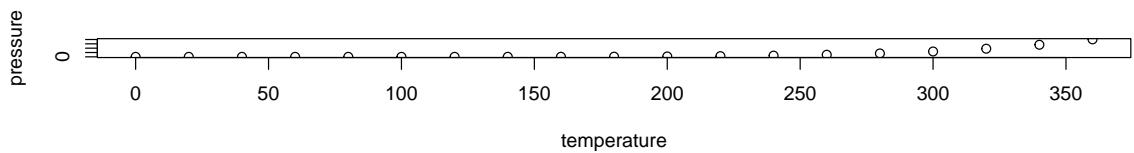
7.2.6.3.2 `out.width` vs. `fig.width` <https://stackoverflow.com/questions/29657777/how-to-make-fig-width-and-out-width-consistent-with-knitr>

when chunk option `cache=FALSE` is set, then `out.width` has no effect because no PDF output is created. Hence one has to specify exact measures in inches for `fig.width` and `fig.height` for each chunk

<https://stackoverflow.com/questions/59567235/a-ggmap-too-small-when-rendered-within-a-rmd-file>



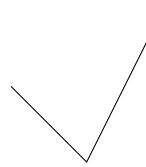
```
plot(pressure)
```



problem: `out.width='100%'` causing LaTeX Error: Not in outer par mode.

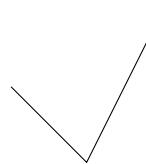
solution: `out.width=if (knitr:::is_html_output()) '100%'`

```
\begin{tikzpicture}
  \draw (-1,1)--(0,0)--(1,2);
\end{tikzpicture}
```



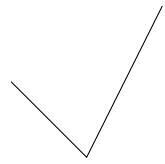
`fig.width=10, fig.height=2`

```
\begin{tikzpicture}
  \draw (-1,1)--(0,0)--(1,2);
\end{tikzpicture}
```



```
out.width=if (knitr:::is_html_output()) '100%'
```

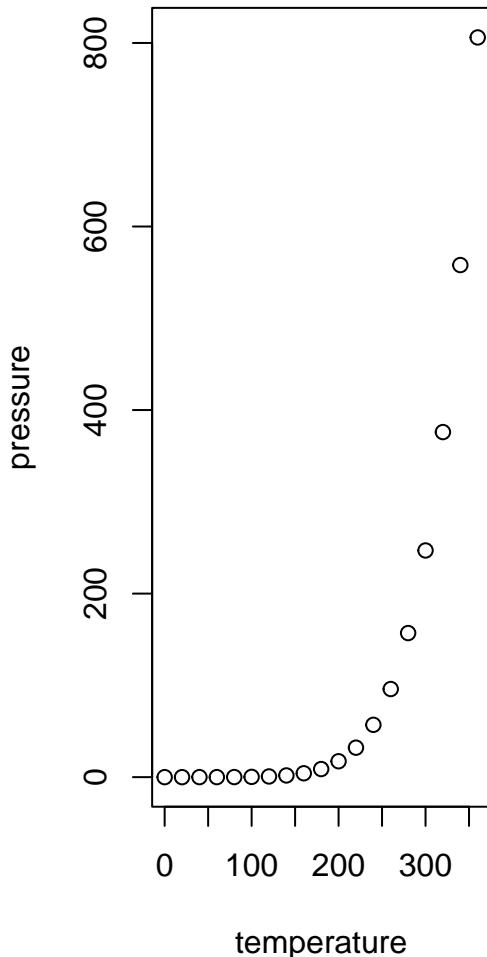
```
\begin{tikzpicture}
  \draw (-1,1)--(0,0)--(1,2);
\end{tikzpicture}
```



7.2.6.4 dynamic knitr plot width and height

<https://stackoverflow.com/questions/15365829/dynamic-height-and-width-for-knitr-plots>

```
plot(pressure)
```



7.2.6.5 web image in PDF

<https://stackoverflow.com/questions/46331896/how-can-i-insert-an-image-from-internet-to-the-pdf-file-produced-by-r-bookdown-i>

```
cover_url = 'https://bookdown.org/yihui/bookdown/images/cover.jpg'
if (!file.exists(cover_file <- xfun::url_filename(cover_url)))
  xfun::download_file(cover_url)
knitr::include_graphics(if (knitr::pandoc_to('html')) cover_url else cover_file)
```

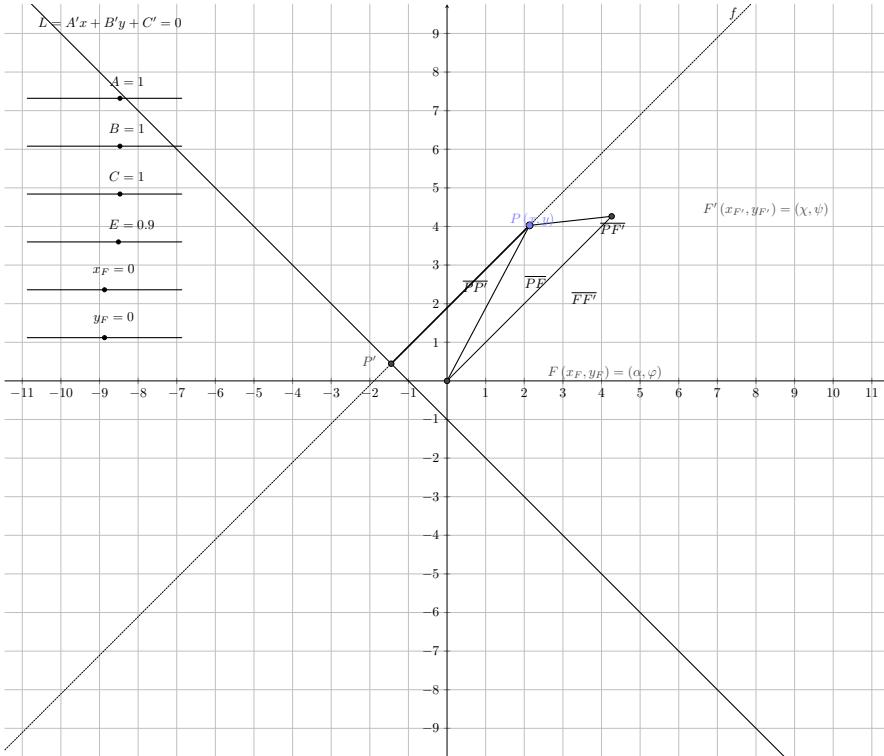


Figure 7.1: conic sections

7.2.6.6 SVG

<https://stackoverflow.com/questions/50165404/how-to-make-a-pdf-using-bookdown-including-svg-images>

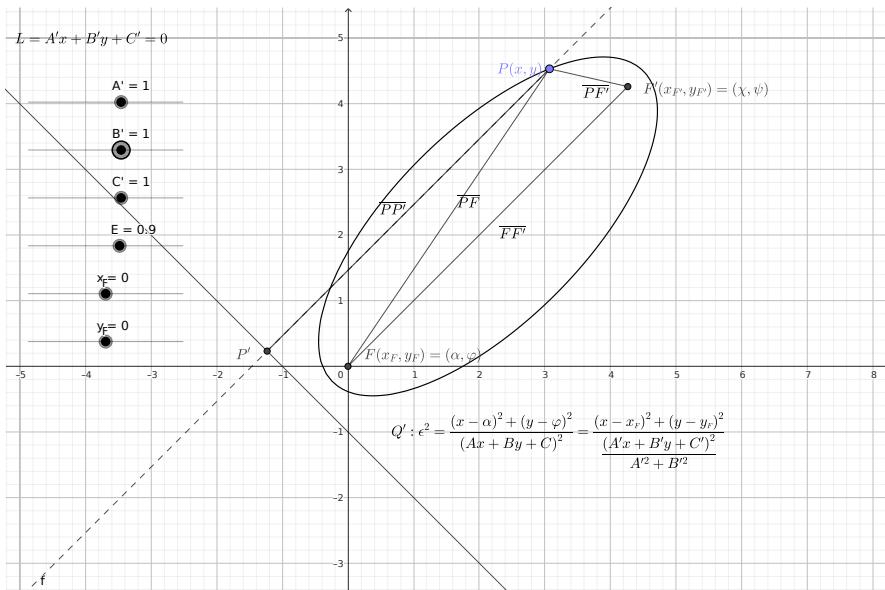
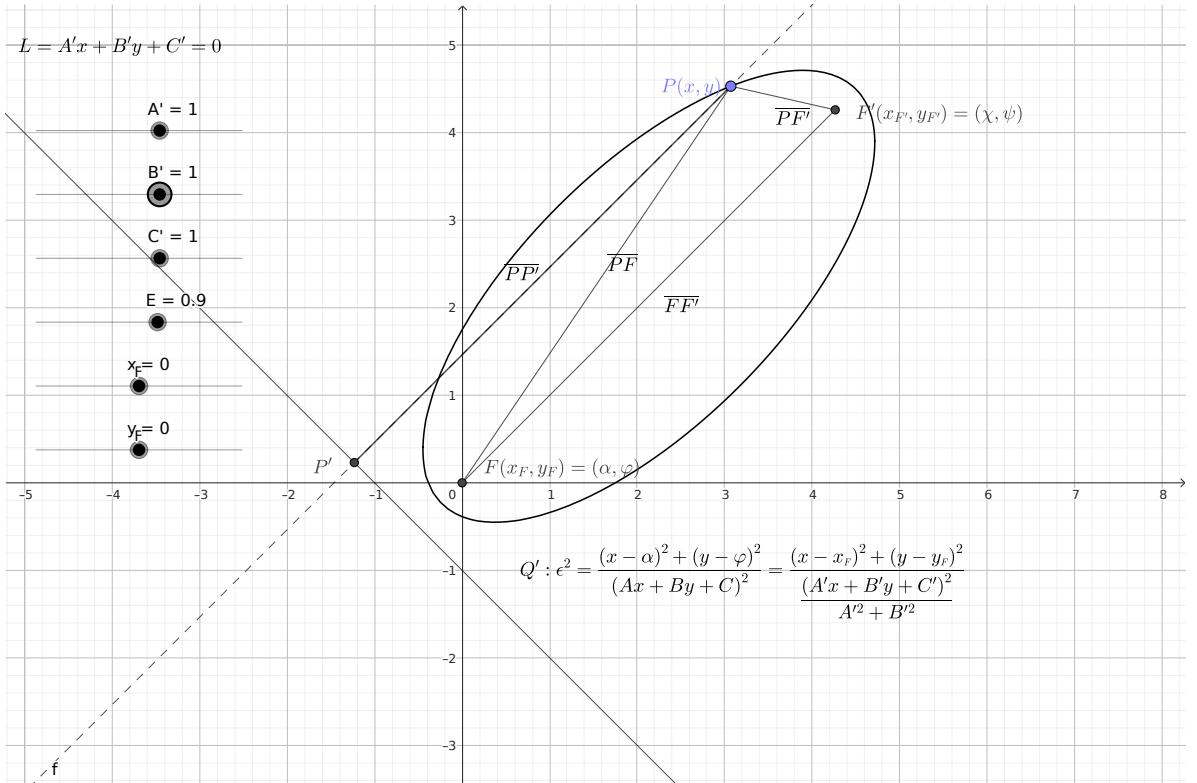


Figure 7.2: conic sections

7.2.7 horizontal rule

```
***
```

horizontal rule (or slide break)

```
dim(iris)
```

```
## [1] 150    5
```

7.2.8 footnote

7.2.9 hyperlink

PDF pandoc internal link will lose focus

equivalence relation [??] equivalence relation¹ equivalence relation[??]

equivalence class [??] equivalence class² equivalence class[??]

partition [??] partition³ partition[??]

- LaTeX
 - TikZ[??]
 - * TikZ-3Dplot
 - * PGFplots
 - xypic = xy-pic⁴
- OverLeaf
- MathCha
- GeoGebra
- Python
 - Matplotlib
 - Seaborn
 - Plotly

7.2.10 code chunk

7.2.10.1 code folding

<https://cosname.github.io/rmarkdown-guide/rmarkdown-document.html#html-code-folding>

¹{??} equivalence relation

²{??} equivalence class

³{??} partition

⁴{??} xy-pic

7.2.11 xaringan

slide realtime preview with RStudio addin Infinite Moon Reader in RStudio viewer

<https://github.com/yihui/xaringan>

<https://www.youtube.com/watch?v=3n9nASHg9gc>

7.3 Bookdown

7.3.1 system locale

<https://bookdown.org/tpemartin/ntpu-programming-for-data-science/appendix-d-.html>

`Sys.getlocale()`

Windows

`Sys.setlocale(category = "LC_ALL", locale = "UTF-8")`

MacOS

`Sys.setlocale(category = "LC_ALL", locale = "en_US.UTF-8")`

<https://bookdown.org/yihui/rmarkdown-cookbook/multi-column.html>

7.3.2 render_book()

<https://bookdown.org/yihui/bookdown/build-the-book.html>

```
render_book(input = ".", output_format = NULL, ..., clean = TRUE,
  envir = parent.frame(), clean_envir = !interactive(),
  output_dir = NULL, new_session = NA, preview = FALSE,
  config_file = "_bookdown.yml")
```

7.3.3 serve_book()

<https://bookdown.org/yihui/bookdown/serve-the-book.html>

```
serve_book(dir = ".", output_dir = "_book", preview = TRUE,
  in_session = TRUE, quiet = FALSE, ...)
```

7.3.4 LaTeX

7.3.4.1 hyperlink, URL, href

<https://www.baeldung.com/cs/latex-hyperref-url-hyperlinks>

<https://www.omdte.com/> -facebook -line /

7.3.4.2 ugly mathptmx \sum

PDF LaTeX \usepackage{fdsymbol} to have \overrightharpoon vector; however, there are too many side effects, including ugly mathptmx \sum , ...

```
\usepackage{fdsymbol} % vector over accent, but will use mathptmx
% replace the rather ugly mathptmx \sum operator with the equivalent Computer Modern one
\let\sum\relax
\DeclareSymbolFont{CMylargesymbols}{OMX}{cmex}{m}{n}
\DeclareMathSymbol{\sum}{\mathop}{CMylargesymbols}{50}
```

<https://tex.stackexchange.com/questions/315102/different-sum-signs>

<https://tex.stackexchange.com/questions/275038/how-to-replace-mathptmx-sum-with-cm-sum>

<https://tex.stackexchange.com/questions/391410/calligraphic-symbols-are-too-fancy-with-mathptmx-package>

<https://blog.csdn.net/kongtaoxing/article/details/131005044>

In `preamble.tex`, add

```
% replace the rather ugly mathptmx \sum operator with the equivalent Computer Modern one
\let\sum\relax
\DeclareSymbolFont{CMylargesymbols}{OMX}{cmex}{m}{n}
\DeclareMathSymbol{\sum}{\mathop}{CMylargesymbols}{50}

\DeclareMathAlphabet{\mathcal}{OMS}{cmsy}{m}{n}
\DeclareSymbolFont{largetsymbol}{OMX}{cmex}{m}{n}
```

7.3.4.3 LaTeX package in HTML document

<https://github.com/rstudio/rmarkdown/issues/1829>

```
---
title: "assignment"
author: "author"
output: html_document
---

$$
\require{cancel}
\cancel{x}
$$
```

\cancel{x}

<https://stackoverflow.com/questions/18189175/how-to-use-textup-with-mathjax>

\textup is not available in MathJax. You can replace it with \mathrm, but \mathrm does not interpret spaces.

7.3.5 depth of table of contents toc_depth

<https://stackoverflow.com/questions/49009212/how-to-change-toc-depth-in-r-bookdown-gitbook>

```
bookdown::gitbook:  
  toc_depth: 2
```

<https://stackoverflow.com/questions/68537309/how-can-i-specific-the-initial-level-to-have-my-table-of-contents-be-expanded-to>

```
toc:  
  collapse: section
```

7.3.6 multi-column layout / two columns

<https://bookdown.org/yihui/rmarkdown-cookbook/multi-column.html>

7.3.6.1 for both HTML and PDF

figure size[??]

Below is a Div containing three child Divs side by side. The Div in the middle is empty, just to add more space between the left and right Divs.

```
::::::::::: {.cols data-latex=""}

::: {.col data-latex="{0.55\textwidth}"}
<!-- -->
:::

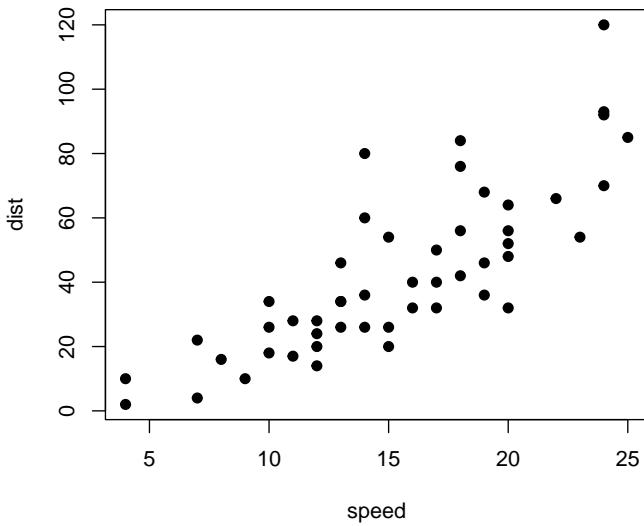
::: {.col data-latex="{0.05\textwidth}"}
\
<!-- an empty Div (with a white space), serving as
a column separator -->
:::

::: {.col data-latex="{0.4\textwidth}"}
The figure on the left-hand side shows the `cars` data.
```

 Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur.

```
:::  
::::::::::
```

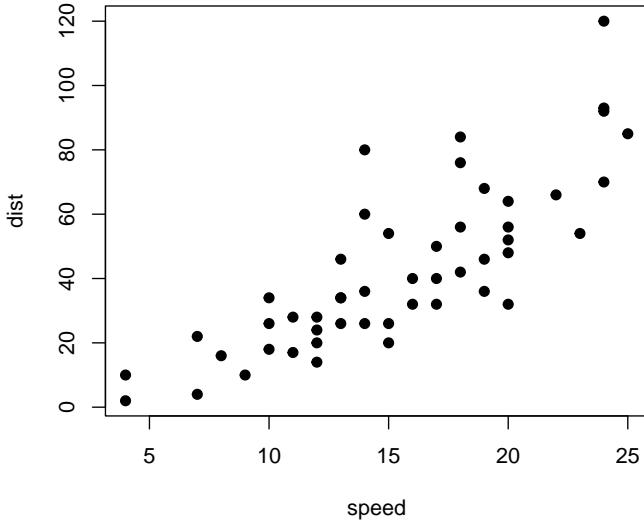
```
{r, echo=FALSE, fig.width=5, fig.height=4}
```



The figure on the left-hand side shows the `cars` data.

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur.

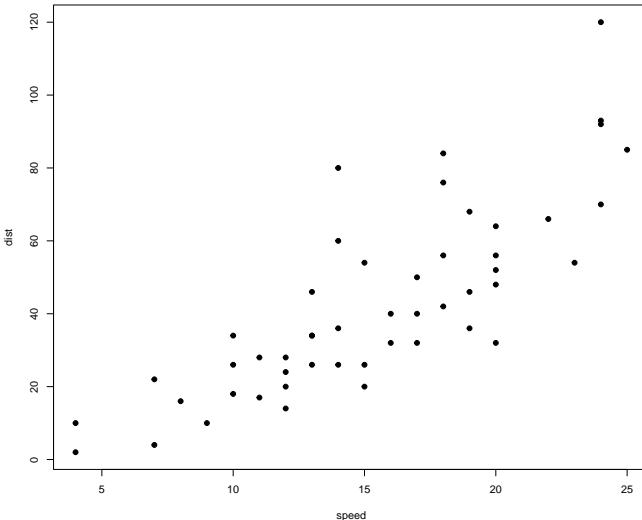
```
{r, echo=FALSE, fig.width=10, fig.height=8, out.width = "100%"}
```



The figure on the left-hand side shows the `cars` data.

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur.

```
{r, echo=FALSE, fig.width=10, fig.height=8}
```



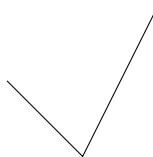
7.3.6.2 multi-column `fig.cap` must use `fig.pos="H"`

<https://community.rstudio.com/t/adding-fig-cap-caption-text-to-code-chunk-causes-figure-to-print-at-top-of-page-instead-of-where-it-should-be/30297>

<https://bookdown.org/yihui/rmarkdown-cookbook/figure-placement.html>

to avoid LaTeX Error: Not in outer par mode for caption in multi-column LaTeX PDF
 in `output.yml` add `extra_dependencies: ["float"]` under `bookdown::pdf_book:`
 include first chunk `knitr::opts_chunk$set(fig.pos = "H", out.extra = "")` in .Rmd
 add `out.width=if (knitr:::is_html_output()) '50%` for TikZ chunk
 thus complete chunk beginning with `{r, echo=FALSE, cache=TRUE, engine='tikz', fig.ext=if (knitr:::is_latex_output()) 'pdf' else 'png', fig.width=10, fig.height=2, out.width=if (knitr:::is_html_output()) '100%', fig.cap='')}`

```
\begin{tikzpicture}
  \draw (-1,1)--(0,0)--(1,2);
\end{tikzpicture}
```



LaTeX package `caption`

<https://tex.stackexchange.com/questions/128485/how-to-make-a-caption-via-captionof-and-extra-margins-adhere-to-minipage-marg>

What is the different between using `\captionof{table}{ABC}` and `\caption{ABC}`?

<https://tex.stackexchange.com/questions/514286/what-is-the-different-between-using-captionoftableabc-and-captionabc>

side-by-side table

<https://stackoverflow.com/questions/73745714/how-to-print-gt-tbl-tables-side-by-side-with-knitr-kable>

R ternary operator

<https://stackoverflow.com/questions/8790143/does-the-ternary-operator-exist-in-r>

7.3.6.3 caption above figure

<https://stackoverflow.com/questions/56979022/caption-above-figure-in-html-rmarkdown>

```
fig.topcaption=TRUE
```

7.3.6.4 for only HTML

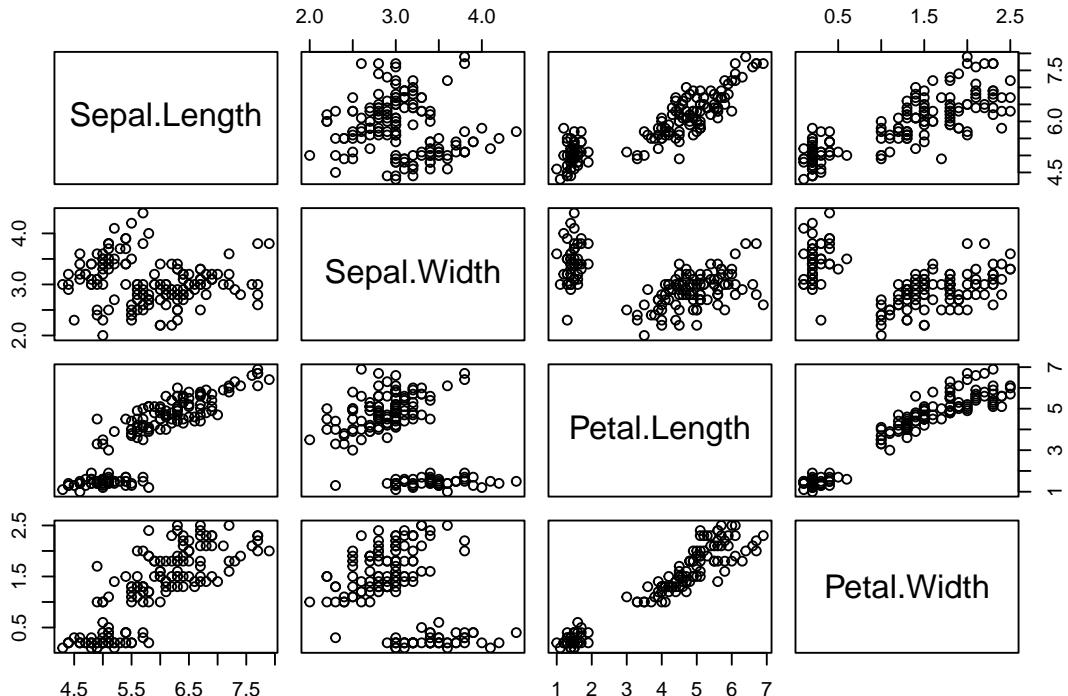
7.3.6.4.1 CSS flex

```
str(iris)
```

```
## 'data.frame': 150 obs. of 5 variables:
## $ Sepal.Length: num 5.1 4.9 4.7 4.6 5 5.4 4.6 5 4.4 4.9 ...
## $ Sepal.Width : num 3.5 3 3.2 3.1 3.6 3.9 3.4 3.4 2.9 3.1 ...
## $ Petal.Length: num 1.4 1.4 1.3 1.5 1.4 1.7 1.4 1.5 1.4 1.5 ...
## $ Petal.Width : num 0.2 0.2 0.2 0.2 0.2 0.4 0.3 0.2 0.2 0.1 ...
## $ Species      : Factor w/ 3 levels "setosa","versicolor",...: 1 1 1 1 1 1 1 1 1 1 ...
```

And this block will be put on the right:

```
plot(iris[, -5])
```



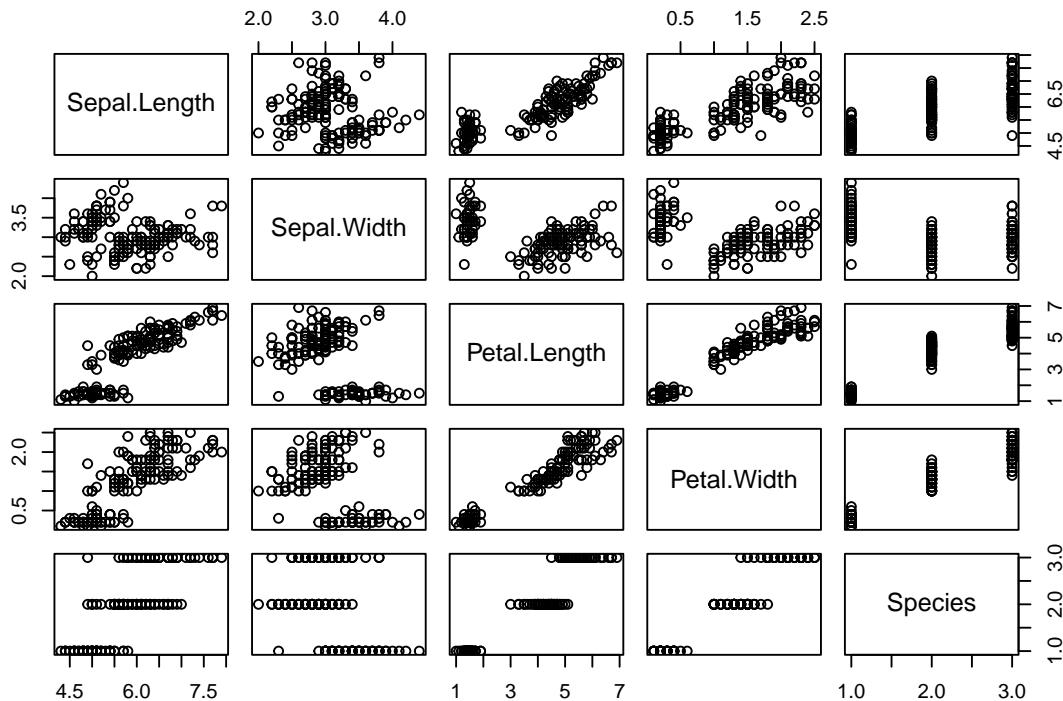
7.3.6.4.2 CSS grid <https://github.com/yihui/knitr/issues/1743>

<https://medium.com/enjoy-life-enjoy-coding/css-grid-7cd763091cf70>

```
head(iris)
```

```
##   Sepal.Length Sepal.Width Petal.Length Petal.Width Species
## 1      5.1       3.5      1.4       0.2  setosa
## 2      4.9       3.0      1.4       0.2  setosa
## 3      4.7       3.2      1.3       0.2  setosa
## 4      4.6       3.1      1.5       0.2  setosa
## 5      5.0       3.6      1.4       0.2  setosa
## 6      5.4       3.9      1.7       0.4  setosa
```

```
plot(iris)
```



7.4 conditional block/chunk for either HTML or PDF, and Chinese issue

<https://stackoverflow.com/questions/76240244/bookdown-conditional-display-of-text-and-code-blocks-latex-pdf-vs-html>

equivalence relation

R is an equivalence relation over $A \times B$

$$\Leftrightarrow \begin{cases} R = \sim = \{\langle x, y \rangle | x \sim y\} \subseteq A \times B & (\text{e}) \text{ equivalence} \\ \vdots & \vdots \\ R = \{\langle x, y \rangle | xRy\} \subseteq A \times B & (R) \text{ relation} \\ \forall \langle x, y \rangle \in R (xRx) & (r) \text{ reflexive} \\ \forall \langle x, y \rangle \in R (xRy \Rightarrow yRx) & (s) \text{ symmetric} \\ \forall \langle x, y \rangle, \langle y, z \rangle \in R \left(\begin{cases} xRy \\ yRz \end{cases} \Rightarrow xRz \right) & (t) \text{ transitive} \end{cases} \Leftrightarrow \begin{cases} R = \{\langle x, y \rangle | xRy\} \subseteq A \times B \\ \forall \langle x, y \rangle \in R (\langle x, x \rangle \in R) \\ \forall \langle x, y \rangle \in R (\langle y, x \rangle \in R) \\ \forall \langle x, y \rangle, \langle y, z \rangle \in R (\langle x, z \rangle \in R) \end{cases}$$

7.5 video embedding

<https://stackoverflow.com/questions/42543206/r-markdown-compile-error>

always_allow_html: true

```
install.packages("webshot")
webshot::install_phantomjs()
```

however webshot not work

Error: cannot find bilibili.com

<https://cran.r-project.org/web/packages/vembedr/vignettes/embed.html>

```
## Warning: package 'vembedr' was built under R version 4.2.3
```

```
## embed_youtube("qeMqtt7NFDM")
```

7.5.1 timestamp

- YouTube: <https://www.youtube.com/embed/%7BvideoID%7D?start=%7Bsecond%7D>
- BiliBili: <https://player.bilibili.com/player.html?bvid=%7BvideoID%7D&autoplay=0&t=%7Bsecond%7D>

7.6 equation term coloring

7.6.1 font color

RegEx replacement in RStudio for `\color{(\w+)}` in LyX to be replaced with `\color{$1}{}` in HTML document, and remain the same for PDF document

In HTML document, if no {} for text range, only the first following term will take effect

`\color{orange}x=y`

$x = y$

\color{orange} and \color{cyan} are better color for HTML GitBook White and Night themes and PDF

```
\color{cyan}{x=y}
```

$x = y$

```
\color{cyan}{x=y}
```

$x = y$

```
:::: {show-in="html"}

$$
\frac{\colorbox{#FFD1DC}{$\epsilon^2\left(y_{\{\{\scriptscriptstyle F\}}}-y_{\{\{\scriptscriptstyle L\}}}\right)^2}}{1-\epsilon^2}
$$

::::

:::: {show-in="pdf"}

$$
\frac{\colorbox{red!50}{\text{\ensuremath{\epsilon^2\left(y_{\{\{\scriptscriptstyle F\}}}-y_{\{\{\scriptscriptstyle L\}}\right)^2}}}}{1-\epsilon^2}
$$

::::
```

7.6.2 background color

<https://bookdown.org/yihui/rmarkdown-cookbook/font-color.html>

LaTex color

<https://latexcolor.com/>

https://www.overleaf.com/learn/latex/Using_colors_in_LaTeX

<https://latex-tutorial.com/color-latex/#:~:text=To%20summarize%2C%20pyellow!50efined%20colors%20in>

LaTex color methods

color frame

<https://tex.stackexchange.com/questions/582748/highlight-equation-with-boxes-and-arrows>

color box

<https://tex.stackexchange.com/questions/567739/how-to-move-and-size-colorbox>

color box with round corners

<https://tex.stackexchange.com/questions/568880/color-box-with-rounded-corners>

highlighting

<https://tex.stackexchange.com/questions/318991/highlighting-math>

<https://forum.remnote.io/t/highlighting-latex-formulas/149>

LyX

<https://tex.stackexchange.com/questions/250069/create-a-color-box> <https://latexlyx.blogspot.com/2013/12/lyx.html>

<https://tex.stackexchange.com/questions/635486/prevent-lyx-from-escaping-math-in-color-box-title>

Bookdown - conditional display of text and code blocks (LaTeX/PDF vs. HTML) <https://stackoverflow.com/questions/76240244/bookdown-conditional-display-of-text-and-code-blocks-latex-pdf-vs-html>

$$F = ma$$

<https://community.rstudio.com/t/highlighting-text-inline-in-rmarkdown-or-bookdown-pdf/35118/4>

$$F = ma$$

$$F = F$$

$$F = ma \tag{7.1}$$

$$F = ma$$

$$Y = \beta_0 + \beta_1 X_1 + \dots + \beta_n X_n$$

7.7 link and reference

<https://stackoverflow.com/questions/57469501/cross-referencing-bookdownhtml-document2-not-working>

$$E = mc^2$$

$$(7.2)$$

```
\@ref(nice-label) ??

[link to partition] [partition] link to partition
[partition] \@ref(partition)
partition [#partition] (??) @ref(#partition)
[equivalence class] \@ref(equivalence-class)
equivalence class (??)
equivalence class [#equivalence class] (@ref(equivalence class)) @ref(#equivalence class)
[equivalence-class] [#equivalence-class] (??) @ref(#equivalence-class)
X [equivalence-class.html] [equivalence-class.html#equivalence-class] (@ref(equivalence-class.html))
@ref(equivalence-class.html#equivalence-class)
equivalence relation [#equivalence relation] (@ref(equivalence relation)) @ref(#equivalence relation)
[equivalence-relation] [#equivalence-relation] (??) @ref(#equivalence-relation)
X [equivalence-relation.html] [equivalence-relation.html#equivalence-relation] (@ref(equivalence-
relation.html)) @ref(equivalence-relation.html#equivalence-relation)
```

7.8 number and reference equations

<https://stackoverflow.com/questions/71595882/rstudio-error-in-windows-running-pdflatex-exe-on-file-name-tex-exit-code-10>

<https://bookdown.org/yihui/rmarkdown/bookdown-markdown.html#equations>

\#eq:emc \@ref(eq:emc)

<https://stackoverflow.com/questions/55923290/consistent-math-equation-numbering-in-bookdown-across-pdf-docx-html-output>

C is an equivalence class of a on A

$$\Leftrightarrow [a]_\sim = C = \left\{ x \left| \begin{array}{l} a \in A \\ x \in A \\ x \sim a \\ \sim \text{ is an equivalence relation over } A \times A = A^2 \end{array} \right. \right\} \subseteq A \neq \emptyset \quad (7.3)$$

$$\Leftrightarrow [a] = [a]_\sim = \left\{ x \left| \begin{array}{l} a \in A \\ x \in A \\ x \sim a \\ \sim \text{ is an equivalence relation on } A \end{array} \right. \right\} \subseteq A \neq \emptyset$$

$$\Rightarrow [a]_\sim = \{x | x \sim a\} \subseteq A \neq \emptyset$$

<https://bookdown.org/yihui/rmarkdown/bookdown-markdown.html#cross-referencing>

This cross reference is the Fig. ??

<https://stackoverflow.com/questions/51595939/bookdown-cross-reference-figure-in-another-file>

I ran into the same issue and came up with this solution if you aim at compiling 2 different pdfs. It relies on LaTeX's xr package for cross references: <https://stackoverflow.com/a/52532269/576684>

7.9 footnote

```
noun^ [This is a footnote]

noun[^202401260000-test-cross-link-1]

[^202401260000-test-cross-link-1]: This is a footnote.
```

noun⁵

7.10 citation

<https://stackoverflow.com/questions/48965247/use-csl-file-for-pdf-output-in-bookdown/49145699#49145699>

citation 1[?] citation 2[?]

citation 3[?] citation 4[?]

7.10.1 citation in fig.cap

<https://tex.stackexchange.com/questions/591882/citation-within-a-latex-figure-caption-in-rmarkdown>

```
(ref:rudolph) *nice* cite: [@Lam94] .
(ref:campbell1963) *nice* cite: [@campbell1963] .
(ref:campbell1963) ([@campbell1963]
(ref:campbell1963) \ [@campbell1963]
```

7.10.2 backreference

<https://community.rstudio.com/t/how-to-create-a-backreference-to-place-of-citation-in-rmarkdown/84866>

<https://blog.csdn.net/RobertChenGuangzhi/article/details/50455429>

<https://latex.org/forum/viewtopic.php?t=3722>

7.11 environment for definition, theorem, proof

<https://bookdown.org/yihui/rmarkdown/bookdown-markdown.html>

<https://github.com/rstudio/rstudio/issues/5264>

@howthebodyworks Ideally, previews of such equations should also work inside a theorem, although I could survive without that.

<https://github.com/rstudio/rstudio/issues/8773>

⁵This is a footnote.

	Sources of Invalidity								External			
	Internal	External							Interaction of Testing and X	Interaction of Selection and X	Reactive Arrangements	Multiple-X Interference
	History	Maturation	Testing	Instrumentation	Regression	Selection	Mortality	Interaction of Selection and Maturation, etc.	Interaction of Testing and X	Interaction of Selection and X	Reactive Arrangements	Multiple-X Interference
<i>Pre-Experimental Designs:</i>												
1. One-Shot Case Study	X	O	—	—	—	—	—	—	—	—	—	—
2. One-Group Pretest-Posttest Design	O	X	O	—	—	—	?	+	+	—	—	?
3. Static-Group Comparison	X	O	—	—	—	+	?	+	+	+	—	—
<i>True Experimental Designs:</i>												
4. Pretest-Posttest Control Group Design	R	O	X	O	+	+	+	+	+	+	+	?
	R	O	—	—	—	—	—	—	—	—	—	?
5. Solomon Four-Group Design	R	O	X	O	+	+	+	+	+	+	+	?
	R	O	—	—	—	—	—	—	—	—	—	?
6. Posttest-Only Control Group Design	R	X	O	—	—	—	—	—	—	—	—	—
	R	O	—	—	—	—	—	—	—	—	—	—

Figure 7.3: pre- and true experimental designs (? p.8)

Theorem 7.1 (Theorem Name). *Here is my theorem.*

Proof Name. Here is my proof. □

Theorem 7.2 (Pythagorean theorem). *For a right triangle, if c denotes the length of the hypotenuse and a and b denote the lengths of the other two sides, we have*

$$a^2 + b^2 \stackrel{??}{=} c^2$$

Definition 7.1 (Definition Name). Here is my definition.

number and reference equations

(??)

(???)

??

7.12 slide or presentation

7.12.1 Xaringan and Infinite Moon Reader

<https://rpubs.com/RW1304/xarigan-zh>

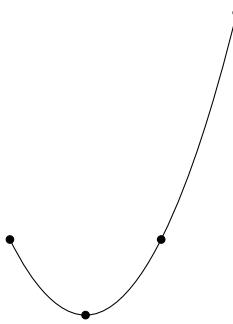


Figure 7.4: parabola arc with points

<https://slides.yihui.org/xaringan/#1>

<https://slides.yihui.org/xaringan/zh-CN.html#1>

<https://github.com/yihui/xaringan/tree/master>

<https://bookdown.org/yihui/rmarkdown/xaringan.html>

7.12.2 ioslides

<https://www.youtube.com/watch?v=gkyjTcpcITM>

<https://bookdown.org/yihui/rmarkdown/ioslides-presentation.html>

<https://stackoverflow.com/questions/63749683/how-to-set-up-theorem-environment-in-the-rmarkdown-presentation>

```
---
title: "Theorem demo"
output:
  ioslides_presentation:
    css: style.css
---
```

```
/* theorem environment _ plain */

/*
.theorem {
  display: block;
  font-style: italic;
  font-size: 24px;
  font-family: "Times New Roman";
  color: black;
}
.theorem::before {
  content: "Theorem. ";
  font-weight: bold;
  font-style: normal;
```

```
}

.theorem[text]::before {
  content: "Theorem (" attr(text) ") ";
}

.theorem p {
  display: inline;
}

/*
```

/ theorem environment _ Copenhagen style */*

```
/*
.theorem {
  display: block;
  font-style: italic;
  font-size: 24px;
  font-family: "Times New Roman";
  color: black;
  border-radius: 10px;
  background-color: rgb(222,222,231);
  box-shadow: 5px 10px 8px #888888;
}

.theorem::before {
  content: "Theorem. ";
  font-weight: bold;
  font-style: normal;
  display: inline-block;
  width: -webkit-fill-available;
  color: white;
  border-radius: 10px 10px 0 0;
  padding: 10px 5px 5px 15px;
  background-color: rgb(38, 38, 134);
}

.theorem p {
  padding: 15px 15px 15px 15px;
}
*/
```

7.12.3 PowerPoint

<https://bookdown.org/yihui/rmarkdown/powerpoint-presentation.html>

Chapter 8

test2

8.1 verbatim

<https://community.rstudio.com/t/continued-issues-with-new-verbatim-in-rstudio/139737>

<https://bookdown.org/yihui/rmarkdown-cookbook/verbatim-code-chunks.html>

```
```r  
1 + 1
...

...
[1] 2
...``
```

We can output arbitrary content **\*\*verbatim\*\***.

```
```r  
1 + 1  
...  
  
...  
## [1] 2  
...``
```

The content can contain inline code like
78.5398163, too.

Chapter 9

partition

$$\begin{aligned} \{A_i\}_{i \in I} = \{A_i | i \in I\} \text{ is a partition of a set } A \\ \Leftrightarrow \begin{cases} \forall i \in I (A_i \neq \emptyset) \\ A = \bigcup_{i \in I} A_i \\ \forall i, j \in I (i \neq j \Rightarrow A_i \cap A_j = \emptyset) \end{cases} \end{aligned}$$

https://proofwiki.org/wiki/Definition:Set_Partition

Chapter 10

equivalence class

C is an equivalence class of a on A

$$\Leftrightarrow [a]_{\sim} = C = \left\{ x \left| \begin{array}{l} a \in A \\ x \in A \\ x \sim a \\ \sim \text{ is an equivalence relation over } A \times A = A^2 \end{array} \right. \right\} \subseteq A \neq \emptyset$$
$$\Leftrightarrow [a] = [a]_{\sim} = \left\{ x \left| \begin{array}{l} a \in A \\ x \in A \\ x \sim a \\ \sim \text{ is an equivalence relation on } A \end{array} \right. \right\} \subseteq A \neq \emptyset$$
$$\Rightarrow [a]_{\sim} = \{x | x \sim a\} \subseteq A \neq \emptyset$$

where the definition of equivalence relation can be found in ??.

Chapter 11

equivalence relation

equivalence relation

R is an equivalence relation over $A \times B$

$$\Leftrightarrow \begin{cases} R = \{ \langle x, y \rangle | x \sim y \} \subseteq A \times B & (\text{e}) \text{ equivalence} \\ \vdots & \end{cases}$$

$$\Leftrightarrow \begin{cases} R = \{ \langle x, y \rangle | xRy \} \subseteq A \times B & (\text{R}) \text{ relation} \\ \forall \langle x, y \rangle \in R (xRx) & (\text{r}) \text{ reflexive} \\ \forall \langle x, y \rangle \in R (xRy \Rightarrow yRx) & (\text{s}) \text{ symmetric} \\ \forall \langle x, y \rangle, \langle y, z \rangle \in R \left(\begin{cases} xRy \\ yRz \end{cases} \Rightarrow xRz \right) & (\text{t}) \text{ transitive} \end{cases} \Leftrightarrow \begin{cases} R = \{ \langle x, y \rangle | xRy \} \subseteq A \times B \\ \forall \langle x, y \rangle \in R (\langle x, x \rangle \in R) \\ \forall \langle x, y \rangle \in R (\langle y, x \rangle \in R) \\ \forall \langle x, y \rangle, \langle y, z \rangle \in R (\langle x, z \rangle \in R) \end{cases}$$

Chapter 12

Python

12.1 using Python in R / RMarkdown

<https://bookdown.org/yihui/rmarkdown/language-engines.html>

```
names(knitr::knit_engines$get())
```

```
## [1] "awk"        "bash"       "coffee"      "gawk"       "groovy"
## [6] "haskell"    "lein"       "mysql"      "node"       "octave"
## [11] "perl"       "php"        "pgsql"      "Rscript"    "ruby"
## [16] "sas"        "scala"      "sed"        "sh"         "stata"
## [21] "zsh"        "asis"       "asy"        "block"      "block2"
## [26] "bslib"      "c"          "cat"        "cc"         "comment"
## [31] "css"        "ditaa"      "dot"        "embed"     "eviews"
## [36] "exec"       "fortran"    "fortran95"  "go"         "highlight"
## [41] "js"          "julia"      "python"     "R"          "Rcpp"
## [46] "sass"       "scss"       "sql"        "stan"      "targets"
## [51] "tikz"       "verbatim"   "theorem"    "lemma"     "corollary"
## [56] "proposition" "conjecture" "definition" "example"   "exercise"
## [61] "hypothesis"  "proof"      "remark"     "solution"
```

https://rstudio.github.io/reticulate/articles/python_packages.html

```
x = 'hello, python world!'
print(x.split(' '))
```

```
## ['hello,', 'python', 'world!']
```

```
library(reticulate)
virtualenv_python()
```

```
library(reticulate)
# conda_list()
```

```
library(reticulate)
virtualenv_list()
```

https://rstudio.github.io/reticulate/reference/install_python.html

```
library(reticulate)
version <- "3.9.12"
# install_python(version)

## create a new environment
# virtualenv_create("r-reticulate", version = version)

# use_virtualenv("r-reticulate")

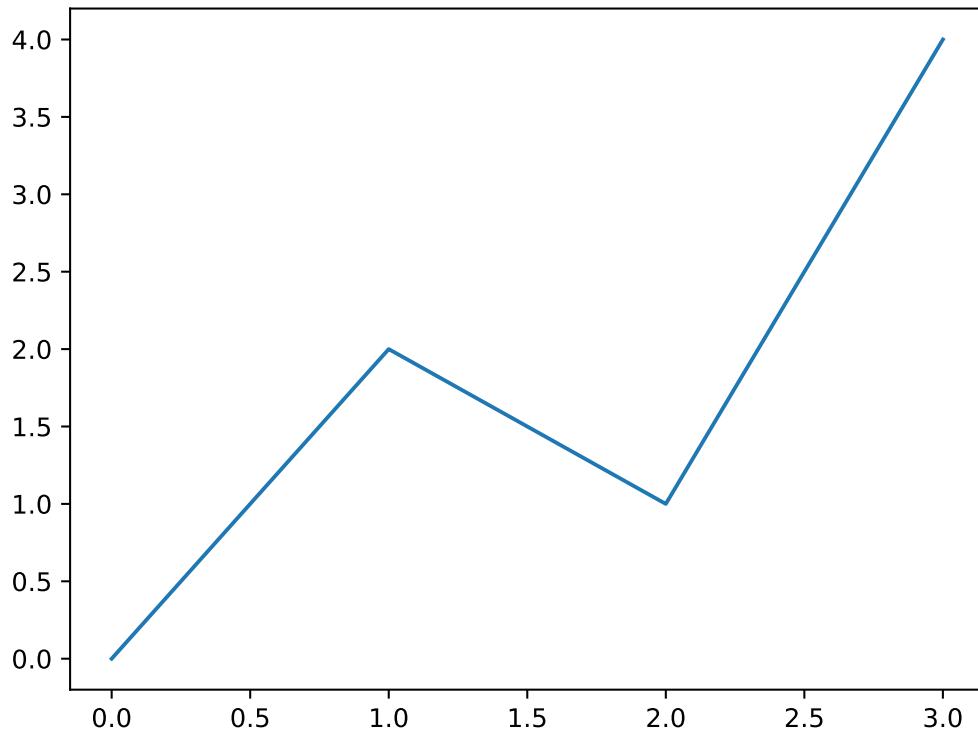
## install Matplotlib
# virtualenv_install("r-reticulate", "matplotlib")

## import Matplotlib (it will be automatically discovered in "r-reticulate")
matplotlib <- import("matplotlib")
```

copy C:\Users\RW\AppData\Local\r-reticulate\r-reticulate\pyenv\pyenv-win\versions\3.9.12\tcl
and C:\Users\RW\AppData\Local\r-reticulate\r-reticulate\pyenv\pyenv-win\versions\3.9.12\tcl
two folders to the folder C:\Users\RW\AppData\Local\r-reticulate\r-reticulate\pyenv\pyenv-win\ver

```
# library(reticulate)
# use_virtualenv("r-reticulate")
# # matplotlib <- import("matplotlib")
# matplotlib$use("Agg", force = TRUE)
```

```
import matplotlib.pyplot as plt
plt.plot([0, 2, 1, 4])
plt.show()
```



12.2 SoloLearn

<https://www.sololearn.com/>

<https://www.sololearn.com/en/learn/courses/python-intermediate>

12.3 list comprehension

<https://www.sololearn.com/en/learn/courses/python-intermediate/lesson/1188906590?p=1>

```
cubes = [i**3 for i in range(5)]  
print(cubes) ## [0, 1, 8, 27, 64]
```

12.4 functional programming

- pure function
- lambda
- map

- filter
- generator
- decorator
- recursion
- *args
- **kwargs

12.5 object-oriented programming = OOP

- class
- inheritance
- magic method
- operator overloading
- data hiding
- static method
- property

Chapter 13

TikZ

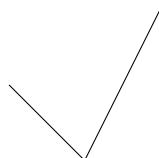
- *TikZ*
 - PGFplots^[??]
 - tikzplotlib^[??]: Python^[??] matplotlib^[??] export to TikZ^[??] .tex

multi-column ??

```
knitr::opts_chunk$set(fig.pos = "H", out.extra = "")
```

<https://bookdown.org/yihui/rmarkdown-cookbook/html-scroll.html>

```
\begin{tikzpicture}
\draw (-1,1)--(0,0)--(1,2);
\end{tikzpicture}
```



How to speed up bookdown generation?

<https://stackoverflow.com/questions/56541371/how-to-speed-up-bookdown-generation>

TikZ and PGFplots

What's the relation between packages PGFplots and TikZ?

<https://tex.stackexchange.com/questions/285925/whats-the-relation-between-packages-pgfplots-and-tikz>

<https://www.youtube.com/watch?v=bQugbYq0BVA>

<https://www.youtube.com/watch?v=ft4Kg9emK1k&list=PLg5nrpKdkk2DWcg3scb75AknF7DJXs8lk&index=18>

```
\begin{tikzpicture}
\def\aa{1.5} % amplitude
\def\bb{2}    % frequency
\draw[->] (-0.2,0)--(4.2,0)
    node[right, font=\small] {$x$};
\draw[->] (0,-4)--(0,0.5)
    node[above] {$y$};
\draw[domain=0:4,smooth,variable=\t,blue,thick]
plot ({\aa * (\bb*\t -
sin(deg(\bb*\t)))},{-\aa * (1 -
cos(deg(\bb*\t)))});
% \node[above] at (2, 0.5)
% {Brachistochrone Curve};
\node[above, font=\footnotesize] at
(2, 1) {Brachistochrone Curve};
\node[above, font=\footnotesize] at
(2, 0) {$\begin{aligned} &x=r(t-\sin t) \\ &y=r(1-\cos t) \end{aligned}$};
\end{tikzpicture}
```

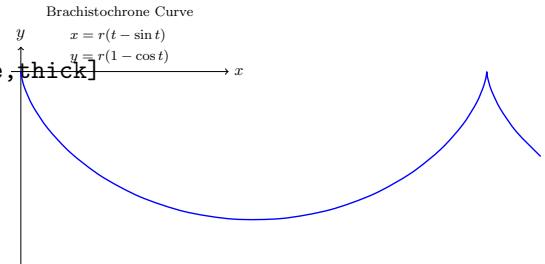


Figure 13.1: Brachistochrone Curve

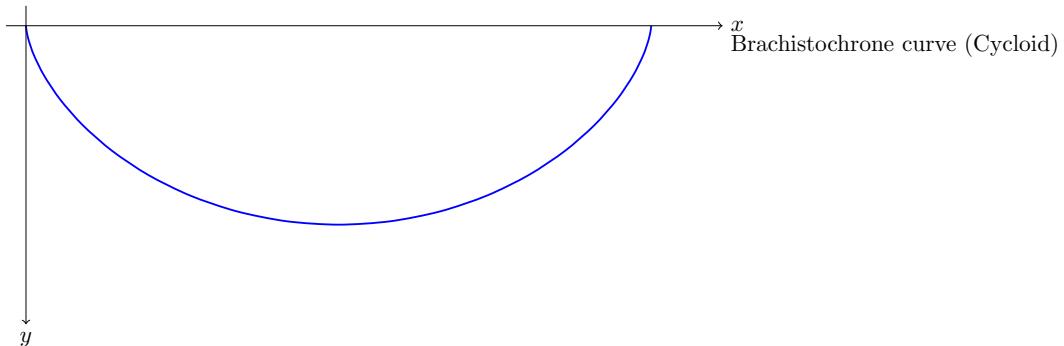


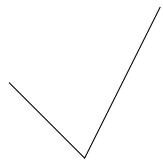
Figure 13.2: Brachistochrone Curve

13.1 2D

https://zhuanlan.zhihu.com/p/127155579?utm_psn=1741479950987960320

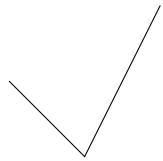
```
\begin{tikzpicture}
\draw (-1,1)--(0,0)--(1,2);
\end{tikzpicture}
```

```
\begin{tikzpicture}
  \draw (-1,1)--(0,0)--(1,2);
\end{tikzpicture}
```



```
out.width=if (knitr:::is_html_output())
'20%'
```

```
\begin{tikzpicture}
  \draw (-1,1)--(0,0)--(1,2);
\end{tikzpicture}
```



```
\begin{tikzpicture}
  \draw[rounded corners]
    (-1,1)--(0,0)--(1,2)--(-1,1);
\end{tikzpicture}
```

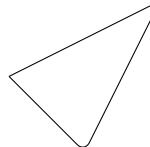


Figure 13.3: rounded corner pseudo-closed triangle

```
\begin{tikzpicture}
  \draw[rounded corners]
    (-1,1)--(0,0)--(1,2)--cycle;
\end{tikzpicture}
```

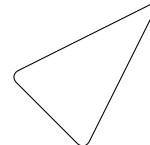


Figure 13.4: rounded corner triangle

```
\begin{tikzpicture}
  \draw[rounded corners]
    (-1,1)--(0,0)--(1,2)--cycle;
  \draw[rounded corners]
    (-1,1)--(0,0)--(1,2)--(-1,1);
\end{tikzpicture}
```

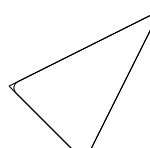


Figure 13.5: triangle vs. pseudo-closed triangle

```
\begin{tikzpicture}
  \draw (0,0) rectangle (4,2);
\end{tikzpicture}
```



Figure 13.6: rectangle

```
\begin{tikzpicture}
  \draw (0,0) rectangle (2,2);
\end{tikzpicture}
```



Figure 13.7: square

```
\begin{tikzpicture}
  \draw (0,0) circle (1);
\end{tikzpicture}
```

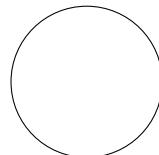


Figure 13.8: circle

```
\begin{tikzpicture}
  \draw (0,0) circle (1);
  \draw (0,0) rectangle (2,2);
\end{tikzpicture}
```

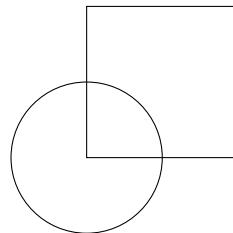


Figure 13.9: circle and square

```
\begin{tikzpicture}
  \draw (1,1) ellipse (2 and 1);
\end{tikzpicture}
```

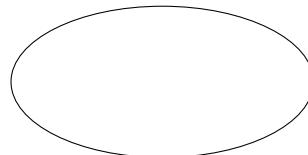


Figure 13.10: ellipse

```
\begin{tikzpicture}
  \draw (1 ,1) arc (0:270:1);
  \draw (6 ,1) arc (0:270:2 and 1);
\end{tikzpicture}
```

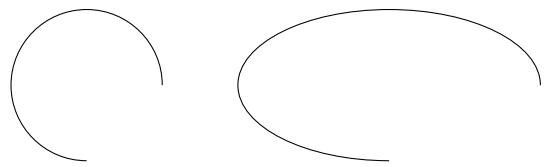


Figure 13.11: circle and ellipse arcs

```
\begin{tikzpicture}
  \draw (-1,1) parabola bend (0,0)
    .. (2,4);
\end{tikzpicture}
```

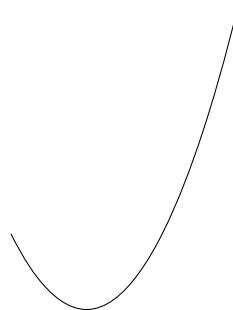


Figure 13.12: parabola arc

```
\begin{tikzpicture}
  \draw (-1,1) parabola bend (0,0)
    .. (2,4);
  \filldraw
    (-1,1) circle (.05)
    ( 0,0) circle (.05)
    ( 1,1) circle (.05)
    ( 2,4) circle (.05);
\end{tikzpicture}
```

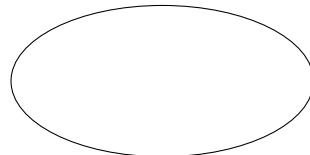


Figure 13.13: parabola arc with points

```
\begin{tikzpicture}
  \draw[step=20pt] (0,0) grid (3,2);
  \draw[help lines ,step=20pt] (4,0)
    .. grid (7,2);
\end{tikzpicture}
```

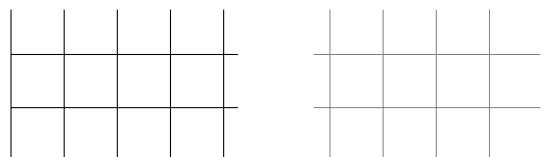


Figure 13.14: grid and help lines

```
\begin{tikzpicture}[scale=0.25]
  \draw[->] (0,0)--(9,0);
  \draw[<-] (0,1)--(9,1);
  \draw[<->] (0,2)--(9,2);
  \draw[>->>] (0,3)--(9,3);
  \draw[|<->|] (0,4)--(9,4);
\end{tikzpicture}
```

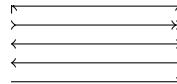


Figure 13.15: arrows

```
\begin{tikzpicture}
  \draw[line width =2pt] (0,6)--(9,6);
  \draw[dotted] (0,5)--(9,5);
  \draw[densely dotted] (0,4)--(9,4);
  \draw[loosely dotted] (0,3)--(9,3);
  \draw[dashed] (0,2)--(9,2);
  \draw[densely dashed] (0,1)--(9,1);
  \draw[loosely dashed] (0,0)--(9,0);
\end{tikzpicture}
```

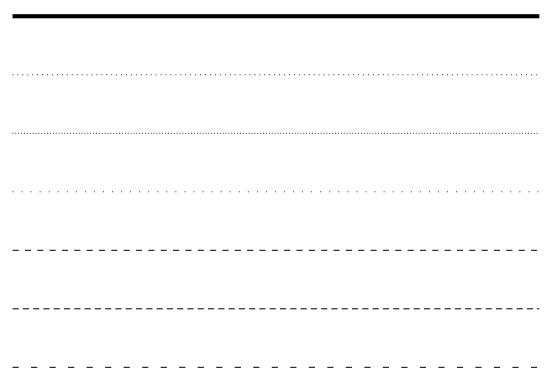


Figure 13.16: lines

```
\begin{tikzpicture}[dline/.style={color=blue, line width=2pt}]
  \draw[dline] (0,0)--(9,0);
\end{tikzpicture}
```



Figure 13.17: head styling

```
\begin{tikzpicture}
  \draw (0,0) rectangle (2,2);
  \draw[shift={( 3, 0)}] (0,0)
    -- rectangle (2,2);
  \draw[shift={( 0, 3)}] (0,0)
    -- rectangle (2,2);
  \draw[shift={( 0,-3)}] (0,0)
    -- rectangle (2,2);
  \draw[shift={(-3, 0)}] (0,0)
    -- rectangle (2,2);
  \draw[shift={( 3, 3)}] (0,0)
    -- rectangle (2,2);
  \draw[shift={(-3, 3)}] (0,0)
    -- rectangle (2,2);
  \draw[shift={( 3,-3)}] (0,0)
    -- rectangle (2,2);
  \draw[shift={(-3,-3)}] (0,0)
    -- rectangle (2,2);
\end{tikzpicture}
```

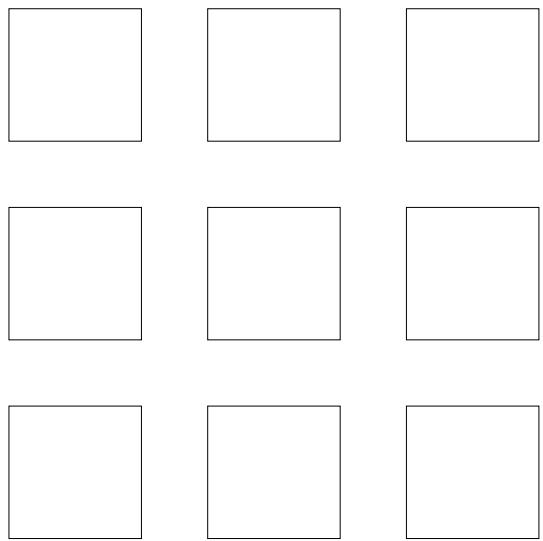


Figure 13.18: transform: shift

```
\begin{tikzpicture}
  \draw (0,0) rectangle (2,2);
  \draw[xshift= 100pt] (0,0) rectangle
    (2,2);
  \draw[xshift=-100pt] (0,0) rectangle
    (2,2);
  \draw[yshift= 100pt] (0,0) rectangle
    (2,2);
  \draw[yshift=-100pt] (0,0) rectangle
    (2,2);
\end{tikzpicture}
```

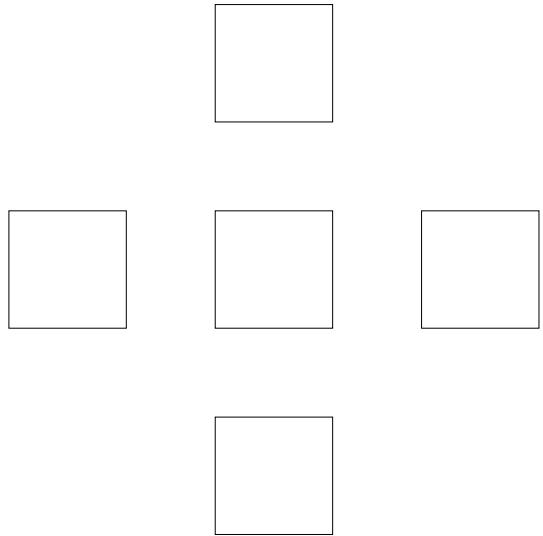


Figure 13.19: transform: shift x, y

```
\begin{tikzpicture}
  \draw (0,0) rectangle (2,2);
  \draw[xshift= 100pt, xscale=1.5]
    (0,0) rectangle (2,2);
  \draw[yshift= 100pt, xscale=0.5]
    (0,0) rectangle (2,2);
  \draw[xshift=-100pt, yscale=1.5]
    (0,0) rectangle (2,2);
  \draw[yshift=-100pt, yscale=0.5]
    (0,0) rectangle (2,2);
\end{tikzpicture}
```

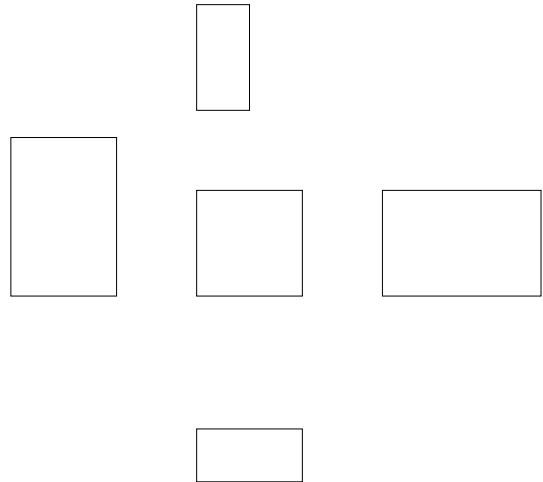


Figure 13.20: transform: scale x, y

```
\begin{tikzpicture}
  \draw (0,0) rectangle (2,2);
  \draw[xshift= 100pt, xscale=1.5]
    (0,0) rectangle (2,2);
  \draw[yshift= 100pt, yscale=1.5]
    (0,0) rectangle (2,2);
  \draw[xshift=-100pt, xscale=0.5]
    (0,0) rectangle (2,2);
  \draw[yshift=-100pt, yscale=0.5]
    (0,0) rectangle (2,2);
\end{tikzpicture}
```

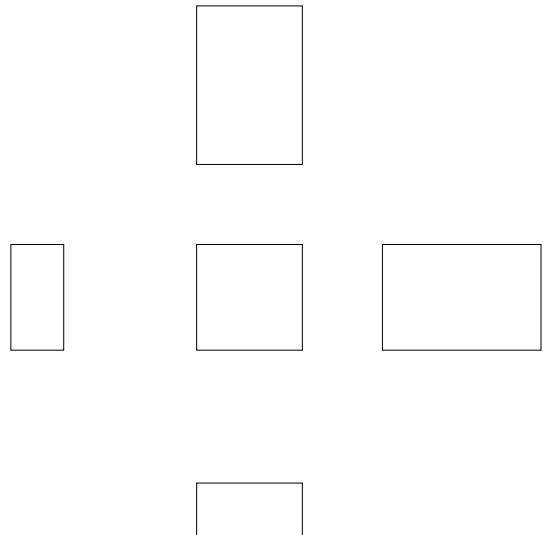


Figure 13.21: transform: scale

```
\begin{tikzpicture}
  \draw (0,0) rectangle (2,2);
  \draw[xshift=125pt,rotate=45] (0,0)
    -- rectangle (2,2);
  \draw[xshift=175pt,rotate
    around={45:(2 ,2)}] (0,0)
    -- rectangle (2,2);
\end{tikzpicture}
```

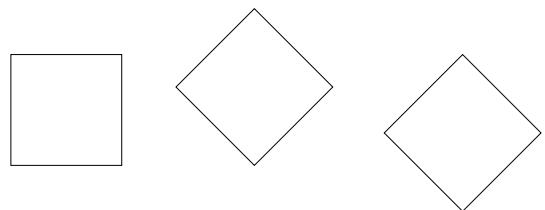


Figure 13.22: transform: rotate

```
\begin{tikzpicture}
  \draw (0,0) rectangle (2,2);
  \draw[xshift=70pt,xslant=1] (0,0)
    -- rectangle (2,2);
  \draw[yshift=70pt,yslant=1] (0,0)
    -- rectangle (2,2);
\end{tikzpicture}
```

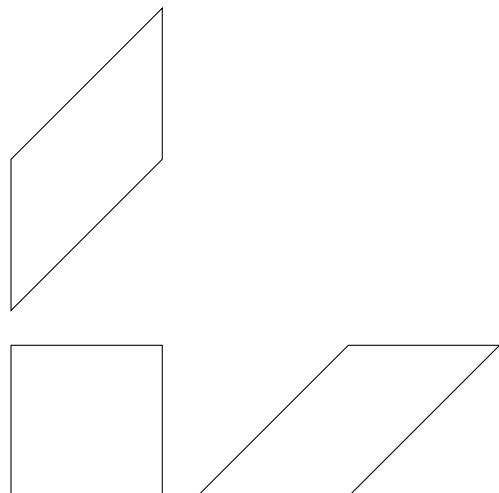


Figure 13.23: transform: slant

```
\tikzset{
  box/.style={
    draw=blue,
    rectangle,
    rounded corners=5pt,
    minimum width=50pt,
    minimum height=20pt,
    inner sep=5pt
  }
\begin{tikzpicture}
  \node[box] (1) at (0,0) {1};
  \node[box] (2) at (4,0) {2};
  \node[box] (3) at (8,0) {3};
  \draw[->] (1)--(2);
  \draw[->] (2)--(3);
  \node at (2,1) {a};
  \node at (6,1) {b};
\end{tikzpicture}
```

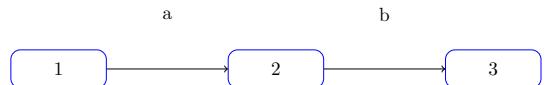


Figure 13.24: flowchart

```
\tikzset{
  box/.style={
    draw=blue,
    fill=blue!20,
    rectangle,
    rounded corners=5pt,
    minimum height=20pt,
    inner sep=5pt
  }
}
\begin{tikzpicture}
\node[box] {1}
  child {node[box] {2}}
  child {node[box] {3}
    child {node[box] {4}}
    child {node[box] {5}}
    child {node[box] {6}}
  };
\end{tikzpicture}
```

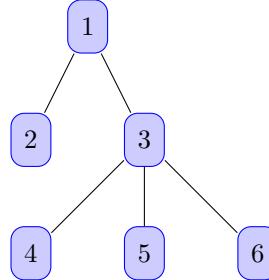


Figure 13.25: tree

```
\begin{tikzpicture}
\draw[->] (-0.2,0)--(6,0)
\draw[->] (0,-0.2)--(0,6)
\draw[domain=0:4] plot (\x ,{0.1*
\exp(\x)}) node[right]
{\color{orange}f(x)=\frac{1}{10}e^x};
\end{tikzpicture}
```

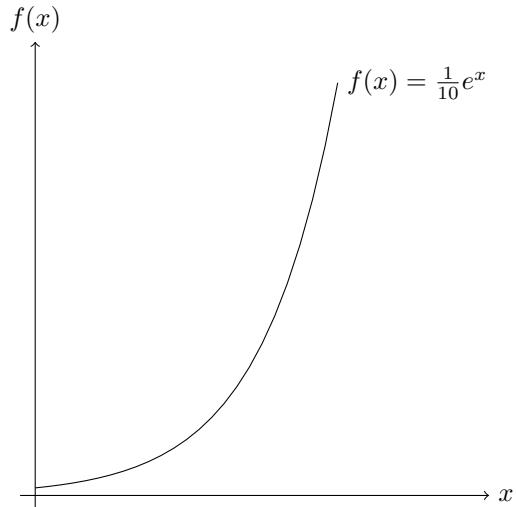


Figure 13.26: function plot

<https://stackoverflow.com/questions/64897575/tikz-libraries-in-bookdown>

It turns out that you can simply put the `\usetikzlibrary{...}` command directly before the `\begin{tikzpicture}` and everything works fine :)

<https://stackoverflow.com/questions/56211210/r-markdown-document-with-html-docx-output-using-latex-package-bbm>

<https://tex.stackexchange.com/questions/171711/how-to-include-latex-package-in-r-markdown>

13.2 3D

https://zhuanlan.zhihu.com/p/431732330?utm_psn=1741857547550638080

<https://github.com/RRWWW/Stereometry>

```
\begin{tikzpicture}
\coordinate (A) at ( 1, 1, 1);
\coordinate (B) at ( 1, 1,-1);
\coordinate (C) at ( 1,-1,-1);
\coordinate (D) at ( 1,-1, 1);
\coordinate (E) at (-1,-1, 1);
\coordinate (F) at (-1,-1,-1);
\coordinate (G) at (-1, 1,-1);
\coordinate (H) at (-1, 1, 1);
\draw (A) node[right=1pt] {$A$}--
      (B) node[right=1pt] {$B$}--
      (C) node[right=1pt] {$C$}--
      (D) node[right=1pt] {$D$}--
      (E) node[left= 1pt] {$E$}--
      (F) node[right=1pt] {$F$}--
      (G) node[right=1pt] {$G$}--
      (H) node[left= 1pt] {$H$}--
      (A) node[right=1pt] {$A$};
\end{tikzpicture}
```

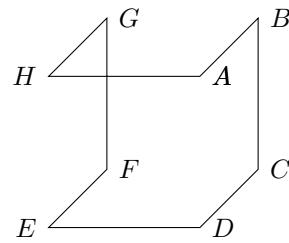


Figure 13.27: cube

```
\usetikzlibrary{patterns}
\usetikzlibrary{3d,calc}
\tdplotsetmaincoords{45}{45}
\begin{tikzpicture}[tdplot_main_coords]
\coordinate (A) at ( 1, 1, 1);
\coordinate (B) at ( 1, 1,-1);
\coordinate (C) at ( 1,-1,-1);
\coordinate (D) at ( 1,-1, 1);
\coordinate (E) at (-1,-1, 1);
\coordinate (F) at (-1,-1,-1);
\coordinate (G) at (-1, 1,-1);
\coordinate (H) at (-1, 1, 1);
\draw (A) node[right=1pt] {$A$}--
      (B) node[right=1pt] {$B$}--
      (C) node[right=1pt] {$C$}--
      (D) node[right=1pt] {$D$}--
      (E) node[left= 1pt] {$E$}--
      (F) node[right=1pt] {$F$}--
      (G) node[right=1pt] {$G$}--
      (H) node[left= 1pt] {$H$}--
      (A) node[right=1pt] {$A$};
\end{tikzpicture}
```

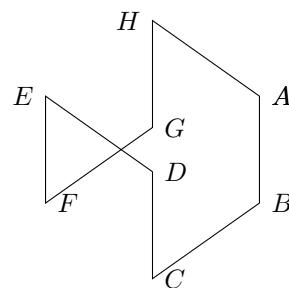


Figure 13.28: cube rotate

```
\usetikzlibrary{patterns}
\usetikzlibrary{3d,calc}
%\tdplotsetmaincoords{70}{110}
\begin{tikzpicture}[rotate around
        y=-15, rotate around z=7]
    \coordinate (A) at ( 1, 1, 1);
    \coordinate (B) at ( 1, 1,-1);
    \coordinate (C) at ( 1,-1,-1);
    \coordinate (D) at ( 1,-1, 1);
    \coordinate (E) at (-1,-1, 1);
    \coordinate (F) at (-1,-1,-1);
    \coordinate (G) at (-1, 1,-1);
    \coordinate (H) at (-1, 1, 1);
    \draw (A) node[right=1pt] {$A$}--
          (B) node[right=1pt] {$B$}--
          (C) node[right=1pt] {$C$}--
          (D) node[right=1pt] {$D$}--
          (E) node[left= 1pt] {$E$}--
          (F) node[right=1pt] {$F$}--
          (G) node[right=1pt] {$G$}--
          (H) node[left= 1pt] {$H$}--
          (A) node[right=1pt] {$A$};
\end{tikzpicture}
```

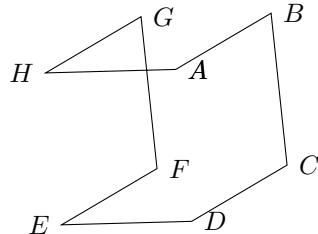


Figure 13.29: cube rotate around

<https://tex.stackexchange.com/questions/388621/optimizing-perspective-tikz-graphic>

```
\usetikzlibrary{patterns}
\usetikzlibrary{3d,calc}
\begin{tikzpicture}[y={(.5cm,.7cm)}]
    \coordinate (A) at ( 1, 1, 1);
    \coordinate (B) at ( 1, 1,-1);
    \coordinate (C) at ( 1,-1,-1);
    \coordinate (D) at ( 1,-1, 1);
    \coordinate (E) at (-1,-1, 1);
    \coordinate (F) at (-1,-1,-1);
    \coordinate (G) at (-1, 1,-1);
    \coordinate (H) at (-1, 1, 1);
    \draw (A) node[right=1pt] {$A$}--
          (B) node[right=1pt] {$B$}--
          (C) node[right=1pt] {$C$}--
          (D) node[right=1pt] {$D$}--
          (E) node[left= 1pt] {$E$}--
          (F) node[right=1pt] {$F$}--
          (G) node[right=1pt] {$G$}--
          (H) node[left= 1pt] {$H$}--
          (A) node[right=1pt] {$A$};
\end{tikzpicture}
```

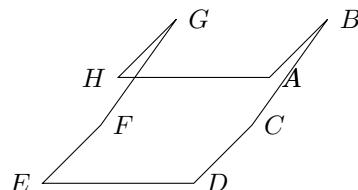


Figure 13.30: cube perspective slant

<https://github.com/XiangyunHuang/bookdown-broken/blob/master/index.Rmd>

```
\smartdiagramset{planet
  ↵   color=gray!40!white,
uniform color list=gray!40!white for
  ↵   10 items}
\smartdiagram[bubble diagram]{Basic
  ↵   skills,
Edit~/\\" (RStudio),
Organize~/\\" (bookdown),
Cooperate~/\\" (Git),
Typeset~/\\" (LaTeX/Pandoc),
Compile~/\\" (GitHub Action)}
```



Figure 13.31: modern statistics plot skills

13.3 plots of functions

<https://tikz.dev/tikz-plots>

A warning before we get started: If you are looking for an easy way to create a normal plot of a function with scientific axes, ignore this section and instead look at the `pgfplots` package or at the `datavisualization` command from Part VI.

<https://tikz.dev/tikz-plots#sec-22.5>

```
\begin{tikzpicture}[domain=0:4]
\draw[very thin,color=gray]
(-0.1,-1.1) grid (3.9,3.9);

\draw[->] (-0.2,0) -- (4.2,0)
node[right] {$x$};
\draw[->] (0,-1.2) -- (0,4.2)
node[above] {$f(x)$};

\draw[color=red] plot (\x,\x)
node[right] {$f(x) = x$};
% \x r means to convert '\x' from
% degrees to _radians:
\draw[color=blue] plot (\x,{sin(\x
r)}) node[right] {$f(x) =
\sin x$};
\draw[color=orange] plot
(\x,{0.05*exp(\x)}) node[right]
{$f(x) = \frac{1}{20} e^x$};
\end{tikzpicture}
```

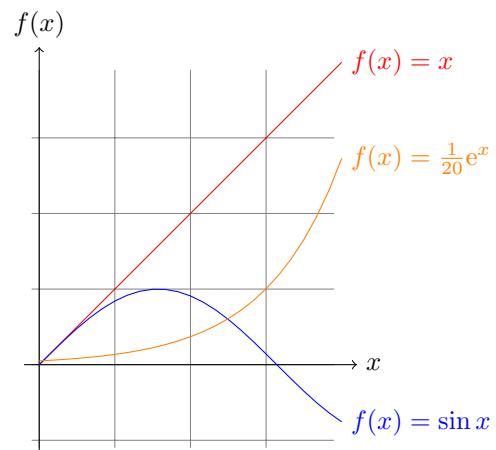


Figure 13.32: plots of functions

```
\tikz
\draw[scale=0.5,domain=-3.141:3.141,smooth,variable=\t]
plot ({\t*sin(\t r)},{\t*cos(\t
r)});
```

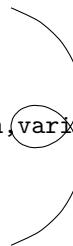


Figure 13.33: 2D parametric function

```
\tikz \draw[domain=0:360,
smooth,
variable=\t]
plot ({sin(\t)},{\t/360},{cos(\t)});
```



Figure 13.34: 3D parametric function

13.4 PGFplots

axis similar to matplotlib figure anatomy, see Fig: ??

<https://tikz.dev/pgfplots/>

<https://tikz.dev/pgfplots/tutorial1>

Not so common is `\pgfplotsset{compat=1.5}`. A statement like this should always be used in order to (a) benefit from a more or less recent feature set and (b) avoid changes to your picture if you recompile it with a later version of pgfplots.

```
\pgfplotsset{width=7cm,compat=1.18}
\begin{tikzpicture}
\begin{axis}[
]
    % density of Normal distribution:
    \addplot [
        red,
        domain=-3e-3:3e-3,
        samples=201,
    ]
        {exp(-x^2 / (2e-3^2)) / (1e-3
        * sqrt(2*pi))};
\end{axis}
\end{tikzpicture}
```

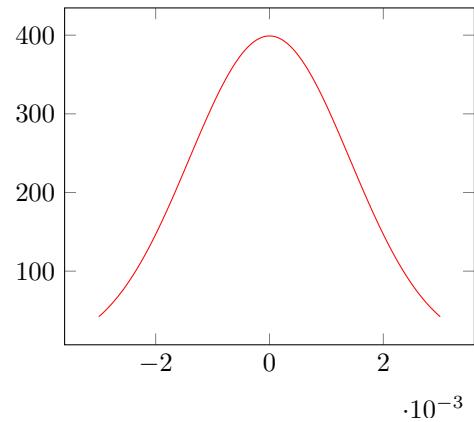


Figure 13.35: PGFplots: normal distribution

13.4.1 the axis environments

<https://tikz.dev/pgfplots/reference-axis>

```
\pgfplotsset{every linear axis/.append style={...}}
```

```
\begin{tikzpicture}
  \begin{axis}[
    no markers,
    axis x line = center,
    axis y line = center,
    xlabel = {$x$}, xlabel style
    ← = {right},
    ylabel = {$y$}, ylabel style
    ← = {above},
    xmin = -8, xmax = 8,
    ymin = 0, ymax = 0.45,
    hide obscured x ticks=false, %
    ← for origin x tick label i.e. xtick
    ← = {0}
    xtick={-4, 0, 4},
    xticklabels={$
    ← \mu_{\scriptscriptstyle 1} $,
    $ \mu_0 $,
    $ \mu_1 $,
    ← \mu_{\scriptscriptstyle 0} $,
    ← \mu_{\scriptscriptstyle 1} $,
    ← \mu_{\scriptscriptstyle 0} $,
    %extra x ticks={0},
    ytick = \emptyset,
    x = 1cm, y = 5cm, % x y
    ← scaling
    %grid = major,
    domain = -10:10,
    samples = 1000
  ]
  \end{axis}
\end{tikzpicture}
```

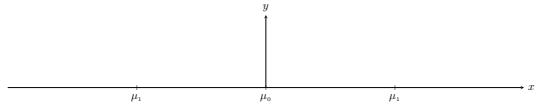


Figure 13.36: beginaxis

<https://tex.stackexchange.com/questions/134959/axis-lines-middle-and-axis-lines-center>

No, there is no difference.

13.4.2 axis descriptions

<https://tikz.dev/pgfplots/reference-axisdescription>

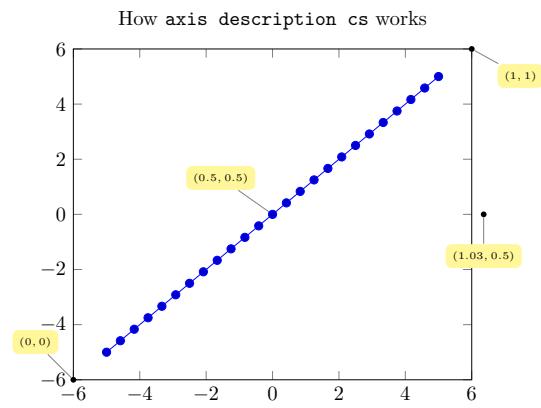
13.4.2.1 placement of axis descriptions

13.4.2.1.1 coordinate system axis description cs https://tikz.dev/pgfplots/reference-axisdescription#pgfp.axis_description_cs

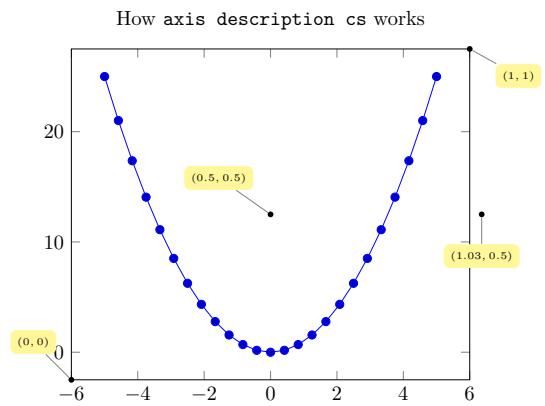
\addplot {x}; can change to \addplot {x^2}; still with auto blue dots

small dot style,pin=angle:LaTeX label at PGFplots axis coordinate system ;

```
\begin{tikzpicture}
  \tikzset{
    every
    ↳ pin/.style={fill=yellow!50!white,rectangle,rounded
    ↳ corners=3pt,font=\tiny},
    ↳ small
    ↳ dot/.style={fill=black,circle,scale=0.3},
  }
  \begin{axis}[
    clip=false,
    title=How \texttt{axis
description cs} works,
]
  \addplot {x};
  %small dot
  ↳ style,pin=angle:LaTeX
  ↳ label at PGFplots axis
  ↳ coordinate system ;
  \node [small
  ↳ dot,pin=120:{\$(0,0\$)}
  ↳ at (axis description
  ↳ cs:0,0)      {};
  \node [small
  ↳ dot,pin=-30:{\$(1,1\$)}
  ↳ at (axis description
  ↳ cs:1,1)      {};
  \node [small
  ↳ dot,pin=-90:{\$(1.03,0.5\$)}
  ↳ at (axis description
  ↳ cs:1.03,0.5) {};
  \node [small
  ↳ dot,pin=125:{\$(0.5,0.5\$)}
  ↳ at (axis description
  ↳ cs:0.5,0.5) {};
  \end{axis}
\end{tikzpicture}
```

Figure 13.37: PGFplots: x

```
\begin{tikzpicture}
  \tikzset{
    every
    pin/.style={fill=yellow!50!white,rectangle,rounded
    corners=3pt,font=\tiny},
    small
    dot/.style={fill=black,circle,scale=0.3},
  }
  \begin{axis}[
    clip=false,
    title=How \texttt{axis
description cs} works,
]
  \addplot {x^2};
%small dot
  \style, pin=angle:LaTeX
  \label at PGFplots axis
  coordinate system ;
  \node [small
  dot,pin=120:{\$(0,0)\$}]
  at (axis description
  cs:0,0) {};
  \node [small
  dot,pin=-30:{\$(1,1)\$}]
  at (axis description
  cs:1,1) {};
  \node [small
  dot,pin=-90:{\$(1.03,0.5)\$}]
  at (axis description
  cs:1.03,0.5) {};
  \node [small
  dot,pin=125:{\$(0.5,0.5)\$}]
  at (axis description
  cs:0.5,0.5) {};
  \end{axis}
\end{tikzpicture}
```

Figure 13.38: PGFplots: x^2

13.4.2.1.2 legend <https://tikz.dev/pgfplots/reference-axisdescription#sec-4.9.4>

13.4.2.1.3 tick option <https://tikz.dev/pgfplots/reference-tickoptions>

13.4.3 declare function

https://tikz.dev/pgfplots/utility-commands#pgf/declare_function

```
\begin{tikzpicture}
\begin{axis}[
    declare function={
        C=4;
        square(\t)=(\t)^2 + C;
    },
]
\addplot+ [samples=2] {C*x};
\addplot {square(x)};
\end{axis}
\end{tikzpicture}
```

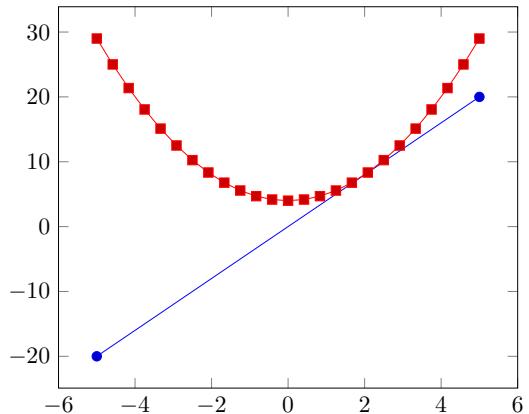


Figure 13.39: declare function

13.4.3.1 pgfmathparse

<https://tikz.dev/math-parsing>

<https://tikz.dev/math-parsing#sec-94.1>

This macro parses and returns the result without units in the macro 0.017. Example: `\pgfmathparse{2pt+3.5pt}` will set `\pgfmathresult` to the text 5.5.

```
\pgfmathsqrt{x} = \pgfmathparse{sqrt(x)}
```

```
\pgfmathln{x} = \pgfmathparse{ln(x)}
```

...

13.4.3.2 pgfmathdeclarefunction

like `pgfplotsinvokeforeach`

replaces any occurrence of #1 inside of (math image)command(math image) once for every element in (math image)list(math image). Thus, it actually assumes that (math image)command(math image) is like a `\newcommand` body.

```
% pgfmathdeclarefunction{name}{num_var}{%
%% #1 = \mu, #2 = \sigma
\pgfmathdeclarefunction{gauss}{2}{%
  \pgfmathparse{1/(#2*sqrt(2*pi))*exp(-((x-#1)^2)/(2*#2^2))}%
}
```

```
% pgfmathdeclarefunction{name}{num_var}{%
%% #1 = \mu, #2 = \sigma
\pgfmathdeclarefunction{gauss}{2}{%
  \pgfmathparse{1/(#2*sqrt(2*pi))*exp(-((x-#1)^2)/(2*#2^2))}%
}
```

```

}

\begin{tikzpicture}
\begin{axis}[
    no markers,
    axis x line = center,
    axis y line = center,
    xlabel = {$x$}, xlabel style = {right},
    ylabel = {$y$}, ylabel style = {above},
    xmin = -8, xmax = 8,
    ymin = 0, ymax = 0.45,
    hide obscured x ticks=false, % for origin x tick label i.e. xtick = {0}
    xtick={-4, 0, 4},
    xticklabels={\$ \mu_{\scriptscriptstyle 1} \$,
                 \$ \mu_{\scriptscriptstyle 0} \$,
                 \$ \mu_{\scriptscriptstyle 1} \$},
    %extra x ticks={0},
    ytick = \emptyset,
    x = 1cm, y = 5cm, % x y scaling
    %grid = major,
    domain = -10:10,
    samples = 1000
]
\addplot [fill=cyan!20, draw=none, domain=-10:-2] {gauss(-4, 1)}
    \closedcycle;
\addplot [fill=cyan!20, draw=none, domain= 2:10] {gauss( 4, 1)}
    \closedcycle;
\addplot [very thick, cyan!50!black] {gauss(-4, 1)};
\addplot [very thick, cyan!50!black] {gauss( 0, 1)};
\addplot [very thick, cyan!50!black] {gauss( 4, 1)};
% \node [anchor=north] at (axis cs: 0, -0.01) {\$ \mu \$};
% \node at (axis cs: -4, -0.02) {\$ \mu \$};
\draw [dashed, thin] (axis cs: -4, 0) -- (axis cs: -4, 1);
\draw [dashed, thin] (axis cs: 4, 0) -- (axis cs: 4, 1);
\end{axis}
\end{tikzpicture}

```

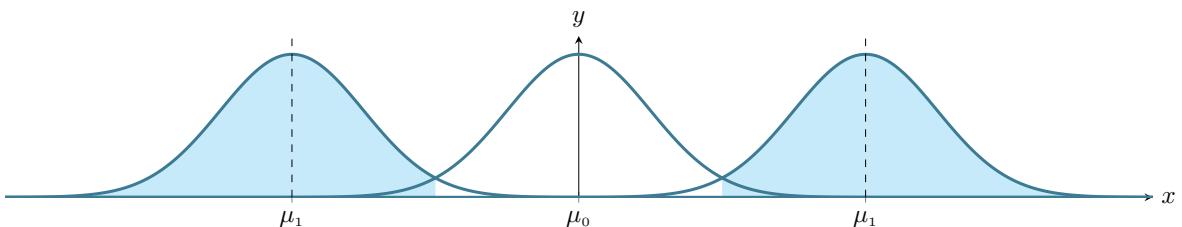


Figure 13.40: PGFmathDeclareFunction: normal distributions hypothesis testing

```
% pgfmathdeclarefunction{name}{num_var}{%
%% #1 = \mu, #2 = \sigma
\pgfmathdeclarefunction{gauss}{2}{%
  \pgfmathparse{1/(\#2*sqrt(2*pi))*exp(-((x-\#1)^2)/(2*\#2^2))}%
}

\begin{tikzpicture}
\begin{axis}[
  no markers, domain=0:10, samples=100,
  axis lines*=left, xlabel=$x$, ylabel=$y$,
  every axis y label/.style={at=(current axis.above origin), anchor=south},
  every axis x label/.style={at=(current axis.right of origin), anchor=west},
  height=5cm, width=12cm,
  xtick={4,6.5}, ytick=\emptyset,
  enlargelimits=false, clip=false, axis on top,
  grid = major
]
\addplot [fill=cyan!20, draw=none, domain=0:5.96] {gauss(6.5,1)} \closedcycle;
\addplot [very thick,cyan!50!black] {gauss(4,1)};
\addplot [very thick,cyan!50!black] {gauss(6.5,1)};
\draw [yshift=-0.6cm, latex-latex] (axis cs:4,0) -- node [fill=white]
  {$1.96\sigma$} (axis cs:5.96,0);
\end{axis}
\end{tikzpicture}
```

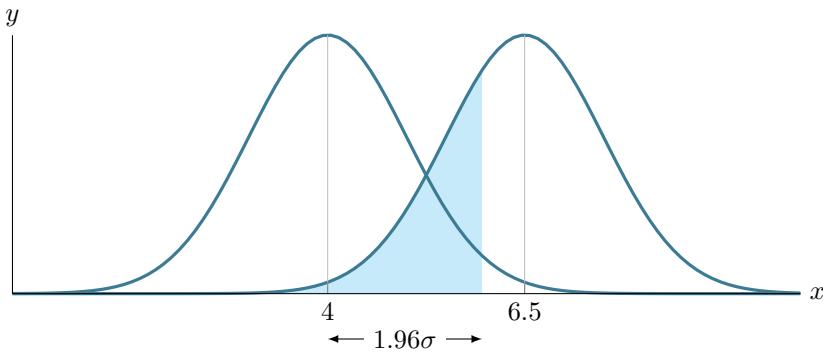


Figure 13.41: PGFmathDeclareFunction: normal distributions

13.4.4 |- and -| in TikZ

<https://tex.stackexchange.com/questions/401425/tikz-what-exactly-does-the-the-notation-for-arrows-do>

(a -| b) where a and b are named nodes or coordinates. This means the coordinate that is at the y-coordinate of a, and x-coordinate of b. Similarly, (a |- b) has the x-coordinate of a and y-coordinate of b.

13.4.5 pgfplotsinvokeforeach

<https://tikz.dev/pgfplots/pgfplotstable-miscellaneous#/pgfplotsinvokeforeach>

like \foreach in TikZ

A variant of \pgfplotsforeachungrouped (and such also of \foreach) which replaces any occurrence of #1 inside of (math image)command(math image) once for every element in (math image)list(math image). Thus, it actually assumes that (math image)command(math image) is like a \newcommand body.

13.4.6 interpolation dashed lines

<https://tex.stackexchange.com/questions/193259/what-is-the-easiest-way-to-accomplish-textual-tick-labels-in-tikz>

```
interpa = (10,10), interpib = (30,30), interp = interpolation
({axis cs:0,0}|-interp#1) = (x of (0,0), y of (interpa)) = (0, 10), ...
```

```
\begin{tikzpicture}
\begin{axis}[
    axis lines=left,
    xmin = 0, xmax = 40,
    ymin = 0, ymax = 40,
    xtick={10,30},
    xticklabels={\$V_i=10\$,\$V_f=30\$},
    ytick={10,30},
    yticklabels={\$P_i=10\$,\$P_f=30\$},
    xlabel={Volume},
    ylabel={Pressure}
]
\addplot[very thick,-latex ]
    coordinates{(10,10) (30,30)}
% interpa = (10,10), interp =
%   (30,30), interp =
%   interpolation
    coordinate[at
    start](interpa)coordinate[at
    end](interpib);
\pgfplotsinvokeforeach {a,b} {
    \draw[ultra thin, dashed]
        % ({axis cs:0,0}|-interp#1) = (x
        %   of (0,0), y of (interpa)) =
        %   (0, 10), ...
        % {axis
        cs:0,0}|-interp#1)--(interp#1)--(interp#1|-{axis
        cs:0,0});
}
\end{axis}
\end{tikzpicture}
```

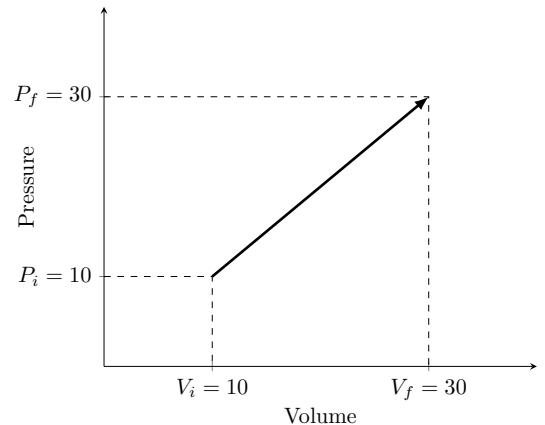


Figure 13.42: tick texts and interpolation dashed lines

13.4.7 Zewbie

<https://zhuanlan.zhihu.com/p/551874337>

axis similar to matplotlib figure anatomy, see Fig: ??

13.4.7.1 coordinate axis/axes fine-tuing

```
\begin{tikzpicture}
  \begin{axis}
    % empty
  \end{axis}
\end{tikzpicture}
```

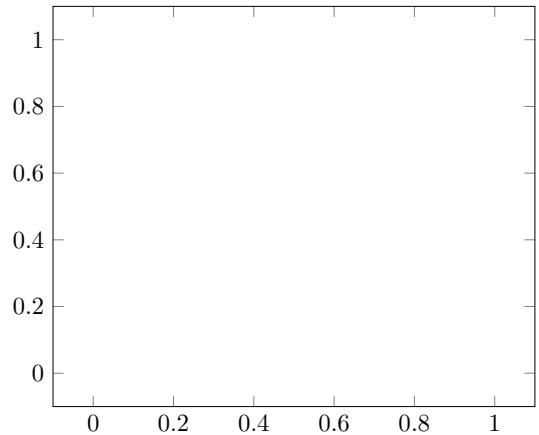


Figure 13.43: PGFplots: 2D axis/axes

13.4.7.1.1 range

```
\begin{tikzpicture}
  \begin{axis}[
    xmin = -1, xmax = 11,
    ymin = -3, ymax = 1,
  ]
    % empty
  \end{axis}
\end{tikzpicture}
```

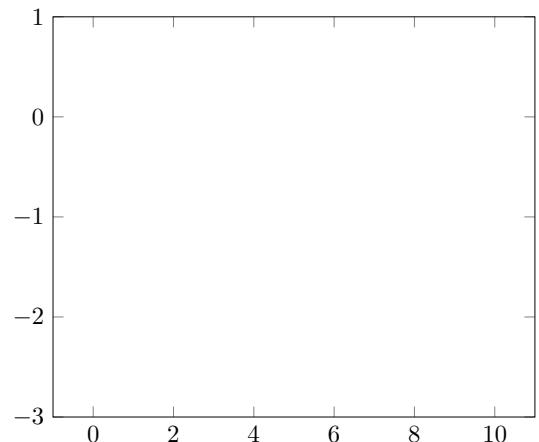


Figure 13.44: PGFplots: axis/axes range

13.4.7.1.2 scaling axis equal image equivalent to unit vector ratio = {1 1 1}

```
\begin{tikzpicture}
\begin{axis}[
    xmin = -1, xmax = 11,
    ymin = -3, ymax = 1,
    axis equal image, % unit
    vector ratio = {1 1 1},
]
% empty
\end{axis}
\end{tikzpicture}
```

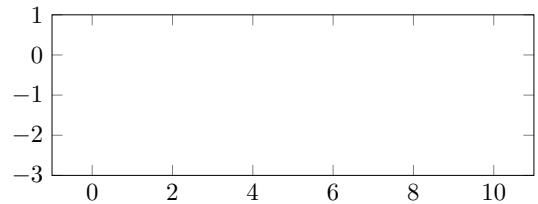


Figure 13.45: PGFplots: axis/axes range

scale only axis
width x axis length, height y axis length

```
\begin{tikzpicture}
\begin{axis}[
    xmin = -1, xmax = 11,
    ymin = -3, ymax = 1,
    scale only axis,
    width = 5cm, height = 7cm,
]
% empty
\end{axis}
\end{tikzpicture}
```

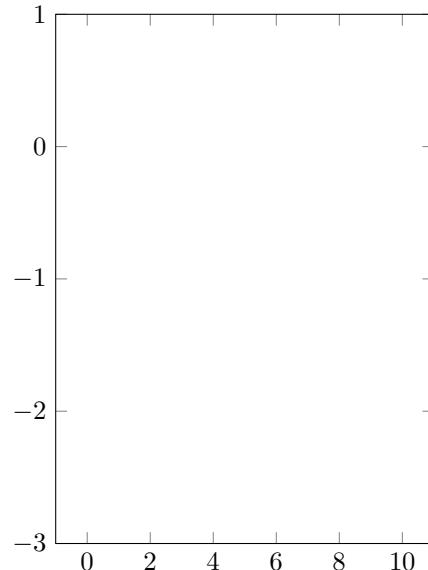


Figure 13.46: PGFplots: axis/axes range

x x unit vector length, y y unit vector length

```
\begin{tikzpicture}
\begin{axis}[
    xmin = -1, xmax = 11,
    ymin = -3, ymax = 1,
    x = 1cm, y = 1cm,
]
% empty
\end{axis}
\end{tikzpicture}
```

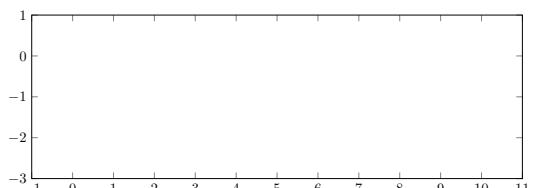


Figure 13.47: PGFplots: axis/axes range

13.4.7.1.3 direction vector

```
\begin{tikzpicture}
\begin{axis}[
    xmin = -1, xmax = 11,
    ymin = -3, ymax = 1,
    x={(.2cm,-.1cm)},
    y={(-.5cm,.5cm)},
]
% empty
\end{axis}
\end{tikzpicture}
```

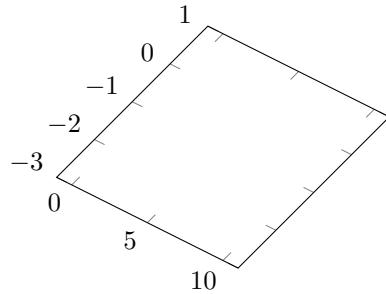


Figure 13.48: PGFplots: axis/axes range

```
unit vector ratio = {1 1}
```

```
\begin{tikzpicture}
\begin{axis}[
    xmin = -1, xmax = 11,
    ymin = -3, ymax = 1,
    unit vector ratio = {1 1},
]
% empty
\end{axis}
\end{tikzpicture}
```

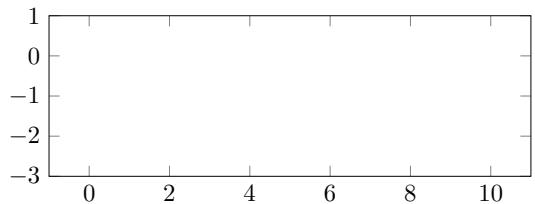


Figure 13.49: PGFplots: axis/axes range

13.4.7.1.4 axis style `axis lines` to assign all axes, either `axis lines = box`(default), `axis lines = center`(axis lines with arrows, `center`, `x: bottom, top, y:`), or `axis lines = none`(not shown), or even axis lines without arrows `axis lines *= center`

`axis x line, axis y line` to assign the respect axis, e.g. `axis x line = center`

`axis lines = center:`

```
\begin{tikzpicture}
  \begin{axis}[
    axis lines = center,
    xmin = -1, xmax = 11,
    ymin = -3, ymax = 1,
  ]
    % empty
  \end{axis}
\end{tikzpicture}
```

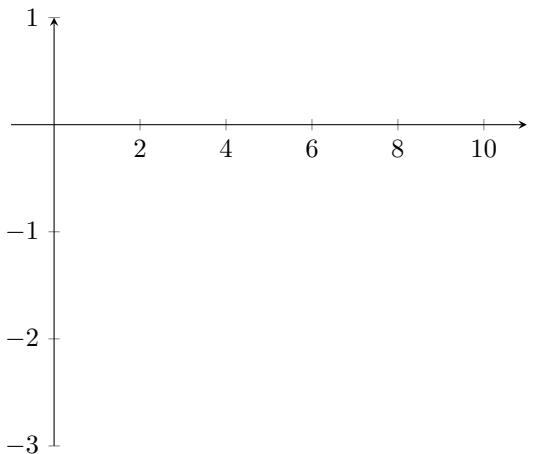


Figure 13.50: PGFplots: axis/axes range

`axis lines *= center:`

x axis line without arrow, y axis box

```
\begin{tikzpicture}
  \begin{axis}[
    axis x line*= center, % x
    axis line without arrow, y axis
    box
    xmin = -1, xmax = 11,
    ymin = -3, ymax = 1,
  ]
    % empty
  \end{axis}
\end{tikzpicture}
```

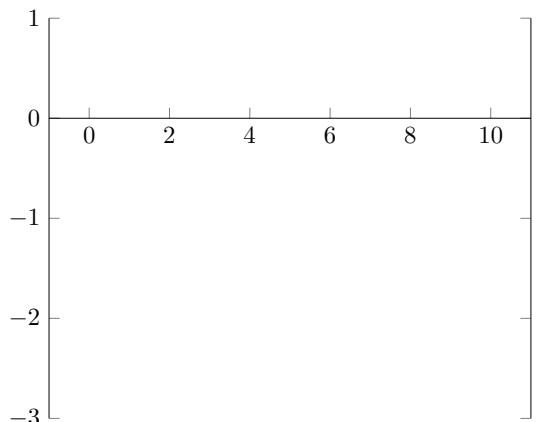


Figure 13.51: PGFplots: axis/axes range

x axis line with arrow, y axis line without arrow

```
\begin{tikzpicture}
\begin{axis}[
    axis x line = center, % x axis
    line with arrow
    axis y line* = center, % y
    axis line without arrow
    xmin = -1, xmax = 11,
    ymin = -3, ymax = 1,
]
% empty
\end{axis}
\end{tikzpicture}
```

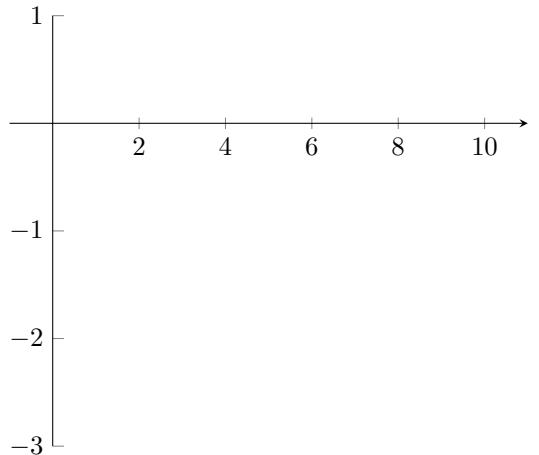


Figure 13.52: PGFplots: axis/axes range

13.4.7.1.5 axis discontinuity crunch, parallel, none

crunch

```
\begin{tikzpicture}
\begin{axis}[
    axis x line = bottom,
    axis y line = center,
    xmin = -2, xmax = 10,
    ymin = 0, ymax = 12,
    axis y discontinuity = crunch,
]
% empty
\end{axis}
\end{tikzpicture}
```

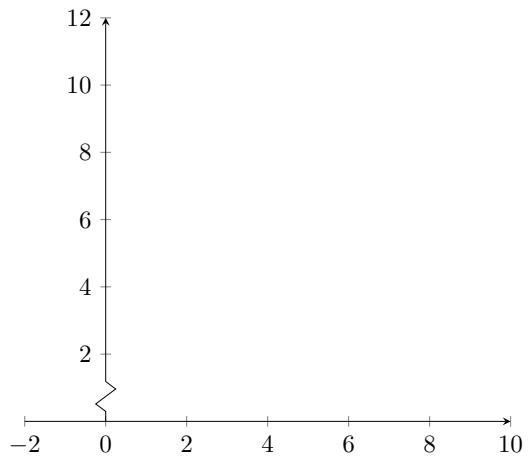


Figure 13.53: PGFplots: axis/axes range

parallel

```
\begin{tikzpicture}
\begin{axis}[
    axis x line = bottom,
    axis y line = center,
    xmin = -2, xmax = 10,
    ymin = 0, ymax = 12,
    axis y discontinuity =
    \parallel,
]
% empty
\end{axis}
\end{tikzpicture}
```

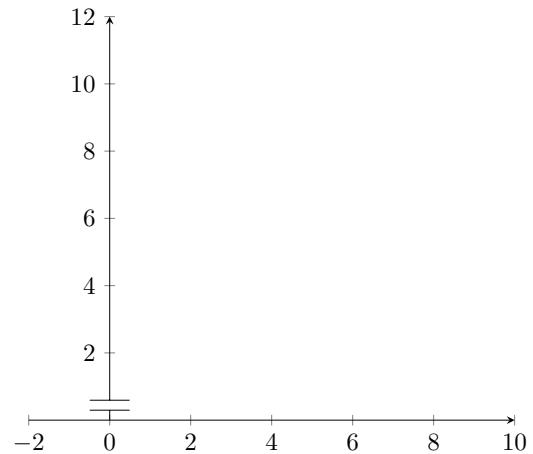


Figure 13.54: PGFplots: axis/axes range

13.4.7.1.6 `tick` `tick pos` `ticklabel` `pos`

```
\begin{tikzpicture}
\begin{axis}[
    xtick pos = upper,
    yticklabel pos = upper,
]
% empty
\end{axis}
\end{tikzpicture}
```

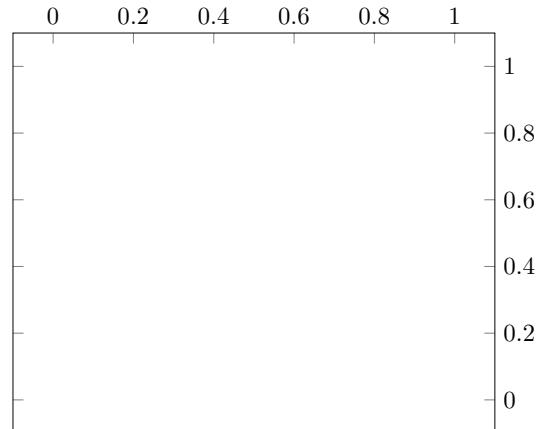


Figure 13.55: PGFplots: axis/axes range

`tick distance`

`tick align: inside, center, outside`

```
\begin{tikzpicture}
\begin{axis}[
    axis lines=center,
    xmin=-1,xmax=3,
    ymin=-3,ymax=3,
    xtick distance=.8,
    ytick distance=1.1,
    tick align=inside,
]
% empty
\end{axis}
\end{tikzpicture}
```

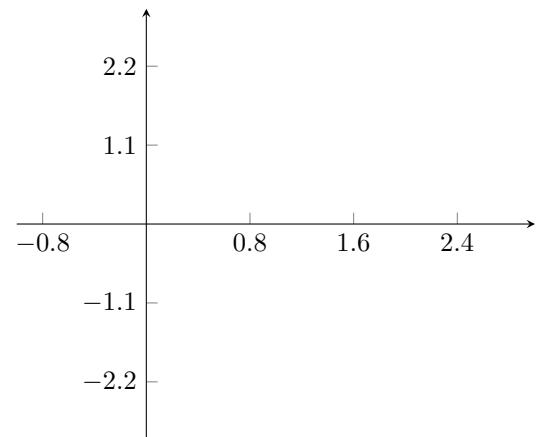


Figure 13.56: PGFplots: axis/axes range

minor tick num

```
\begin{tikzpicture}
\begin{axis}[
    axis y line=none,axis x
    line=center,
    ymin=0,ymax=0,xmin=-3,xmax=3,
    xtick distance=2,tick
    align=inside,
    minor tick num=2,
]
% empty
\end{axis}
\end{tikzpicture}
```

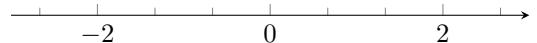


Figure 13.57: PGFplots: axis/axes range

xtick=\emptyset|data|{<coordinates>}

```
\begin{tikzpicture}
\begin{axis}[
    axis y line=none, axis x
    line=center,
    ymin=0, ymax=0, xmin=-3, xmax=3,
    xtick={-2.5,0,1}, minor
    xtick={1/3,2/3},
    tick align=inside,
]
% empty
\end{axis}
\end{tikzpicture}
```

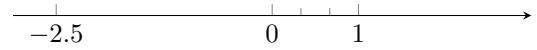


Figure 13.58: PGFplots: axis/axes range

extra x ticks=<coordinates>

```
\begin{tikzpicture}
\begin{axis}[
    axis y line=none, axis x
    line=center,
    ymin=0, ymax=0, xmin=-2.3, xmax=4.9,
    xtick distance=2, minor tick
    num=1,
    extra x ticks={e,pi},
    extra x tick
    labels={$e$,$\pi$},
    tick align=inside,
]
% empty
\end{axis}
\end{tikzpicture}
```

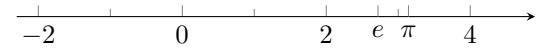


Figure 13.59: PGFplots: axis/axes range

ticklabels=<labels> extra x tick labels=<labels>

hide obscured x ticks = false for origin x tick label

```
\begin{tikzpicture}
\begin{axis}[
    axis y line=none, axis x
    & line=center,
    & ymin=0, ymax=0, xmin=-2.3*pi, xmax=2.3*pi,
    & xtick distance=pi,
    & xticklabels={-$-2\pi$,-$\pi$,$0$,$\pi$,$2\pi$},
    ]
    % empty
\end{axis}
\end{tikzpicture}
```

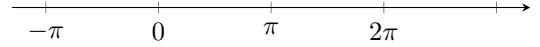


Figure 13.60: PGFplots: axis/axes range

13.4.7.2 addplot+

What does addplot+ do exactly?

<https://tex.stackexchange.com/questions/275959/what-does-addplot-do-exactly>

<https://tikz.dev/pgfplots/reference-addplot#/addplot+>

Every `\addplot` directive receives a pre-defined style (line color, marker style etc) through a pre-defined cycle list that is automatically chosen depending on the index of the current `\addplot` instruction. If you want to add some of your styles manually (like I want red colour instead of blue, say), you can add them through options to `\addplot` like `\addplot[<your options>]`. Now the question is whether you want your own style (your options) to be appended to or replace one of these cycle lists assigned. This is decided by the + sign. If you use `\addplot+ [<your options>]`, your style is appended to and by `\addplot[<your options>]`, your options will replace the assigned cycle list.

13.4.7.3 point

`only marks` only points without lines

zero y axis range `ymin=0, ymax=0` and `axis y line=none`, making 1D x axis

```
\begin{tikzpicture}
\begin{axis}[
    xlabel=$x$,
    axis y line=none,
    axis x line=center,
    tick align=inside,
    xmin=-1.5, xmax=4.9, ymin=0,
    ymax=0,
    xtick distance=1,
    x=1cm
]
\addplot+ coordinates {(e,0)}
    node [pin=90:{\$e\$}] {};
\addplot+ coordinates {(pi,0)}
    node [pin=90:{\$\\pi\$}] {};
\addplot+ coordinates
    {( -1,0)};
\end{axis}
\end{tikzpicture}
```



Figure 13.61: PGFplots: 1D points with pins

```
\begin{tikzpicture}
\begin{axis}[
    xlabel=$x$, ylabel=$y$,
    axis lines=center,
    tick align=inside,
    xmin=-1.5, xmax=4.9,
    ymin=-3.3, ymax=3.9,
    xtick distance=1, ytick
    distance=1,
    axis equal image
]
\addplot+ [only marks]
    coordinates {
        (-1,-2) (pi,pi/4) (3,2)
        (0,0)};
\addplot+ coordinates {(2,1)};
\addplot+ coordinates
    {(3,-2)};
\end{axis}
\end{tikzpicture}
```

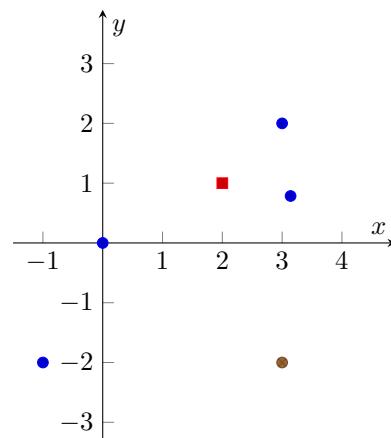


Figure 13.62: PGFplots: 2D points

```
\begin{tikzpicture}
\begin{axis}[axis equal image]
\addplot+ [only marks]
table [x=xdata,y=ydata]
{data/func.dat};
\end{axis}
\end{tikzpicture}
```

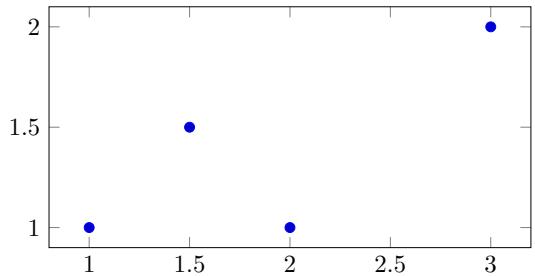


Figure 13.63: PGFplots: data points

`axis equal image` to fix aspect ratio 1:1

```
\begin{tikzpicture}
\begin{axis}[title=5 sampling
points,
xlabel=$x$,ylabel=$y$,
axis equal image]
\addplot+ [only
marks,domain=-2:2,samples=5]
{x^2};
\end{axis}
\end{tikzpicture}
```

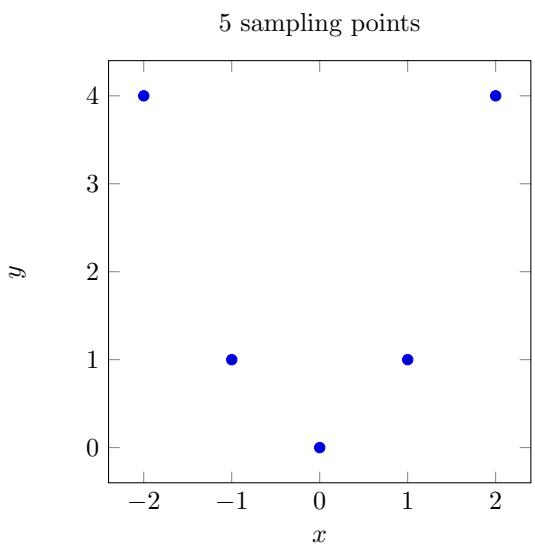


Figure 13.64: PGFplots: function sampling 5 points

```
\begin{tikzpicture}
\begin{axis}[title=55 sampling
points,
xlabel=$x$,ylabel=$y$,
axis equal image]
\addplot+ [only
marks, domain=-2:2, samples=55]
{x^2};
\end{axis}
\end{tikzpicture}
```

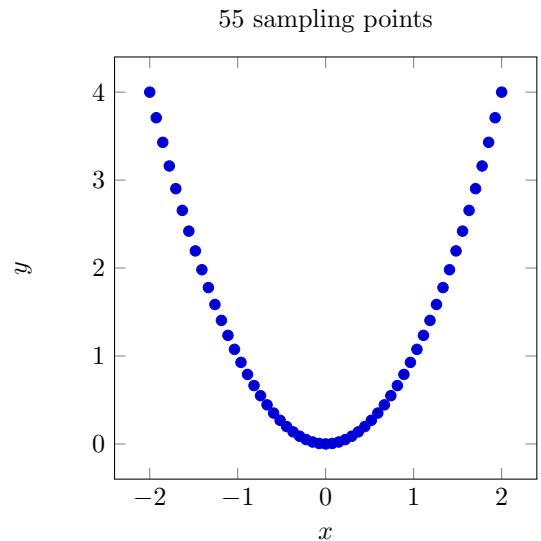


Figure 13.65: PGFplots: function sampling 55 points

```
\begin{tikzpicture}
\begin{axis}[
    trig format plots=rad, %
    angle in radian
    axis equal image]
\addplot+ [only
marks, variable=t, domain=0:pi*3/2,
samples=20]
({cos(t)},{sin(t)});
\end{axis}
\end{tikzpicture}
```

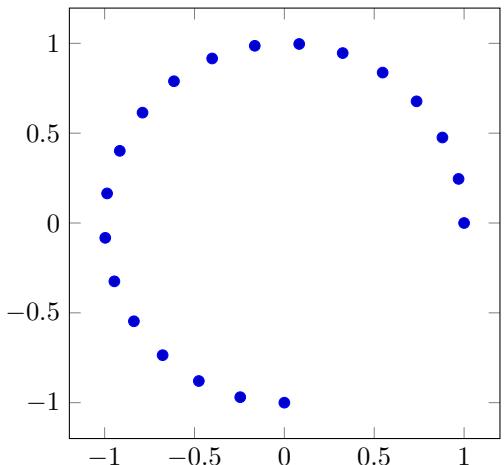


Figure 13.66: PGFplots: parametric function sampling

```
\begin{tikzpicture}
\begin{axis}[
    xlabel=$x$,ylabel=$y$,zlabel=$z$,
    axis lines=center,
    tick align=inside,
    xmin=-1.5,xmax=3.9,
    ymin=-1.5,ymax=3.9,
    zmin=-0.5,zmax=3.9,
    xtick distance=1,
    ytick distance=1,
    ztick distance=1,
    % width=10cm,
    % scale only axis,
    view={120}{30}, % perspective
    angle
    axis equal image,]
\addplot3+
    coordinates{(1,0,0)};
\addplot3+
    coordinates{(0,1,0)};
\addplot3+
    coordinates{(0,0,1)};
\end{axis}
\end{tikzpicture}
```



Figure 13.67: PGFplots: 3D points

```
\begin{tikzpicture}
\begin{axis}[
    xlabel=$x$,ylabel=$y$,zlabel=$z$,
    grid=major
    ]
\addplot3+ [only marks]
    {x^2+y^2};
\end{axis}
\end{tikzpicture}
```

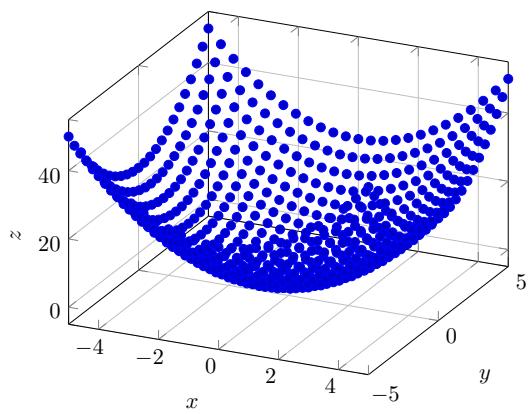


Figure 13.68: PGFplots: 3D function sampling points

13.4.7.4 line

```
\begin{tikzpicture}
\begin{axis}[ytick=data]
\addplot coordinates {
(1,0.15) (2,0.21) (3,0.33)
(4,0.4)
(2.5,.1) (3.5,.1)
};
\end{axis}
\end{tikzpicture}
```

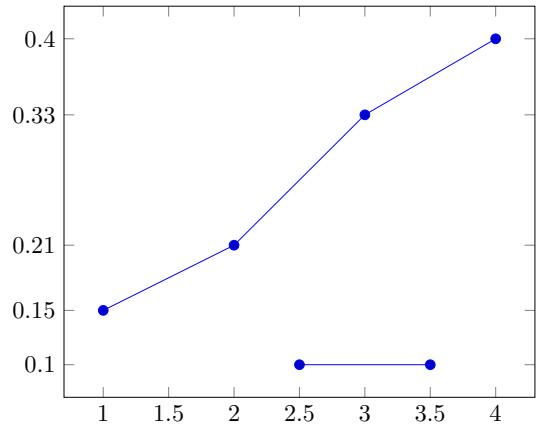


Figure 13.69: lines connecting adjacent points

`smooth` to make smooth curves or lines

```
\begin{tikzpicture}
\begin{axis}[ytick=data]
\addplot+ [smooth] coordinates
{
(1,0.15) (2,0.21) (3,0.33)
(4,0.4)};
\end{axis}
\end{tikzpicture}
```

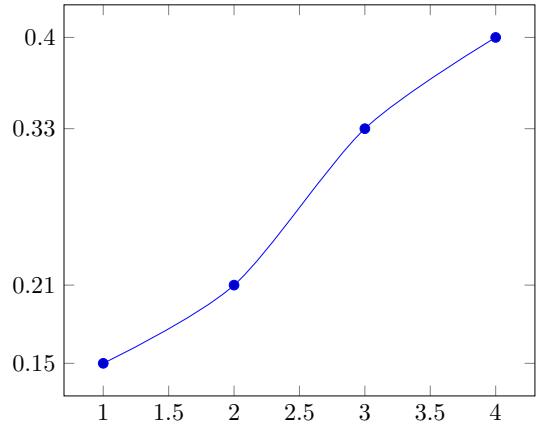
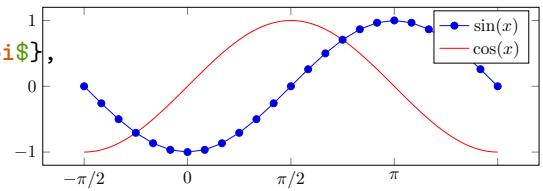


Figure 13.70: smooth lines connecting adjacent points

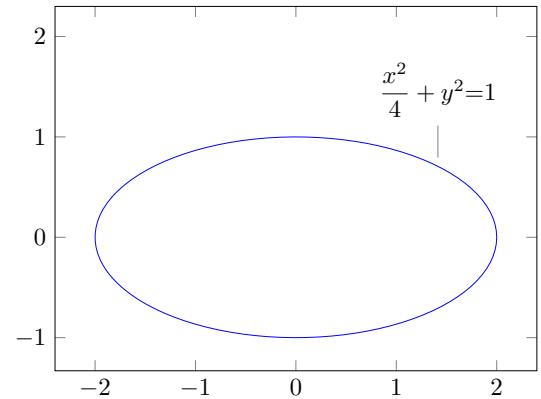
`no markers` to make no markers or points on the curves or lines

`\addlegendentry` to add legends

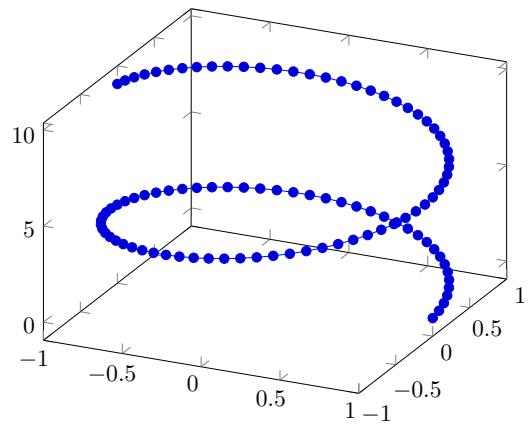
```
\begin{tikzpicture}
\begin{axis}[
    trig format plots=rad,
    xtick distance=pi/2, ytick
    distance=1,
    xticklabels={-$-\pi$,$-\pi/2$,0,$\pi/2$,$\pi$},
    width=10cm, scale only axis,
    axis equal image]
\addplot+ [domain=-pi:pi]
    {sin(x)};
\addlegendentry{$\sin(x)$}
\addplot+ [no
    markers,domain=-pi:pi,samples=100]
    {cos(x)};
\addlegendentry{$\cos(x)$}
\end{axis}
\end{tikzpicture}
```

Figure 13.71: $\sin(x)$ and $\cos(x)$

```
\begin{tikzpicture}
\begin{axis}[
    trig format plots=rad,
    ymax=2.3,
    axis equal image]
\addplot+ [no markers,
    variable=t,
    domain=0:2*pi,
    samples=100]
    ({2*cos(t)},{sin(t)});
\node
    [pin=90:$\frac{x^2}{4}+y^2=1$]
    at ({2*cos(45)},{sin(45)}) {};
\end{axis}
\end{tikzpicture}
```

Figure 13.72: $\frac{x^2}{4} + y^2 = 1$

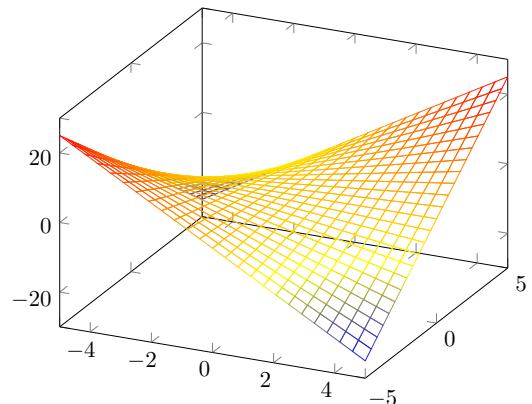
```
\begin{tikzpicture}
\begin{axis}[trig format
    ↪ plots=rad]
\addplot3+ [variable=t,
            domain=0:3*pi,
            samples=100,
            samples y=0]
            ({cos(t)},{sin(t)},{t});
\end{axis}
\end{tikzpicture}
```

Figure 13.73: $(\cos(t), \sin(t), t)$

13.4.7.5 plane

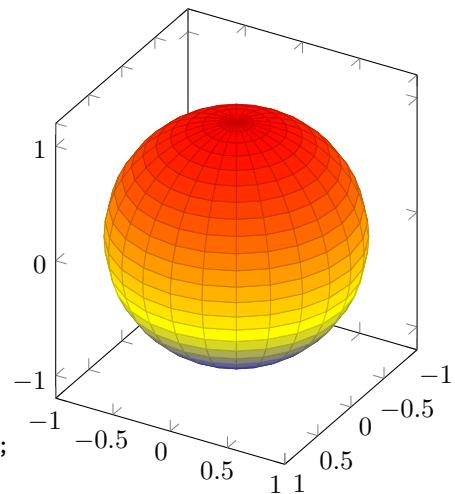
[mesh]

```
\begin{tikzpicture}
\begin{axis}
\addplot3+ [no markers, mesh]
    ↪ {x*y};
\end{axis}
\end{tikzpicture}
```

Figure 13.74: $f(x, y) = xy$

[surf] surface

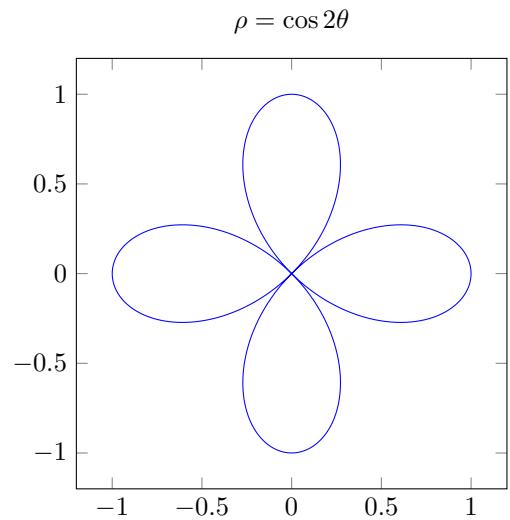
```
\begin{tikzpicture}
\begin{axis}[
    view={120}{30},
    trig format plots=rad,
    width=10cm,
    scale only axis,
    axis equal image
]
\addplot3+ [no markers,
            surf,
            domain=0:2*pi,
            domain y=0:pi]
    ({sin(y)*cos(x)},{sin(y)*sin(x)},{cos(y)});
\end{axis}
\end{tikzpicture}
```

Figure 13.75: $x^2 + y^2 + z^2 = 1$

13.4.7.6 polar coordinate

```
data cs=polar|polarrad
```

```
\begin{tikzpicture}
\begin{axis}[
    title={$\rho=\cos 2\theta$},
    axis equal image
]
\addplot+ [no markers,
            data cs=polar,
            domain=0:360,
            samples=360
            ] (\x,{cos(2*\x)});
\end{axis}
\end{tikzpicture}
```

Figure 13.76: polar coordinate $\rho = \cos 2\theta$

```
\usepgfplotslibrary{polar} to use \begin{polaraxis}
```

```
\usepgfplotslibrary{polar}
\begin{tikzpicture}
  \begin{polaraxis}
    \addplot+ coordinates
      {(0,0) (60,1)
      (90,{sqrt(3)/2})} -- cycle;
  \end{polaraxis}
\end{tikzpicture}
```

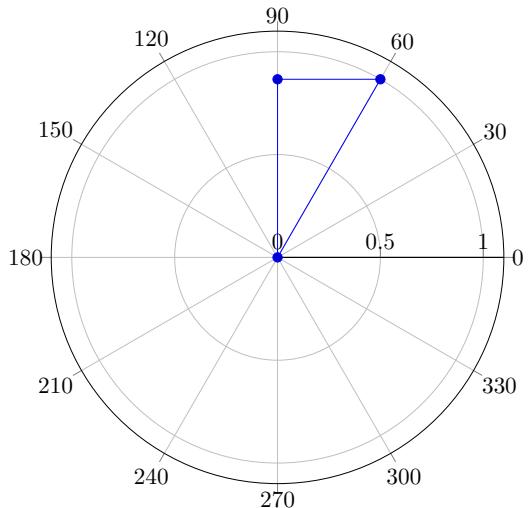


Figure 13.77: polar coordinate axes

<https://zhuanlan.zhihu.com/p/128341873>

13.4.8 Arnav Bandekar: Using pgfplots to make economic graphs in LaTeX

<https://towardsdatascience.com/using-pgfplots-to-make-economic-graphs-in-latex-bcdc8e27c0eb>

13.4.9 PGFplots gallery

<https://pgfplots.sourceforge.net/gallery.html>

```
\begin{tikzpicture}
\begin{axis}[
  xmin=-3, xmax=3,
  ymin=-3, ymax=3,
  extra x ticks={-1,1},
  extra y ticks={-2,2},
  extra tick style={grid=major},
]
\draw[red] \pgfextra{
  \pgfpathellipse{\pgfplotspointaxisxy{0}{0}}
  {\pgfplotspointaxisdirectionxy{1}{0}}
  {\pgfplotspointaxisdirectionxy{0}{2}}
  % see also the documentation of
  % 'axis direction cs' which
  % allows a simpler way to draw
  % this ellipse
};
\draw[blue] \pgfextra{
  \pgfpathellipse{\pgfplotspointaxisxy{0}{0}}
  {\pgfplotspointaxisdirectionxy{1}{1}}
  {\pgfplotspointaxisdirectionxy{0}{2}}
};
\addplot [only marks,mark=*]
  coordinates { (0,0) };
\end{axis}
\end{tikzpicture}
```

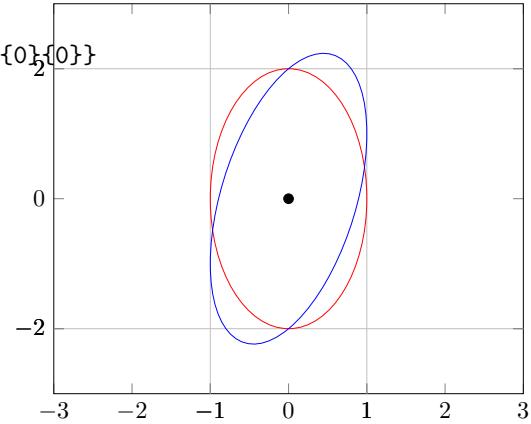


Figure 13.78: declare function

13.5 TikZplotLib / tikzplotlib

Python^[??]

```
library(reticulate)

## Warning: package 'reticulate' was built under R version 4.2.3

# virtualenv_list()
# virtualenv_python()
# use_virtualenv("r-reticulate")

# conda_list()
```

```
use_condaenv(condaenv = 'sandbox-3.9')

## install TikZplotLib
# virtualenv_install("r-reticulate", "tikzplotlib")

## import TikZplotLib (it will be automatically discovered in "r-reticulate")
tikzplotlib <- import("tikzplotlib")
```

Error: ImportError: cannot import name 'common_texification' from 'matplotlib.backends.bac

<https://github.com/NixOS/nixpkgs/issues/289305>

The “solution” is to use **matplotlib 3.6**, but I guess in nixpkgs a single version is used at a time. The last working upgrade is from 0911608 I guess (I tried using virtualenv + pip + nix-ld + export LD_LIBRARY_PATH="LD_LIBRARYPATH:NIX_LD_LIBRARY_PATH")

<https://stackoverflow.com/questions/60882638/install-a-particular-version-of-python-package-in-a-virtualenv-created-with-reti>

```
#reticulate::virtualenv_install(packages = c("matplotlib==3.6.0"))
```

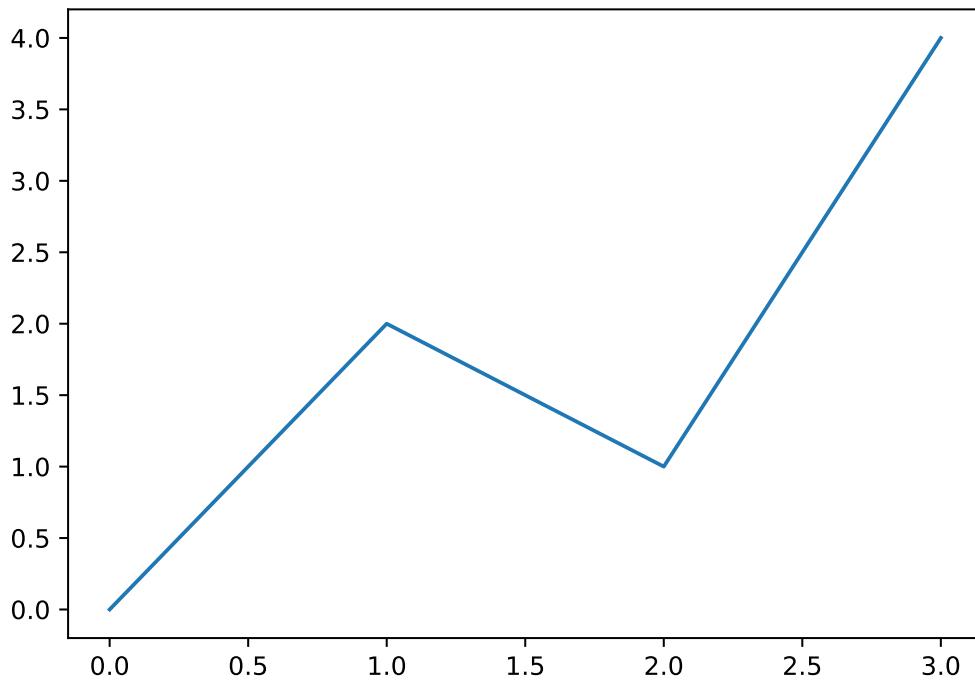
```
reticulate::conda_list()
```

##	name	python
## 1	base	D:\Anaconda3\python.exe
## 2	fiftyone	D:\Anaconda3\envs\fiftyone\python.exe
## 3	keras	D:\Anaconda3\envs\keras\python.exe
## 4	labelme	D:\Anaconda3\envs\labelme\python.exe
## 5	manim	D:\Anaconda3\envs\manim\python.exe
## 6	mmyolo	D:\Anaconda3\envs\mmyolo\python.exe
## 7	r-reticulate	D:\Anaconda3\envs\r-reticulate\python.exe
## 8	rsconnect-jupyter	D:\Anaconda3\envs\rsconnect-jupyter\python.exe
## 9	sandbox	D:\Anaconda3\envs\sandbox\python.exe
## 10	sandbox-3.9	D:\Anaconda3\envs\sandbox-3.9\python.exe

```
reticulate::use_condaenv(condaenv = 'sandbox-3.9')
```

```
import matplotlib.pyplot as plt

plt.plot([0, 2, 1, 4])
plt.show()
```



```
import tikzplotlib

# tikzplotlib.save("test.tex")
tikzplotlib.get_tikz_code()

## '% This file was created with tikzplotlib v0.10.1.\n\\begin{tikzpicture}\n\n\\end{tikzpicture}
```

```
import matplotlib.pyplot as plt

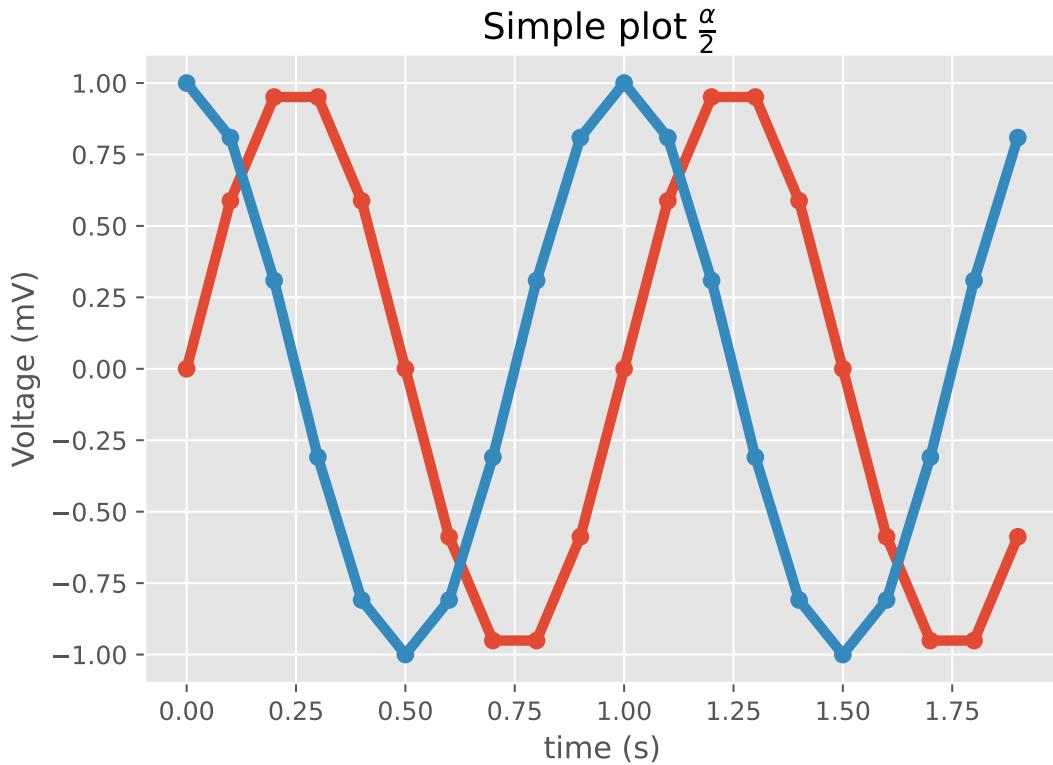
plt.close()

import matplotlib.pyplot as plt
import numpy as np

plt.style.use("ggplot")

t = np.arange(0.0, 2.0, 0.1)
s = np.sin(2 * np.pi * t)
s2 = np.cos(2 * np.pi * t)
plt.plot(t, s, "o-", lw=4.1)
plt.plot(t, s2, "o-", lw=4.1)
plt.xlabel("time (s)")
plt.ylabel("Voltage (mV)")
```

```
plt.title("Simple plot $\frac{\alpha}{2}$")
plt.grid(True)
plt.show()
```



```
import tikzplotlib

# tikzplotlib.save("test.tex")
tikzplotlib.get_tikz_code()
```

```
## '% This file was created with tikzplotlib v0.10.1.\n\\begin{tikzpicture}\n\n\\end{tikzpicture}
```

13.6 animation

<https://zhuanlan.zhihu.com/p/338402487>

Chapter 14

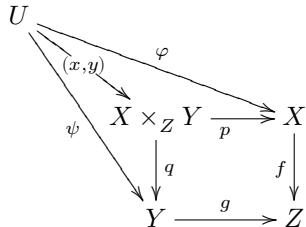
xy-pic

<https://bookdown.org/yihui/rmarkdown-cookbook/install-latex-pkgs.html>

`tinytex::install_tinytex()`

the following xymatrix from LaTeX package xy for xy-pic is not shown or rendered in HTML:

`\$\\LaTeX$` can only be used in HTML, not PDF



Chapter 15

statistics

Chapter 16

covariance matrix

16.1 covariance matrix

?

16.1.1 calculation

$$\begin{aligned} C[X] = \text{Cov}[X] = V[X] &= E[(X - E(X))(X - E(X))^T] \\ &= E[(X - E(X)) [X^T - E(X)^T]] \\ &= E[XX^T - E(X)X^T - XE(X)^T + E(X)E(X)^T] \\ &= E[XX^T] - E[E(X)X^T] - E[XE(X)^T] + E[E(X)E(X)^T] \\ &= E[XX^T] - E(X)E[X^T] - E[X]E(X)^T + E(X)E(X)^T \\ &= E[XX^T] - E(X)E(X)^T - E(X)E(X)^T + E(X)E(X)^T \\ &= E[XX^T] - E(X)E(X)^T \end{aligned}$$

$$\begin{aligned} X = [X]_{1 \times 1} = X \Rightarrow C(X) = C[X] &= E[XX^T] - E(X)E(X)^T \\ &= E[XX] - E(X)E(X) \\ &= E(X^2) - [E(X)]^2 = V(X) \end{aligned}$$

16.1.2 $V[X + b] = V[X]$

$$\begin{aligned} V[X + b] &= E[((X + b) - E(X + b))((X + b) - E(X + b))^T] \\ &\stackrel{E(X+b)=E(X)+b}{=} E[(X + b - E(X) - b)(X + b - E(X) - b)^T] \\ &= E[(X - E(X))(X - E(X))^T] = V[X] \end{aligned}$$

16.1.3 $\text{V}[AX] = A\text{V}[X]A^T$

$$\begin{aligned}
 \text{V}[AX] &= \text{E} \left[[(AX) - \text{E}(AX)] [(AX) - \text{E}(AX)]^T \right] \\
 &\stackrel{\text{E}(AX)=A\text{E}(X)}{=} \text{E} \left[[AX - A\text{E}(X)] [AX - A\text{E}(X)]^T \right] \\
 &= \text{E} \left[A[X - \text{E}(X)] [A[X - \text{E}(X)]]^T \right] \\
 &= \text{E} \left[A[X - \text{E}(X)] [X - \text{E}(X)]^T A^T \right] \\
 &= A\text{E} \left[[X - \text{E}(X)] [X - \text{E}(X)]^T \right] A^T = A\text{V}[X]A^T
 \end{aligned}$$

16.1.4 $\text{V}[AX + b] = A\text{V}[X]A^T$

$$\text{V}[AX + b] = \text{V}[AX] = A\text{V}[X]A^T$$

Chapter 17

Gosper algorithm

Chapter 18

Lorentz transformation

18.1 Einstein

<https://wap.hillpublisher.com/UpFile/202204/20220414165340.pdf>

18.2 Bondi *k*-calculus

https://en.wikipedia.org/wiki/Bondi_k-calculus

18.3 wordline in Minkowski space

18.3.1 Wick rotation

<https://ncatlab.org/nlab/show/Wick+rotation>

18.3.1.1 Osterwalder-Schrader reconstruction theorem

<https://ncatlab.org/nlab/show/Osterwalder-Schrader+theorem>

Chapter 19

R

19.1 TonyKuoYJ

R

<https://bookdown.org/tonykuoyj/eloquentr/getting-started.html>
<https://bookdown.org/tonykuoyj/eloquentr/easy-installation.html#about-packages>
install.packages()
library()
<https://bookdown.org/tonykuoyj/eloquentr/getting-started.html>

19.1.1 quick intro

Ctrl + Alt + I to insert a new code chunk in RStudio

Ctrl + Enter to run the current line

Ctrl + Shift + Enter to run the current chunk

```
R.version
```

```
##           _  
## platform      x86_64-w64-mingw32  
## arch        x86_64  
## os          mingw32  
## crt         ucrt  
## system     x86_64, mingw32  
## status  
## major        4  
## minor       2.1  
## year        2022  
## month       06  
## day         23  
## svn rev    82513
```

```

## language      R
## version.string R version 4.2.1 (2022-06-23 ucrt)
## nickname      Funny-Looking Kid

a <- 23 # prime
a

## [1] 23

combine <- c(11, 13) # twin prime
combine

## [1] 11 13

# ?c
# help(c)

```

Ctrl + L to clean R console

path with slash / in R, differing backslash \ in M\$ Windows

19.1.1.1 function

```

add <- function(x, y) {
  return(x + y)
}

add(11, 13)

```

```
## [1] 24
```

$$BMI = \frac{BW \text{ [Kg]}}{BH \text{ [m]}^2}$$

```

get_bmi <- function (bw, bh) {
  return (bw/(bh/100)^2)
}

```

```
get_bmi(70, 170)
```

```
## [1] 24.22145
```

19.1.2 R style

<https://bookdown.org/tonykuoyj/eloquentr/styleguide.html>
 snake_case rather than camelCase

19.1.3 data workflow or forward pipe

from *chaining method* in *object-oriented programming* to **functional programming**

19.1.3.1 %>% operator

```
abs(-5:5)
```

```
## [1] 5 4 3 2 1 0 1 2 3 4 5
```

```
# install.packages("magrittr")
```

```
library(magrittr)
```

```
##
```

```
## Attaching package: 'magrittr'
```

```
## The following object is masked _by_ '.GlobalEnv':
```

```
##
```

```
##     add
```

```
-5:5 %>% abs()
```

```
## [1] 5 4 3 2 1 0 1 2 3 4 5
```

```
# with readability but too many lines
```

```
sys_date <- Sys.Date()
```

```
sys_date_yr <- format(sys_date, format = "%Y")
```

```
sys_date_num <- as.numeric(sys_date_yr)
```

```
sys_date_num
```

```
## [1] 2024
```

```
# less line but also less readability
```

```
sys_date_num <- as.numeric(format(Sys.Date(), format = "%Y"))
```

```
sys_date_num
```

```
## [1] 2024
```

```
# use %>% operator to demonstrate data workflow or forward pipe
```

```
sys_date_num <- Sys.Date() %>%
```

```
  format(format = "%Y") %>%
```

```
  as.numeric()
```

```
sys_date_num
```

```
## [1] 2024
```

19.1.4 data processing with dplyr

<https://bookdown.org/tonykuoyj/eloquentr/dplyr.html>

some functions functioning like those in **SQL**

```
library(dplyr)

## Warning: package 'dplyr' was built under R version 4.2.3

##
## Attaching package: 'dplyr'

## The following objects are masked from 'package:stats':
## 
##     filter, lag

## The following objects are masked from 'package:base':
## 
##     intersect, setdiff, setequal, union

# install.packages("gapminder")

library(gapminder)

## Warning: package 'gapminder' was built under R version 4.2.3

head(gapminder)

## # A tibble: 6 x 6
##   country   continent   year lifeExp     pop gdpPercap
##   <fct>     <fct>     <int>   <dbl>   <int>     <dbl>
## 1 Afghanistan Asia      1952    28.8  8425333    779.
## 2 Afghanistan Asia      1957    30.3  9240934    821.
## 3 Afghanistan Asia      1962    32.0  10267083   853.
## 4 Afghanistan Asia      1967    34.0  11537966   836.
## 5 Afghanistan Asia      1972    36.1  13079460   740.
## 6 Afghanistan Asia      1977    38.4  14880372   786.

library(gapminder)
library(dplyr)
library(magrittr)

gapminder %>%
  filter(year == 2007)
```

```
## # A tibble: 142 x 6
##   country     continent year lifeExp      pop gdpPercap
##   <fct>       <fct>    <int>   <dbl>     <int>     <dbl>
## 1 Afghanistan Asia     2007    43.8  31889923     975.
## 2 Albania      Europe   2007    76.4  3600523      5937.
## 3 Algeria      Africa   2007    72.3  33333216     6223.
## 4 Angola       Africa   2007    42.7  12420476     4797.
## 5 Argentina    Americas  2007    75.3  40301927    12779.
## 6 Australia    Oceania   2007    81.2  20434176    34435.
## 7 Austria      Europe   2007    79.8  8199783     36126.
## 8 Bahrain      Asia     2007    75.6  708573      29796.
## 9 Bangladesh   Asia     2007    64.1  150448339    1391.
## 10 Belgium     Europe   2007    79.4  10392226    33693.
## # i 132 more rows
```

```
library(gapminder)
library(dplyr)
library(magrittr)

gapminder %>%
  filter(year == 2007) %>%
  select(country)
```

```
## # A tibble: 142 x 1
##   country
##   <fct>
## 1 Afghanistan
## 2 Albania
## 3 Algeria
## 4 Angola
## 5 Argentina
## 6 Australia
## 7 Austria
## 8 Bahrain
## 9 Bangladesh
## 10 Belgium
## # i 132 more rows
```

```
library(gapminder)
library(dplyr)
library(magrittr)

gapminder %>%
  mutate(pop_in_thousands = pop / 1000)
```

```
## # A tibble: 1,704 x 7
##   country     continent year lifeExp      pop gdpPercap pop_in_thousands
##   <fct>       <fct>    <int>   <dbl>     <int>     <dbl>           <dbl>
## 1 Afghanistan Asia     1952    28.8  8425333     779.      8425.
## 2 Afghanistan Asia     1957    30.3  9240934     821.      9241.
```

```

## 3 Afghanistan Asia      1962    32.0 10267083    853.    10267.
## 4 Afghanistan Asia     1967    34.0 11537966    836.    11538.
## 5 Afghanistan Asia     1972    36.1 13079460    740.    13079.
## 6 Afghanistan Asia     1977    38.4 14880372    786.    14880.
## 7 Afghanistan Asia     1982    39.9 12881816    978.    12882.
## 8 Afghanistan Asia     1987    40.8 13867957    852.    13868.
## 9 Afghanistan Asia     1992    41.7 16317921    649.    16318.
## 10 Afghanistan Asia    1997    41.8 22227415    635.    22227.
## # i 1,694 more rows

```

```

library(gapminder)
library(dplyr)
library(magrittr)

gapminder %>%
  arrange(year)

```

```

## # A tibble: 1,704 x 6
##   country   continent year lifeExp      pop gdpPercap
##   <fct>     <fct>    <int>   <dbl>    <int>    <dbl>
## 1 Afghanistan Asia      1952    28.8  8425333    779.
## 2 Albania     Europe    1952    55.2  1282697   1601.
## 3 Algeria     Africa    1952    43.1  9279525   2449.
## 4 Angola      Africa    1952    30.0  4232095   3521.
## 5 Argentina   Americas   1952    62.5  17876956   5911.
## 6 Australia   Oceania   1952    69.1  8691212  10040.
## 7 Austria     Europe    1952    66.8  6927772   6137.
## 8 Bahrain     Asia      1952    50.9  120447    9867.
## 9 Bangladesh  Asia      1952    37.5  46886859   684.
## 10 Belgium    Europe    1952    68    8730405   8343.
## # i 1,694 more rows

```

total population in the world in 2007

```

library(gapminder)
library(dplyr)
library(magrittr)

gapminder %>%
  filter(year == 2007) %>%
  summarise(ttl_pop = sum(as.numeric(pop)))

```

```

## # A tibble: 1 x 1
##       ttl_pop
##       <dbl>
## 1 6251013179

```

total population group by the continents in 2007

```
library(gapminder)
library(dplyr)
library(magrittr)

gapminder %>%
  filter(year == 2007) %>%
  group_by(continent) %>%
  summarise(ttl_pop = sum(as.numeric(pop)))
```

```
## # A tibble: 5 x 2
##   continent     ttl_pop
##   <fct>        <dbl>
## 1 Africa      929539692
## 2 Americas    898871184
## 3 Asia        3811953827
## 4 Europe      586098529
## 5 Oceania     24549947
```

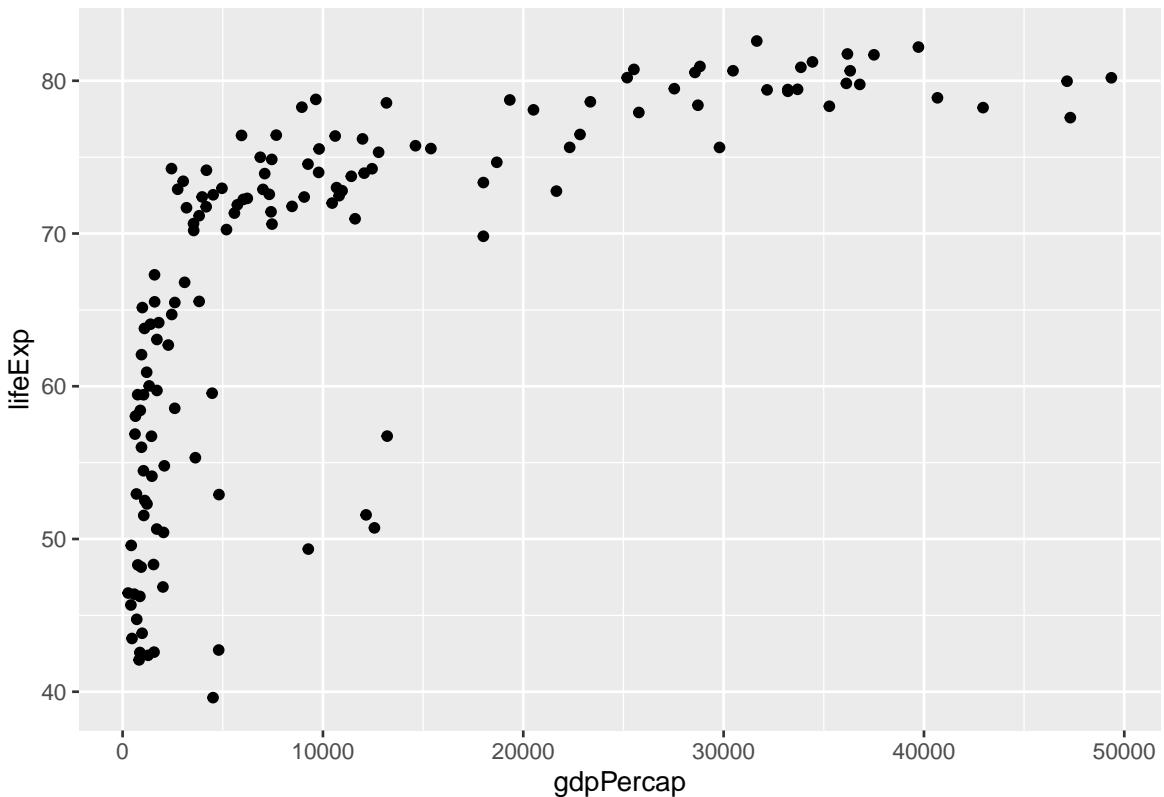
19.1.5 visualization statically with ggplot2

```
library(ggplot2)
```

```
## Warning: package 'ggplot2' was built under R version 4.2.3
```

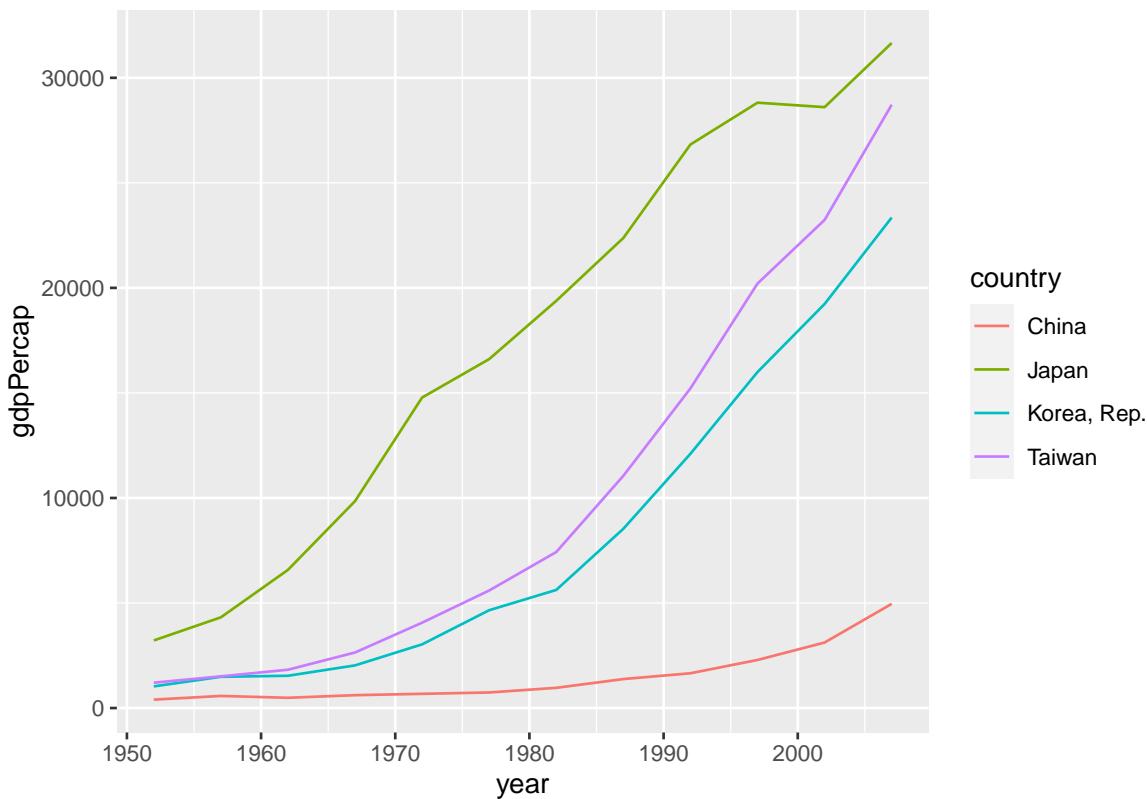
```
library(gapminder)

gapminder_2007 <- gapminder %>%
  filter(year == 2007)
scatter_plot <- ggplot(gapminder_2007, aes(x = gdpPercap, y = lifeExp)) +
  geom_point()
scatter_plot
```



```
library(ggplot2)
library(gapminder)

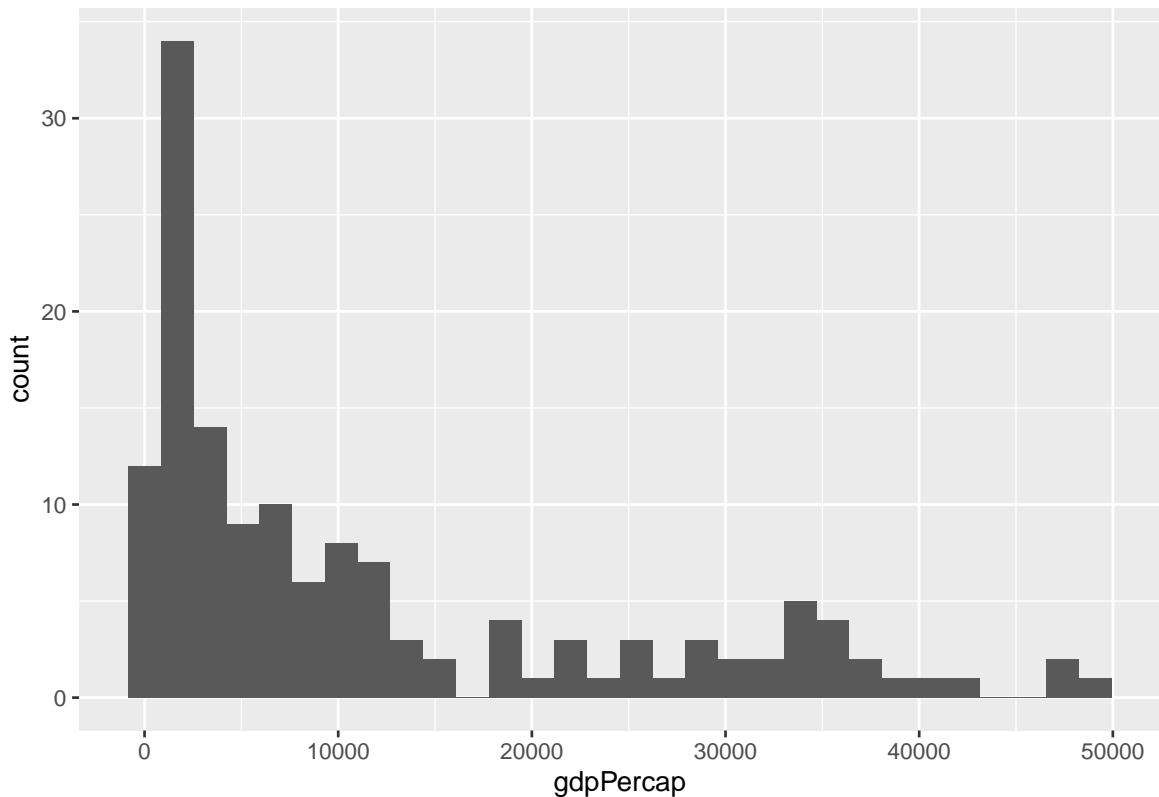
north_asia <- gapminder %>%
  filter(country %in% c("China", "Japan", "Taiwan", "Korea, Rep."))
line_plot <- ggplot(north_asia, aes(x = year, y = gdpPercap, colour = country)) +
  geom_line()
line_plot
```



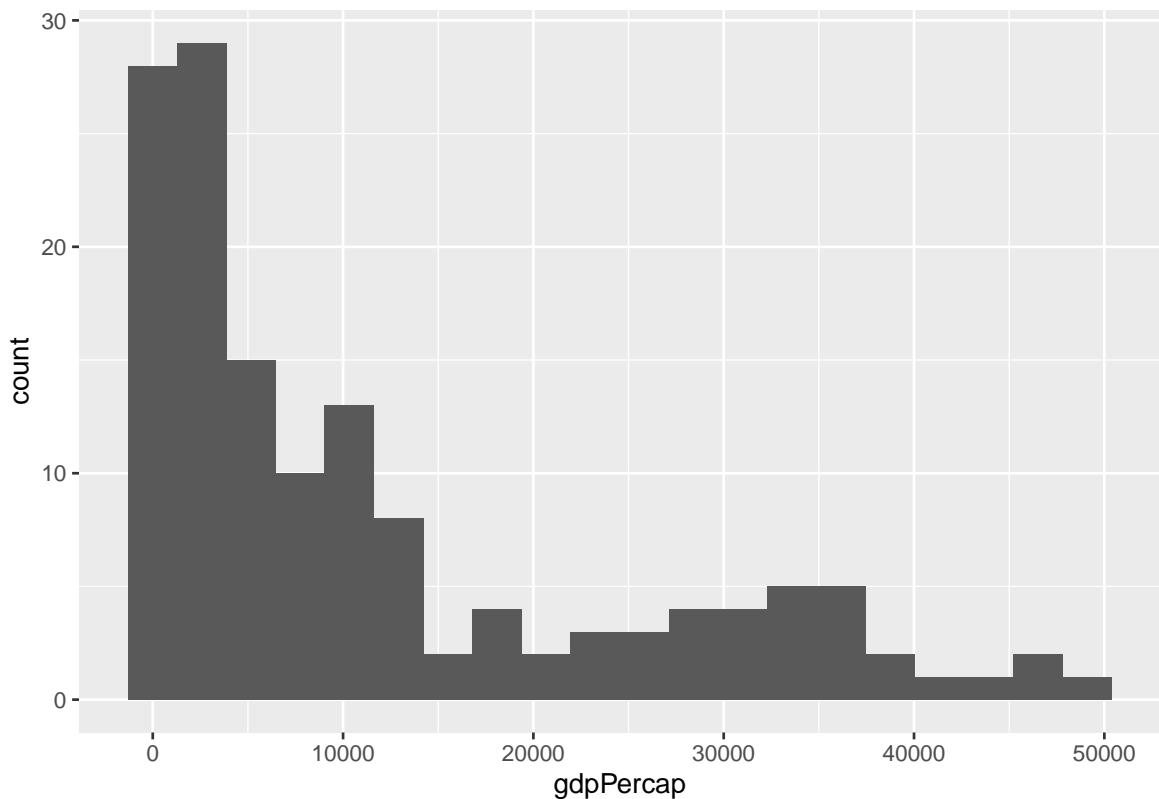
```
library(ggplot2)
library(gapminder)

hist_plot <- ggplot(gapminder_2007, aes(x = gdpPerCap)) +
  geom_histogram()
hist_plot

## `stat_bin()` using `bins = 30`. Pick better value with `binwidth`.
```

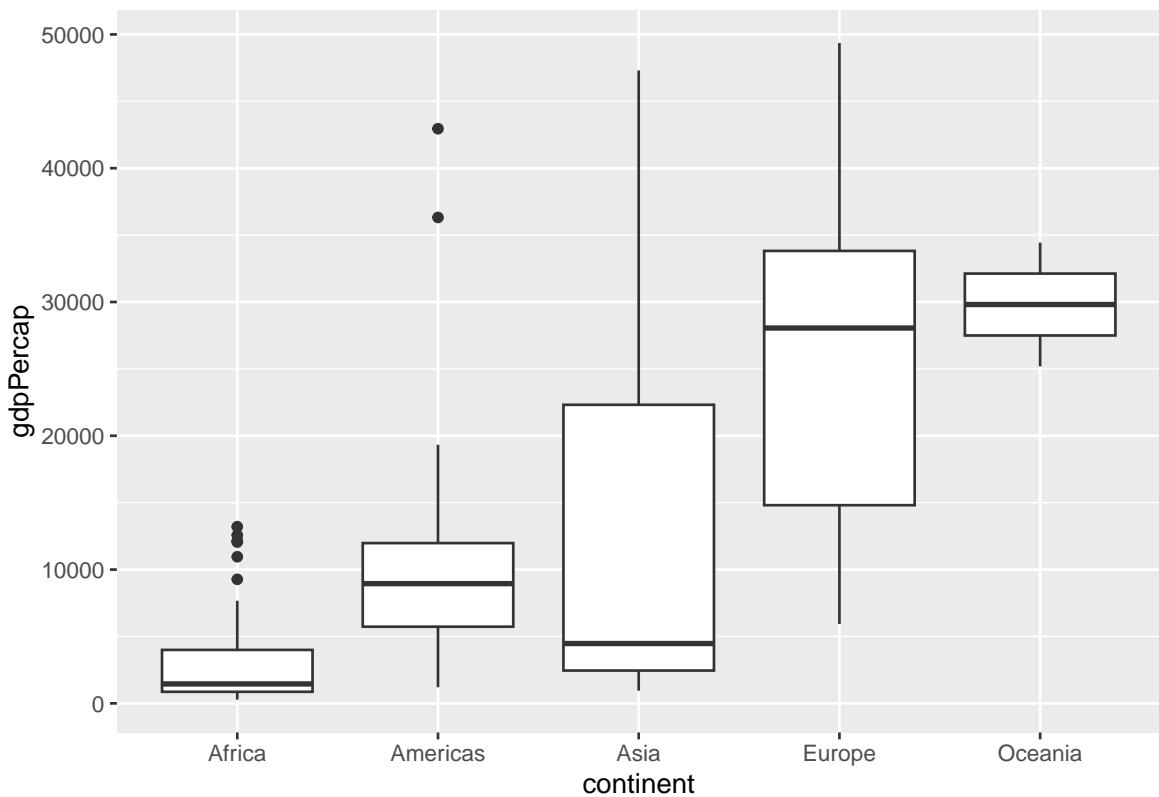


```
hist_plot <- ggplot(gapminder_2007, aes(x = gdpPercap)) +  
  geom_histogram(bins = 20)  
hist_plot
```



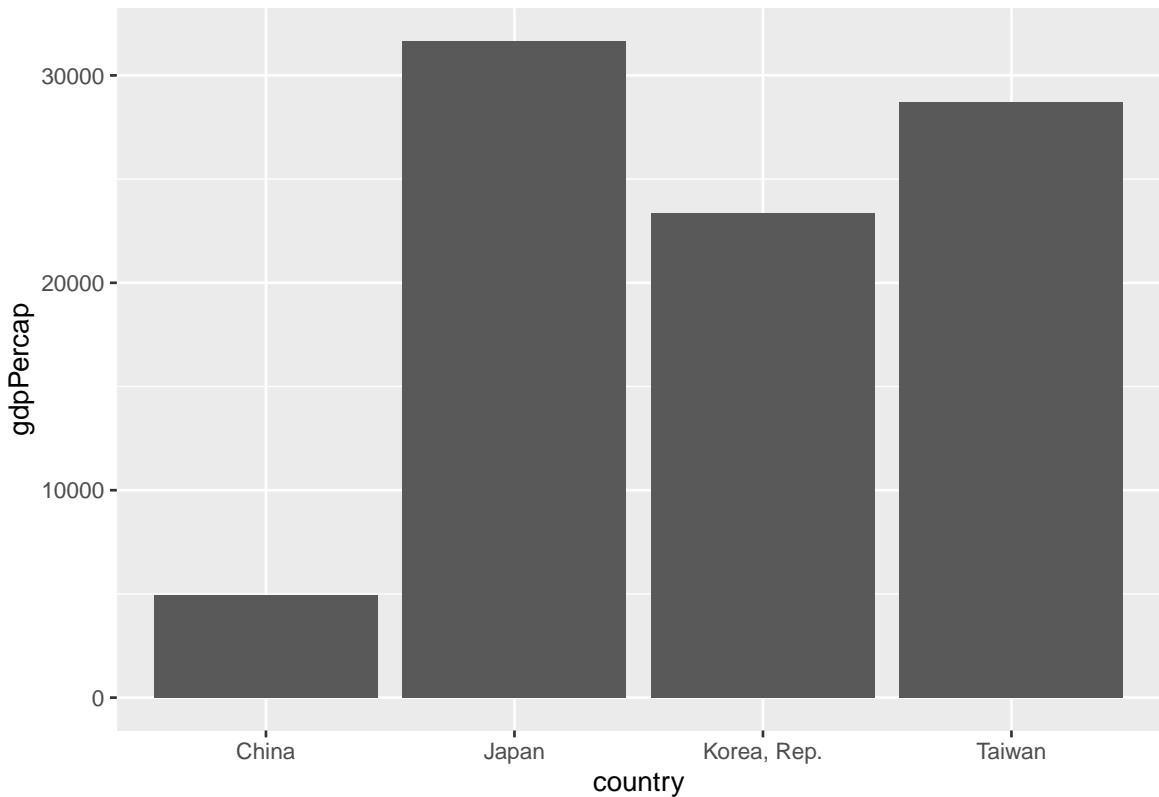
```
library(ggplot2)
library(gapminder)

box_plot <- ggplot(gapminder_2007, aes(x = continent, y = gdpPercap)) +
  geom_boxplot()
box_plot
```



```
library(ggplot2)
library(gapminder)

gdpPercap_2007_na <- gapminder %>%
  filter(year == 2007 & country %in% c("China", "Japan", "Taiwan", "Korea, Rep."))
bar_plot <- ggplot(gdpPercap_2007_na, aes(x = country, y = gdpPercap)) +
  geom_bar(stat = "identity")
bar_plot
```



19.1.6 loop

<https://bookdown.org/tonykuoyj/eloquentr/for.html>

```
month.name
```

```
## [1] "January"    "February"   "March"      "April"       "May"        "June"  
## [7] "July"        "August"      "September"  "October"     "November"   "December"
```

```
month.name[1]
```

```
## [1] "January"
```

```
for (month in month.name) {  
  print(month)  
}
```

```
## [1] "January"  
## [1] "February"  
## [1] "March"  
## [1] "April"
```

```
## [1] "May"
## [1] "June"
## [1] "July"
## [1] "August"
## [1] "September"
## [1] "October"
## [1] "November"
## [1] "December"
```

19.1.7 variable type

<https://bookdown.org/tonykuoyj/eloquentr/variable-types.html>

https://www.w3schools.com/r/r_data_types.asp

- numeric
- integer
- complex = complex number
- character
- logical = boolean

`class(2L)`

```
## [1] "integer"
```

`class(2.0L)`

```
## [1] "integer"
```

`class(2.3L)`

```
## [1] "numeric"
```

time: POSIXct POSIXt

`class(Sys.time())`

```
## [1] "POSIXct" "POSIXt"
```

`0 %in% -5:5`

```
## [1] TRUE
```

19.1.7.1 date

1970-01-01 = 0L

```
date_of_origin <- as.Date("1970-01-01")
as.integer(date_of_origin)
```

```
## [1] 0
```

check if type of x is Date

```
inherits(x, what = "Date")
```

convert character to Date

```
as.Date("01-01-1970", format = "%m-%d-%Y")
```

19.1.7.2 time

1970-01-01 00:00:00 GMT = 0L

tz = time zone

```
time_of_origin <- as.POSIXct("1970-01-01 00:00:00", tz = "GMT")
as.integer(time_of_origin)
```

```
## [1] 0
```

check if type of x is time

```
inherits(x, what = "POSIXct")
```

convert character to time

```
as.POSIXct("1970-01-01 00:00:00", tz = "GMT")
```

19.1.7.3 quotient %/% operator

https://www.w3schools.com/r/r_operators.asp

```
7 %/% 3
```

```
## [1] 2
```

19.1.8 data type

<https://bookdown.org/tonykuoyj/eloquentr/vector-factor.html>

- 1D
 - vector^[??]
 - factor^[??]
- 2D

- matrix^[??]
- data frame^[??]
- nD
 - array^[??]
 - list^[??]

19.1.8.1 vector

```
four_seasons <- c("spring", "summer", "autumn", "winter")
four_seasons
```

```
## [1] "spring" "summer" "autumn" "winter"
```

```
favorite_season <- four_seasons[3]
favorite_season
```

```
## [1] "autumn"
```

```
favorite_seasons <- four_seasons[c(-2, -4)]
favorite_seasons
```

```
## [1] "spring" "autumn"
```

only one variable type for a vector

```
lucky_numbers <- c(7L, 24)
class(lucky_numbers[1])
```

```
## [1] "numeric"
```

```
lucky_numbers <- c(7L, FALSE)
lucky_numbers
```

```
## [1] 7 0
```

```
class(lucky_numbers[2])
```

```
## [1] "integer"
```

```
mixed_vars <- c(TRUE, 7L, 24, "spring")
mixed_vars
```

```
## [1] "TRUE"    "7"       "24"      "spring"
```

```
class(mixed_vars[1])  
  
## [1] "character"  
  
class(mixed_vars[2])  
  
## [1] "character"  
  
class(mixed_vars[3])  
  
## [1] "character"  
  
  
four_seasons <- c("spring", "summer", "autumn", "winter")  
my_favorite_seasons <- four_seasons == "spring" | four_seasons == "autumn"  
four_seasons[my_favorite_seasons]
```

19.1.8.1.1 logic

```
## [1] "spring" "autumn"
```

```
rep(7L, times = 8)
```

19.1.8.1.2 rep repeat

```
## [1] 7 7 7 7 7 7 7 7
```

```
rep("R", times = 10)
```

```
## [1] "R" "R" "R" "R" "R" "R" "R" "R" "R" "R"
```

```
seq(from = 7, to = 77, by = 7)
```

19.1.8.1.3 seq sequence

```
## [1] 7 14 21 28 35 42 49 56 63 70 77
```

11:20

```
## [1] 11 12 13 14 15 16 17 18 19 20
```

19.1.8.2 factor

<https://bookdown.org/tonykuoyj/eloquentr/vector-factor.html#factor>

```
four_seasons <- c("spring", "summer", "autumn", "winter")
four_seasons
```

```
## [1] "spring" "summer" "autumn" "winter"
```

```
four_seasons_factor <- factor(four_seasons)
four_seasons_factor
```

```
## [1] spring summer autumn winter
## Levels: autumn spring summer winter
```

```
four_seasons <- c("spring", "summer", "autumn", "winter")
four_seasons_factor <- factor(four_seasons, ordered = TRUE, levels = c("summer",
  ↪ "winter", "spring", "autumn"))
four_seasons_factor
```

```
## [1] spring summer autumn winter
## Levels: summer < winter < spring < autumn
```

```
temperatures <- c("warm", "hot", "cold")
temp_factors <- factor(temperatures, ordered = TRUE, levels = c("cold", "warm",
  ↪ "hot"))
temp_factors
```

```
## [1] warm hot cold
## Levels: cold < warm < hot
```

if no levels specified, the levels will be specified alphabetically, sometimes not really true

```
temperatures <- c("warm", "hot", "cold")
temp_factors <- factor(temperatures, ordered = TRUE)
temp_factors
```

```
## [1] warm hot cold
## Levels: cold < hot < warm
```

19.1.8.3 matrix

<https://bookdown.org/tonykuoyj/eloquentr/matrix-dataframe-more.html>

```
my_mat <- matrix(1:6, nrow = 2)
my_mat

##      [,1] [,2] [,3]
## [1,]    1    3    5
## [2,]    2    4    6

class(my_mat)

## [1] "matrix" "array"

my_mat2 <- matrix(1:6, nrow = 2, byrow = TRUE)
my_mat2

##      [,1] [,2] [,3]
## [1,]    1    2    3
## [2,]    4    5    6

my_mat2[2, 3]

## [1] 6

my_mat2[2, ]

## [1] 4 5 6

my_mat2[, 3]

## [1] 3 6

filter <- my_mat2 < 6 & my_mat2 > 1
my_mat2[filter]

## [1] 4 2 5 3

boolean will become value in a matrix, like vector

my_mat3 <- matrix(c(1, 2, TRUE, FALSE, 3, 4), nrow = 2)
my_mat3

##      [,1] [,2] [,3]
## [1,]    1    1    3
## [2,]    2    0    4
```

```
class(my_mat3[, 2])
```

```
## [1] "numeric"
```

19.1.8.4 data frame

- variable: column
- observation: row
- value: cell

```
team_name <- c("Chicago Bulls", "Golden State Warriors")
```

```
wins <- c(72, 73)
```

```
losses <- c(10, 9)
```

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

```
season <- c("1995-96", "2015-16")
```

```
great_nba_teams <- data.frame(team_name, wins, losses, is_champion, season)
```

```
great_nba_teams
```

```
##              team_name wins losses is_champion   season
```

```
## 1      Chicago Bulls    72     10       TRUE 1995-96
```

```
## 2 Golden State Warriors    73      9      FALSE 2015-16
```

```
great_nba_teams[1, 1]
```

```
## [1] "Chicago Bulls"
```

```
great_nba_teams[1, ]
```

```
##              team_name wins losses is_champion   season
```

```
## 1 Chicago Bulls    72     10       TRUE 1995-96
```

```
great_nba_teams[, 1]
```

```
## [1] "Chicago Bulls"           "Golden State Warriors"
```

```
stringsAsFactors = TRUE
```

```
team_name <- c("Chicago Bulls", "Golden State Warriors")
```

```
wins <- c(72, 73)
```

```
losses <- c(10, 9)
```

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

```
season <- c("1995-96", "2015-16")
```

```
great_nba_teams <- data.frame(team_name, wins, losses, is_champion, season,
  ↪ stringsAsFactors = TRUE)
```

```
great_nba_teams[, 1]
```

```

## [1] Chicago Bulls      Golden State Warriors
## Levels: Chicago Bulls Golden State Warriors

stringsAsFactors = FALSE

team_name <- c("Chicago Bulls", "Golden State Warriors")
wins <- c(72, 73)
losses <- c(10, 9)
is_champion <- c(TRUE, FALSE)
season <- c("1995-96", "2015-16")

great_nba_teams <- data.frame(team_name, wins, losses, is_champion, season,
  ↪ stringsAsFactors = FALSE)
great_nba_teams[, 1]

```

```
## [1] "Chicago Bulls"      "Golden State Warriors"
```

```
great_nba_teams$team_name
```

19.1.8.4.1 selecting variable or column

```

## [1] "Chicago Bulls"      "Golden State Warriors"

great_nba_teams[, "team_name"]
```

```
## [1] "Chicago Bulls"      "Golden State Warriors"
```

```

filter <- great_nba_teams$is_champion == TRUE
great_nba_teams[filter, ]
```

19.1.8.4.2 filtering observation or row

```

##      team_name wins losses is_champion   season
## 1 Chicago Bulls    72     10       TRUE 1995-96
```

```
str(great_nba_teams)
```

19.1.8.4.3 check mixed data type

```
## 'data.frame':   2 obs. of  5 variables:
##   $ team_name  : chr  "Chicago Bulls" "Golden State Warriors"
##   $ wins       : num  72 73
##   $ losses     : num  10 9
##   $ is_champion: logi  TRUE FALSE
##   $ season     : chr  "1995-96" "2015-16"
```

19.2 W3School

<https://www.w3schools.com/r/default.asp>

19.2.1 same multiple variable

https://www.w3schools.com/r/r_variables_multiple.asp

```
# Assign the same value to multiple variables in one line
var1 <- var2 <- var3 <- "Orange"
```

```
# Print variable values
```

```
var1
```

```
## [1] "Orange"
```

```
var2
```

```
## [1] "Orange"
```

```
var3
```

```
## [1] "Orange"
```

19.2.2 legal variable name

https://www.w3schools.com/r/r_variables_name.asp

```
# Legal variable names:
```

```
myvar <- "John"
my_var <- "John"
myVar <- "John"
MYVAR <- "John"
myvar2 <- "John"
.myvar <- "John"
```

```
## Illegal variable names:
```

```
# 2myvar <- "John"
```

```
# my-var <- "John"  
# my var <- "John"  
# _my_var <- "John"  
# my_v@ar <- "John"  
# TRUE <- "John"
```

19.2.3 complex number

https://www.w3schools.com/r/r_data_types.asp

https://www.w3schools.com/r/r_numbers.asp

19.2.4 escape character

https://www.w3schools.com/r/r_strings_esc.asp

19.2.5 global assignment <<-

```
my_function <- function() {  
  txt <- "fantastic"  
  paste("R is", txt)  
}  
  
my_function()
```

[1] "R is fantastic"

```
print(txt)
```

[1] "fantastic"

```
txt <- "awesome"  
my_function <- function() {  
  txt <- "fantastic"  
  paste("R is", txt)  
}
```

```
my_function()
```

[1] "R is fantastic"

```
paste("R is", txt)
```

[1] "R is fantastic"

19.2.6 data type

19.2.6.1 array

https://www.w3schools.com/r/r_arrays.asp

```
# An array with one dimension with values ranging from 1 to 24
```

```
thisarray <- c(1:24)
```

```
thisarray
```

```
## [1] 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
```

```
# An array with more than one dimension
```

```
multiarray <- array(thisarray, dim = c(4, 3, 2))
```

```
multiarray
```

```
## , , 1
```

```
##
```

```
## [,1] [,2] [,3]
```

```
## [1,] 1 5 9
```

```
## [2,] 2 6 10
```

```
## [3,] 3 7 11
```

```
## [4,] 4 8 12
```

```
##
```

```
## , , 2
```

```
##
```

```
## [,1] [,2] [,3]
```

```
## [1,] 13 17 21
```

```
## [2,] 14 18 22
```

```
## [3,] 15 19 23
```

```
## [4,] 16 20 24
```

```
multiarray[2, 3, 2]
```

```
## [1] 22
```

19.2.6.2 list

https://www.w3schools.com/r/r_lists.asp

19.3 Apan Liao

R

<https://www.youtube.com/playlist?list=PL5AC0ADBF65924EAD>

19.3.1 data input

https://www.youtube.com/watch?v=STcIxf_vUWY&list=PL5AC0ADBF65924EAD&index=1

- `scan()`
- `read`
 - `read.table()`
 - `read.csv()`

19.3.2 descriptive statistics

https://www.youtube.com/watch?v=GL3Wv_45LaU&list=PL5AC0ADBF65924EAD&index=2

Chapter 20

Laplace transform

Chapter 21

conic section

conic section /

https://en.wikipedia.org/wiki/Conic_section

<https://tex.stackexchange.com/questions/222882/drawing-minimal-xy-axis>

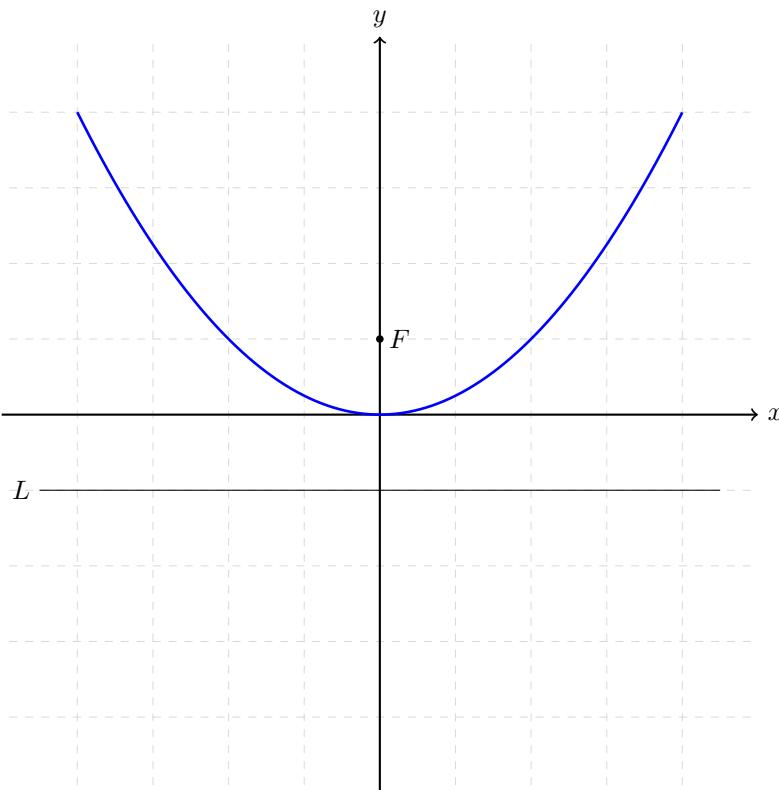


Figure 21.1: parabola defined by focus, directrix, eccentricity

21.1 Cartesian coordinate: focus, directrix, eccentricity

focus, directrix, eccentricity , ,

$$\begin{cases} F = (0, y_F) & F : \text{focus} \\ L = y - y_L = 0 & L : \text{directrix} \\ \epsilon = \frac{\overline{PF}}{d(P, L)} = \frac{\|(x, y) - (0, y_F)\|}{\|y - y_L\|} & \begin{cases} P = (x, y) \\ \epsilon : \text{eccentricity} \end{cases} \end{cases}$$

$$0 \leq \epsilon = \frac{\overline{PF}}{d(P, L)} = \frac{\overline{PF}}{\overline{PP'}} = \frac{\|(x, y) - (0, y_F)\|}{\|(x, y) - (x, y_L)\|} = \frac{\|(x, y - y_F)\|}{\|(0, y - y_L)\|} = \frac{\sqrt{x^2 + (y - y_F)^2}}{\sqrt{(y - y_L)^2}} \quad (21.1)$$

$$\epsilon^2 = \frac{x^2 + (y - y_F)^2}{(y - y_L)^2} = \frac{x^2 + y^2 - 2y_F y + y_F^2}{y^2 - 2y_L y + y_L^2} \quad (21.2)$$

$$0 = x^2 + (1 - \epsilon^2) y^2 - 2(y_F - \epsilon^2 y_L) y + (y_F^2 - \epsilon^2 y_L^2) \quad (21.3)$$

$$\stackrel{\epsilon \neq 1}{=} x^2 + (1 - \epsilon^2) \left[y^2 - \frac{2(y_F - \epsilon^2 y_L)}{1 - \epsilon^2} y + \frac{y_F^2 - \epsilon^2 y_L^2}{1 - \epsilon^2} \right] \quad (21.4)$$

$$= x^2 + (1 - \epsilon^2) \quad (21.5)$$

$$\left[y^2 - \frac{2(y_F - \epsilon^2 y_L)}{1 - \epsilon^2} y + \left(\frac{y_F - \epsilon^2 y_L}{1 - \epsilon^2} \right)^2 - \left(\frac{y_F - \epsilon^2 y_L}{1 - \epsilon^2} \right)^2 + \frac{y_F^2 - \epsilon^2 y_L^2}{1 - \epsilon^2} \right] \quad (21.6)$$

$$= x^2 + (1 - \epsilon^2) \left[\left(y - \frac{y_F - \epsilon^2 y_L}{1 - \epsilon^2} \right)^2 + \frac{(y_F^2 - \epsilon^2 y_L^2)(1 - \epsilon^2) - (y_F - \epsilon^2 y_L)^2}{(1 - \epsilon^2)^2} \right] \quad (21.7)$$

$$= x^2 + (1 - \epsilon^2) \left(y - \frac{y_F - \epsilon^2 y_L}{1 - \epsilon^2} \right)^2 + \frac{(y_F^2 - \epsilon^2 y_L^2)(1 - \epsilon^2) - (y_F - \epsilon^2 y_L)^2}{1 - \epsilon^2} \quad (21.8)$$

$$\begin{aligned} & (y_F^2 - \epsilon^2 y_L^2)(1 - \epsilon^2) - (y_F - \epsilon^2 y_L)^2 \\ &= (1 - \epsilon^2) y_F^2 - (\epsilon^2 - \epsilon^4) y_L^2 - y_F^2 + 2\epsilon^2 y_F y_L - \epsilon^4 y_L^2 \\ &= -\epsilon^2 y_F^2 - \epsilon^2 y_L^2 + 2\epsilon^2 y_F y_L = -\epsilon^2 (y_F - y_L)^2 \end{aligned}$$

$$\begin{aligned} \frac{\epsilon^2 (y_F - y_L)^2}{1 - \epsilon^2} &\stackrel{\epsilon \neq 1}{=} x^2 + (1 - \epsilon^2) \left(y - \frac{y_F - \epsilon^2 y_L}{1 - \epsilon^2} \right)^2 \\ &\stackrel{\epsilon \neq 0, 1}{=} 1 \begin{cases} \left(\frac{x - 0}{\frac{\epsilon(y_F - y_L)}{\sqrt{1 - \epsilon^2}}} \right)^2 + \left(\frac{y - \frac{y_F - \epsilon^2 y_L}{1 - \epsilon^2}}{\frac{\epsilon(y_F - y_L)}{1 - \epsilon^2}} \right)^2 & 1 - \epsilon^2 > 0 \Rightarrow 0 < \epsilon < 1 \\ -\left(\frac{x - 0}{\frac{\epsilon(y_F - y_L)}{\sqrt{\epsilon^2 - 1}}} \right)^2 + \left(\frac{y - \frac{y_F - \epsilon^2 y_L}{1 - \epsilon^2}}{\frac{\epsilon(y_F - y_L)}{1 - \epsilon^2}} \right)^2 & 1 - \epsilon^2 < 0 \Rightarrow \epsilon > 1 \end{cases} \end{aligned}$$

$$\epsilon = 0 \text{ or } \lim_{|y_L| \rightarrow \infty} \epsilon = 0$$

$$r = \overline{PF} = \|(x, y) - (0, y_F)\| = \|(x, y - y_F)\| = \sqrt{x^2 + (y - y_F)^2}$$

$$\epsilon = \frac{r}{d(P, L)} = \frac{\overline{PF}}{\overline{PP'}} = \frac{\|(x, y) - (0, y_F)\|}{\|(x, y) - (x, y_L)\|} = \frac{\|(x, y - y_F)\|}{\|(0, y - y_L)\|} = \frac{\sqrt{x^2 + (y - y_F)^2}}{|y - y_L|}$$

$$\lim_{|y_L| \rightarrow \infty} \epsilon = \lim_{|y_L| \rightarrow \infty} \frac{r}{d(P, L)} = \lim_{|y_L| \rightarrow \infty} \frac{\sqrt{x^2 + (y - y_F)^2}}{|y - y_L|} = 0$$

$$\epsilon = 1$$

$$\begin{aligned} 0 &= x^2 + (1 - \epsilon^2) y^2 - 2(y_F - \epsilon^2 y_L) y + (y_F^2 - \epsilon^2 y_L^2) \\ &\stackrel{\epsilon=1}{=} x^2 + (1 - 1^2) y^2 - 2(y_F - 1^2 y_L) y + (y_F^2 - 1^2 y_L^2) \\ &= x^2 - 2(y_F - y_L) y + (y_F^2 - y_L^2) \\ &= x^2 - 2(y_F - y_L) y + (y_F + y_L)(y_F - y_L) \\ x^2 &= 2(y_F - y_L) \left(y - \frac{y_F + y_L}{2} \right) \end{aligned}$$

Let one curve vertex $P = V = (0, 0)$ on the curve, and fix the directrix L or y_L ,

$$\epsilon \neq 1$$

$$\begin{aligned} 1 &\stackrel{P(x,y)=V(0,0)}{=} 0 + \left(\frac{0 - \frac{y_F - \epsilon^2 y_L}{1 - \epsilon^2}}{\frac{\epsilon(y_F - y_L)}{1 - \epsilon^2}} \right)^2 \\ &\Rightarrow y_F - \epsilon^2 y_L = \pm \epsilon(y_F - y_L) \\ &\Rightarrow \begin{cases} (1 - \epsilon)y_F = \epsilon(\epsilon - 1)y_L & + \\ (1 + \epsilon)y_F = \epsilon(\epsilon + 1)y_L & - \end{cases} \\ &\Rightarrow y_F = \begin{cases} -\epsilon y_L & + \\ \epsilon y_L & - \end{cases} \end{aligned}$$

$$\epsilon = 1$$

$$\begin{aligned} x^2 &= 2(y_F - y_L) \left(y - \frac{y_F + y_L}{2} \right) \\ &\stackrel{P(x,y)=V(0,0)}{\Rightarrow} 0^2 = 2(y_F - y_L) \left(0 - \frac{y_F + y_L}{2} \right) \\ &\Rightarrow 0 = (y_F - y_L)(y_F + y_L) \\ &\Rightarrow y_F = \mp y_L \end{aligned}$$

or by definition of eccentricity (??)

$$0 \leq \epsilon = \frac{\overline{PF}}{d(P, L)} = \frac{\overline{PF}}{\overline{PP'}} = \frac{\|(x, y) - (0, y_F)\|}{\|(x, y) - (x, y_L)\|} = \frac{\|(x, y - y_F)\|}{\|(0, y - y_L)\|} = \frac{\sqrt{x^2 + (y - y_F)^2}}{\sqrt{(y - y_L)^2}}$$

$$\stackrel{P(x,y)=V(0,0)}{=} \frac{\sqrt{0^2 + (0 - y_F)^2}}{\sqrt{(0 - y_L)^2}} = \sqrt{\left(\frac{y_F}{y_L}\right)^2}$$

$$\epsilon^2 = \left(\frac{y_F}{y_L}\right)^2 \Rightarrow y_F = \mp \epsilon y_L$$

actually,

$$y_F = -\epsilon y_L$$

21.2 two-definition equivalence for ellipse and hyperbola

<https://math.stackexchange.com/questions/1833973/prove-that-the-directrix-focus-and-focus-focus-definitions-are-equivalent>

<https://www.geogebra.org/calculator/zkppuxwp>

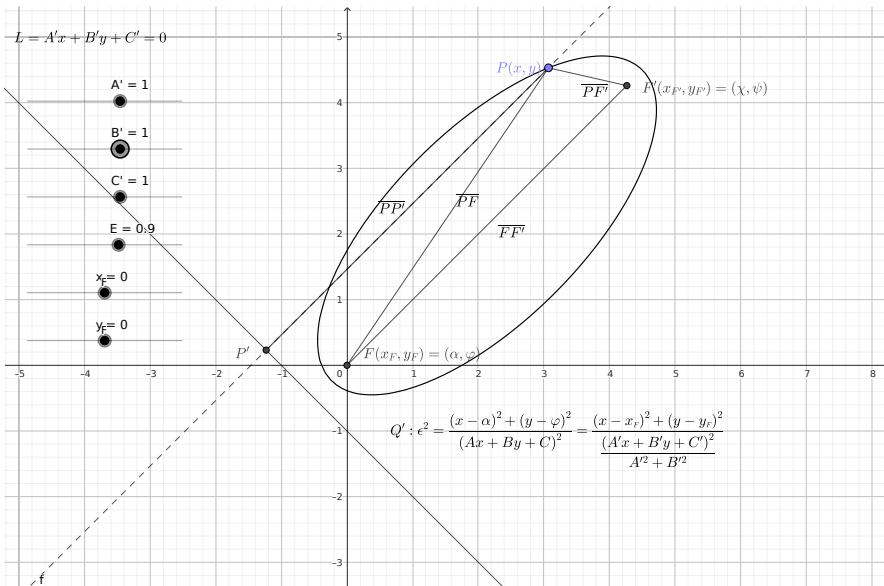


Figure 21.2: conic sections

$$\begin{cases} P = (x, y) \\ F = (x_F, y_F) = (\alpha, \varphi) & F' = (x_{F'}, y_{F'}) = (\chi, \psi) \\ L = A'x + B'y + C' = 0 \end{cases}$$

21.2.1 first definition for conic sections including ellipses and hyperbolas

distance from a point to a line^[??]

$$0 \leq \epsilon = \frac{\overline{PF}}{d(P, L)} = \frac{\sqrt{(x - x_F)^2 + (y - y_F)^2}}{\frac{|A'x + B'y + C'|}{\sqrt{A'^2 + B'^2}}} = \frac{\sqrt{(x - \alpha)^2 + (y - \varphi)^2}}{|Ax + By + C|}, \begin{cases} A = \frac{A'}{\sqrt{A'^2 + B'^2}} \\ B = \frac{B'}{\sqrt{A'^2 + B'^2}} \\ C = \frac{C'}{\sqrt{A'^2 + B'^2}} \end{cases}$$

$$A^2 + B^2 = \left(\frac{A'}{\sqrt{A'^2 + B'^2}} \right)^2 + \left(\frac{B'}{\sqrt{A'^2 + B'^2}} \right)^2 = 1$$

or allowing $\epsilon < 0$ by squaring the definition

$$\epsilon^2 = \frac{(x - \alpha)^2 + (y - \varphi)^2}{(Ax + By + C)^2} = \frac{(x - x_F)^2 + (y - y_F)^2}{\frac{(A'x + B'y + C')^2}{A'^2 + B'^2}}$$

$$(x - \alpha)^2 + (y - \varphi)^2 = [\epsilon(Ax + By + C)]^2$$

21.2.2 second definition for ellipses and hyperbolas

$$2c = \overline{FF'} = \|(x_F, y_F) - (x_{F'}, y_{F'})\| = \|(\alpha, \varphi) - (\chi, \psi)\| \\ = \sqrt{(\alpha - \chi)^2 + (\chi - \psi)^2}$$

$$D = \begin{cases} \sqrt{(x - x_F)^2 + (y - y_F)^2} + \sqrt{(x - x_{F'})^2 + (y - y_{F'})^2} & \text{ellipse} \\ \sqrt{(x - x_F)^2 + (y - y_F)^2} - \sqrt{(x - x_{F'})^2 + (y - y_{F'})^2} & \text{hyperbola} \end{cases} \\ = \sqrt{(x - x_F)^2 + (y - y_F)^2} \pm \sqrt{(x - x_{F'})^2 + (y - y_{F'})^2} \\ = \sqrt{(x - \alpha)^2 + (y - \varphi)^2} \pm \sqrt{(x - \chi)^2 + (y - \psi)^2}$$

$$(x - \alpha)^2 + (y - \varphi)^2 = \left(D \mp \sqrt{(x - \chi)^2 + (y - \psi)^2} \right)^2 \\ = D^2 \mp 2D\sqrt{(x - \chi)^2 + (y - \psi)^2} \\ + (x - \chi)^2 + (y - \psi)^2$$

$$\begin{aligned}
D^2 &= (x - \alpha)^2 + (y - \varphi)^2 + (x - \chi)^2 + (y - \psi)^2 \\
&\quad \pm 2\sqrt{[(x - \alpha)^2 + (y - \varphi)^2][(x - \chi)^2 + (y - \psi)^2]} \\
&\quad [(x - \alpha)^2 + (y - \varphi)^2 + (x - \chi)^2 + (y - \psi)^2 - D^2] \\
&= \mp 2\sqrt{[(x - \alpha)^2 + (y - \varphi)^2][(x - \chi)^2 + (y - \psi)^2]} \\
&\quad [(x - \alpha)^2 + (y - \varphi)^2 + (x - \chi)^2 + (y - \psi)^2]^2 + D^4 \\
&\quad - 2D^2 [(x - \alpha)^2 + (y - \varphi)^2 + (x - \chi)^2 + (y - \psi)^2] \\
&= 4[(x - \alpha)^2 + (y - \varphi)^2][(x - \chi)^2 + (y - \psi)^2] \\
&\quad [(x - \alpha)^2 + (y - \varphi)^2]^2 + [(x - \chi)^2 + (y - \psi)^2]^2 \\
&\quad + 2[(x - \alpha)^2 + (y - \varphi)^2][(x - \chi)^2 + (y - \psi)^2] + D^4 \\
&\quad - 2D^2 [(x - \alpha)^2 + (y - \varphi)^2 + (x - \chi)^2 + (y - \psi)^2] \\
&= 4[(x - \alpha)^2 + (y - \varphi)^2][(x - \chi)^2 + (y - \psi)^2] \\
0 &= [(x - \alpha)^2 + (y - \varphi)^2]^2 + [(x - \chi)^2 + (y - \psi)^2]^2 \\
&\quad - 2[(x - \alpha)^2 + (y - \varphi)^2][(x - \chi)^2 + (y - \psi)^2] + D^4 \\
&\quad - 2D^2 [(x - \alpha)^2 + (y - \varphi)^2 + (x - \chi)^2 + (y - \psi)^2] \\
0 &= \left\{ [(x - \alpha)^2 + (y - \varphi)^2] - [(x - \chi)^2 + (y - \psi)^2] \right\}^2 + D^4 \\
&\quad - 2D^2 \left\{ [(x - \alpha)^2 + (y - \varphi)^2] + [(x - \chi)^2 + (y - \psi)^2] \right\} \\
0 &= \left\{ [(x - \chi)^2 + (y - \psi)^2] - [(x - \alpha)^2 + (y - \varphi)^2] \right\}^2 + D^4 \\
&\quad - 2D^2 \left\{ [(x - \chi)^2 + (y - \psi)^2] - [(x - \alpha)^2 + (y - \varphi)^2] \right\} \\
&\quad - 4D^2 [(x - \alpha)^2 + (y - \varphi)^2] \\
&\quad (2D)^2 [(x - \alpha)^2 + (y - \varphi)^2] \\
&= \left\{ [(x - \chi)^2 + (y - \psi)^2] - [(x - \alpha)^2 + (y - \varphi)^2] - D^2 \right\}^2 \\
&= \left\{ [(x - \chi)^2 - (x - \alpha)^2] + [(y - \psi)^2 - (y - \varphi)^2] - D^2 \right\}^2 \\
&= \{(2x - \chi - \alpha)(\alpha - \chi) + (2y - \psi - \varphi)(\varphi - \psi) - D^2\}^2 \\
&= \{2(\alpha - \chi)x - (\alpha^2 - \chi^2) + 2(\varphi - \psi)y - (\varphi^2 - \psi^2) - D^2\}^2 \\
&= \{2(\alpha - \chi)x + 2(\varphi - \psi)y - [(\alpha^2 - \chi^2) + (\varphi^2 - \psi^2) + D^2]\}^2
\end{aligned}$$

$D \neq 0$

$$\begin{aligned}
&(x - \alpha)^2 + (y - \varphi)^2 \\
&= \left[\frac{\alpha - \chi}{D}x + \frac{\varphi - \psi}{D}y - \left(\frac{\alpha^2 - \chi^2}{2D} + \frac{\varphi^2 - \psi^2}{2D} + \frac{D}{2} \right) \right]^2
\end{aligned}$$

$$\begin{cases}
(x - \alpha)^2 + (y - \varphi)^2 = [\epsilon(Ax + By + C)]^2 \\
(x - \alpha)^2 + (y - \varphi)^2 = \left[\frac{\alpha - \chi}{D}x + \frac{\varphi - \psi}{D}y - \left(\frac{\alpha^2 - \chi^2}{2D} + \frac{\varphi^2 - \psi^2}{2D} + \frac{D}{2} \right) \right]^2
\end{cases}$$

$$(A, B, C) \rightleftarrows (\chi, \psi, D)$$

$$\begin{cases} \epsilon A = \pm \frac{\alpha - \chi}{D} & \chi \pm \epsilon AD = \alpha \\ \epsilon B = \pm \frac{\varphi - \psi}{D} & \psi \pm \epsilon BD = \varphi \\ \epsilon C = \mp \left(\frac{\alpha^2 - \chi^2}{2D} + \frac{\varphi^2 - \psi^2}{2D} + \frac{D}{2} \right) \end{cases}$$

$$\begin{aligned} 2\epsilon C &= \mp \left(\frac{\alpha - \chi}{D} (\alpha + \chi) + \frac{\varphi - \psi}{D} (\varphi + \psi) + D \right) \\ &= \mp (\pm \epsilon A (\alpha + \chi) \pm \epsilon B (\varphi + \psi) + D) \\ \mp \epsilon (A\alpha + B\varphi + 2C) &= \pm \epsilon A\chi \pm \epsilon B\psi + D \end{aligned}$$

$$\begin{pmatrix} 1 & 0 & \pm \epsilon A \\ 0 & 1 & \pm \epsilon B \\ \pm \epsilon A & \pm \epsilon B & 1 \end{pmatrix} \begin{pmatrix} \chi \\ \psi \\ D \end{pmatrix} = \begin{pmatrix} \alpha \\ \varphi \\ \mp \epsilon (A\alpha + B\varphi + 2C) \end{pmatrix}$$

$$\begin{pmatrix} 1 & 0 & \pm \epsilon A & \alpha \\ 0 & 1 & \pm \epsilon B & \varphi \\ 0 & \pm \epsilon B & 1 \mp \epsilon^2 A^2 & \mp \epsilon (2A\alpha + B\varphi + 2C) \end{pmatrix}$$

$$\begin{pmatrix} 1 & 0 & \pm \epsilon A & \alpha \\ 0 & 1 & \pm \epsilon B & \varphi \\ 0 & 0 & 1 \mp \epsilon^2 A^2 \mp \epsilon^2 B^2 & \mp \epsilon (2A\alpha + 2B\varphi + 2C) \end{pmatrix}$$

$$\begin{pmatrix} 1 & 0 & \pm \epsilon A & \alpha \\ 0 & 1 & \pm \epsilon B & \varphi \\ 0 & 0 & 1 & \frac{\mp 2\epsilon (A\alpha + B\varphi + C)}{1 \mp \epsilon^2 (A^2 + B^2)} \end{pmatrix}$$

$$A^2 + B^2 = \left(\frac{A'}{\sqrt{A'^2 + B'^2}} \right)^2 + \left(\frac{B'}{\sqrt{A'^2 + B'^2}} \right)^2 = 1$$

$$\begin{cases} \chi = \alpha \mp \epsilon AD = \alpha \mp \epsilon \frac{A'}{\sqrt{A'^2 + B'^2}} D \\ \psi = \varphi \mp \epsilon BD = \varphi \mp \epsilon \frac{B'}{\sqrt{A'^2 + B'^2}} D \\ D = \frac{\mp 2\epsilon (A\alpha + B\varphi + C)}{1 \mp \epsilon^2 (A^2 + B^2)} = \frac{\mp 2\epsilon}{1 \mp \epsilon^2} \frac{A'\alpha + B'\varphi + C'}{\sqrt{A'^2 + B'^2}} \quad A^2 + B^2 = 1 \end{cases}$$

actually, only one of two solutions is true

$$\begin{cases} \chi = \alpha - \epsilon AD = \alpha - \epsilon \frac{A'}{\sqrt{A'^2 + B'^2}} D = \alpha - \frac{2\epsilon^2}{\epsilon^2 - 1} \frac{A'^2 \alpha + A' B' \varphi + A' C'}{A'^2 + B'^2} \\ \psi = \varphi - \epsilon BD = \varphi - \epsilon \frac{B'}{\sqrt{A'^2 + B'^2}} D = \varphi - \frac{2\epsilon^2}{\epsilon^2 - 1} \frac{A' B' \alpha + B'^2 \varphi + B' C'}{A'^2 + B'^2} \\ D = \frac{-2\epsilon (A\alpha + B\varphi + C)}{1 - \epsilon^2 (A^2 + B^2)} = \frac{-2\epsilon}{1 - \epsilon^2} \frac{A' \alpha + B' \varphi + C'}{\sqrt{A'^2 + B'^2}} = \frac{2\epsilon}{\epsilon^2 - 1} \frac{A' \alpha + B' \varphi + C'}{\sqrt{A'^2 + B'^2}} \end{cases}$$

$$\left\{ \begin{array}{l} \chi = \frac{(\epsilon^2 - 1)(A'^2 + B'^2)\alpha - 2\epsilon^2(A'^2\alpha + A'B'\varphi + A'C')}{(\epsilon^2 - 1)(A'^2 + B'^2)} \\ \psi = \frac{(\epsilon^2 - 1)(A'^2 + B'^2)\varphi - 2\epsilon^2(A'B'\alpha + B'^2\varphi + B'C')}{(\epsilon^2 - 1)(A'^2 + B'^2)} \\ \left| \frac{D}{d(F, L)} \right| = \left| \frac{2\epsilon}{1 - \epsilon^2} \right| \Rightarrow \left(\frac{D}{d(F, L)} \right)^2 = \left(\frac{2\epsilon}{1 - \epsilon^2} \right)^2 \end{array} \right.$$

$$\begin{aligned} & (\epsilon^2 - 1)(A'^2 + B'^2)\alpha - 2\epsilon^2(A'^2\alpha + A'B'\varphi + A'C') \\ &= (-(\epsilon^2 + 1)A'^2 + (\epsilon^2 - 1)B'^2)\alpha - 2\epsilon^2(A'B'\varphi + A'C') \\ &= (-(\epsilon^2 + 1)A'^2 + (\epsilon^2 - 1)B'^2)\alpha - 2\epsilon^2(A'B'\varphi + A'C') \end{aligned}$$

Can the above be more simplified?

$$\begin{aligned} \overline{FF'}^2 &= (\alpha - \chi)^2 + (\varphi - \psi)^2 \\ &= (\alpha - (\alpha - \epsilon AD))^2 + (\varphi - (\varphi - \epsilon BD))^2 \\ &= (\epsilon D)^2 (A^2 + B^2) \\ &= (\epsilon D)^2 \end{aligned}$$

21.2.3 eccentricity and its equivalent representation

$$\left(\frac{c}{a} \right)^2 = \left(\frac{\overline{PF}}{d(P, L)} \right)^2 = \epsilon^2 = \left(\frac{\overline{FF'}}{D} \right)^2 = \left(\frac{2c}{D} \right)^2 \Rightarrow D = 2a$$

$$\left(\frac{D}{d(F, L)} \right)^2 = \left(\frac{2\epsilon}{1 - \epsilon^2} \right)^2$$

21.3 Cartesian coordinate: standard form / standard equation

circle	$\left(\frac{y - k}{a} \right)^2 + \left(\frac{x - h}{a} \right)^2 = 1$	$b = a$
ellipse	$\left(\frac{y - k}{b} \right)^2 + \left(\frac{x - h}{a} \right)^2 = 1$	vertical $b > a$
	$\left(\frac{y - k}{b} \right)^2 + \left(\frac{x - h}{a} \right)^2 = 1$	horizontal $a > b$
parabola	$(y - k) - 4c(x - h)^2 = 0$	vertical
	$-4c(y - k)^2 + (x - h) = 0$	horizontal
hyperbola	$\left(\frac{y - k}{b} \right)^2 - \left(\frac{x - h}{a} \right)^2 = 1$	vertical $\frac{x - h}{a} = 0 \Rightarrow \frac{y - k}{b} = \pm 1$
	$-\left(\frac{y - k}{b} \right)^2 + \left(\frac{x - h}{a} \right)^2 = 1$	horizontal $\frac{y - k}{b} = 0 \Rightarrow \frac{x - h}{a} = \pm 1$

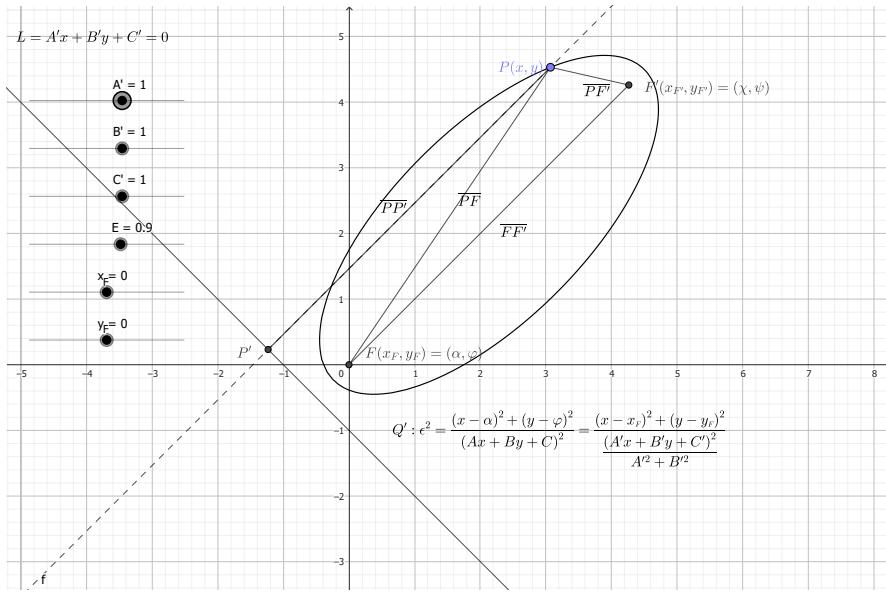


Figure 21.3: conic sections: ellipse

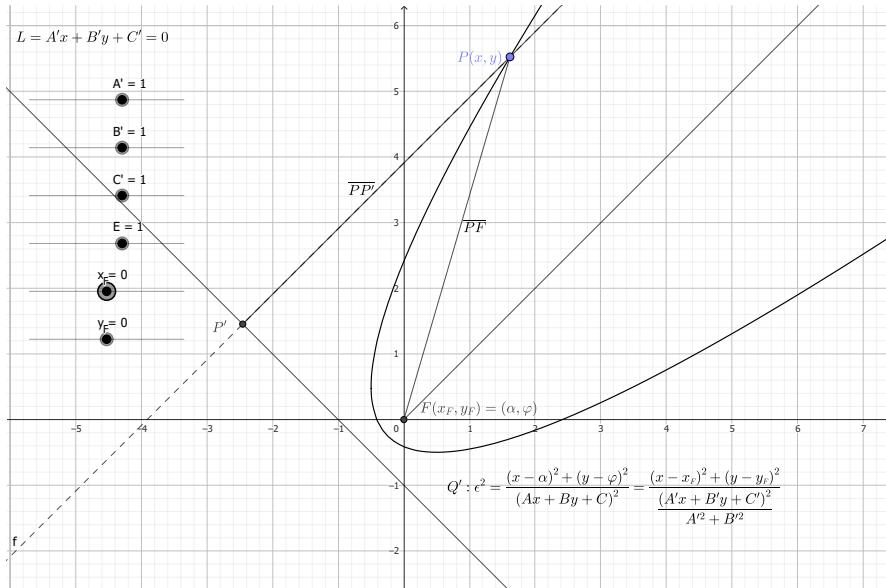


Figure 21.4: conic sections: parabola

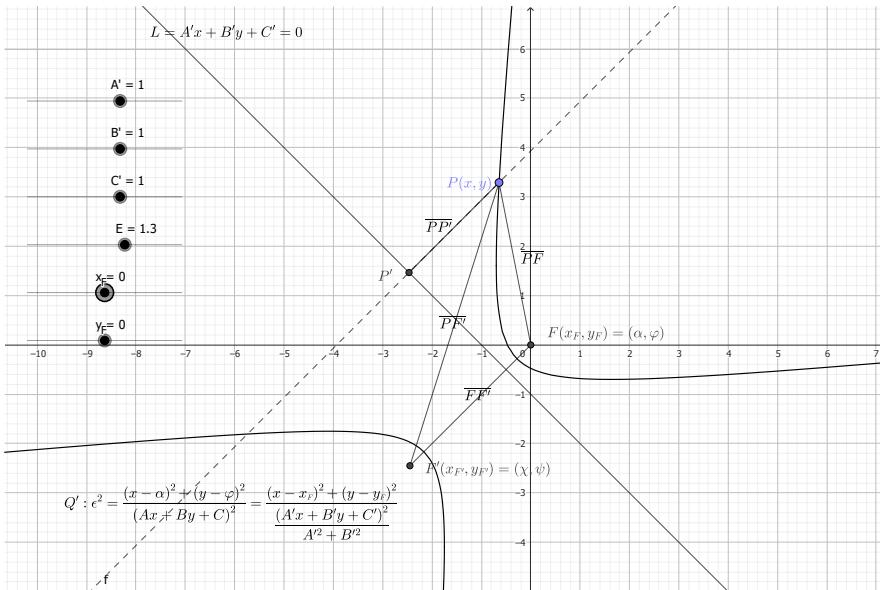


Figure 21.5: conic sections: hyperbola

21.4 parametric equation

circle	$\left(\frac{y-k}{a}\right)^2 + \left(\frac{x-h}{a}\right)^2 = 1$	$\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} a & 0 & h \\ 0 & a & k \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos t \\ \sin t \\ 1 \end{pmatrix} = \begin{pmatrix} \cos t & 0 & h \\ 0 & \sin t & k \\ 0 & 0 & 1 \end{pmatrix}$
ellipse	$\left(\frac{y-k}{b}\right)^2 + \left(\frac{x-h}{a}\right)^2 = 1$	$\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} a & 0 & h \\ 0 & b & k \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos t \\ \sin t \\ 1 \end{pmatrix} = \begin{pmatrix} \cos t & 0 & h \\ 0 & \sin t & k \\ 0 & 0 & 1 \end{pmatrix}$
parabola	$(y - k) - 4c(x - h)^2 = 0$	$\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & h \\ 0 & 4c & k \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} t \\ t^2 \\ 1 \end{pmatrix} = \begin{pmatrix} t & 0 & h \\ 0 & t^2 & k \\ 0 & 0 & 1 \end{pmatrix}$
	$-4c(y - k)^2 + (x - h) = 0$	$\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} 4c & 0 & h \\ 0 & 1 & k \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} t^2 \\ t \\ 1 \end{pmatrix} = \begin{pmatrix} t^2 & 0 & h \\ 0 & t & k \\ 0 & 0 & 1 \end{pmatrix}$
hyperbola	$\left(\frac{y-k}{b}\right)^2 - \left(\frac{x-h}{a}\right)^2 = 1$	$\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} a & 0 & h \\ 0 & b & k \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \pm \cosh t \\ \sinh t \\ 1 \end{pmatrix} = \begin{pmatrix} \tan t & 0 & h \\ 0 & \sec t & k \\ 0 & 0 & 1 \end{pmatrix}$
	$-\left(\frac{y-k}{b}\right)^2 + \left(\frac{x-h}{a}\right)^2 = 1$	$\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} a & 0 & h \\ 0 & b & k \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \sinh t \\ \pm \cosh t \\ 1 \end{pmatrix} = \begin{pmatrix} \sec t & 0 & h \\ 0 & \tan t & k \\ 0 & 0 & 1 \end{pmatrix}$

tangent half-angle formula^[??]

21.5 polar coordinate

$$(x - \alpha)^2 + (y - \varphi)^2 = [\epsilon(Ax + By + C)]^2$$

$$\begin{cases} x = r \cos \theta \\ y = r \sin \theta \end{cases}$$

$$(r \cos \theta - \alpha)^2 + (r \sin \theta - \varphi)^2 = [\epsilon (Ar \cos \theta + Br \sin \theta + C)]^2$$

If $\begin{cases} F = (x_F, y_F) = (\alpha, \varphi) = (0, 0) \\ L = Ax + By + C = x + p = 0 \end{cases}$

$$(r \cos \theta)^2 + (r \sin \theta)^2 = [\epsilon (r \cos \theta + p)]^2$$

$$r^2 =$$

$$\begin{aligned} r &= \pm \epsilon (r \cos \theta + p) \\ &= \pm (r \epsilon \cos \theta + \epsilon p) \end{aligned}$$

$$r(1 \mp \epsilon \cos \theta) = \epsilon p$$

$$r = \frac{\epsilon p}{1 \mp \epsilon \cos \theta}$$

<https://www.geogebra.org/calculator/azksjxbq>

$r = \frac{\epsilon p}{1 - \epsilon \cos \theta}$ will not cross $L = x + p = 0$ on graphs, so maybe it is a more correct solution

$$r = \frac{\epsilon p}{1 - \epsilon \cos \theta}$$

21.6 Cartesian coordinate: general form / quadratic equation

<https://ccjou.wordpress.com/2013/05/24/> /

https://en.wikipedia.org/wiki/Matrix_representation_of_conic_sections

$$ax^2 + bxy + cy^2 + dx + ey + f = 0$$

$$(x \ y) \begin{pmatrix} a & b/2 \\ b/2 & c \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = (x \ y) \begin{pmatrix} ax + (b/2)y \\ (b/2)x + cy \end{pmatrix} = ax^2 + bxy + cy^2$$

$$\begin{aligned} 0 &= (x \ y) \begin{pmatrix} a & b/2 \\ b/2 & c \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + (d \ e) \begin{pmatrix} x \\ y \end{pmatrix} + f \\ &= x^\top A x + b^\top x + f, \quad \begin{cases} A = \begin{pmatrix} a & b/2 \\ b/2 & c \end{pmatrix} & A \text{ real symmetric} \\ b = \begin{pmatrix} d \\ e \end{pmatrix} \\ x = \begin{pmatrix} x \\ y \end{pmatrix} \end{cases} \end{aligned}$$

real symmetric matrix diagonalizable^[??]

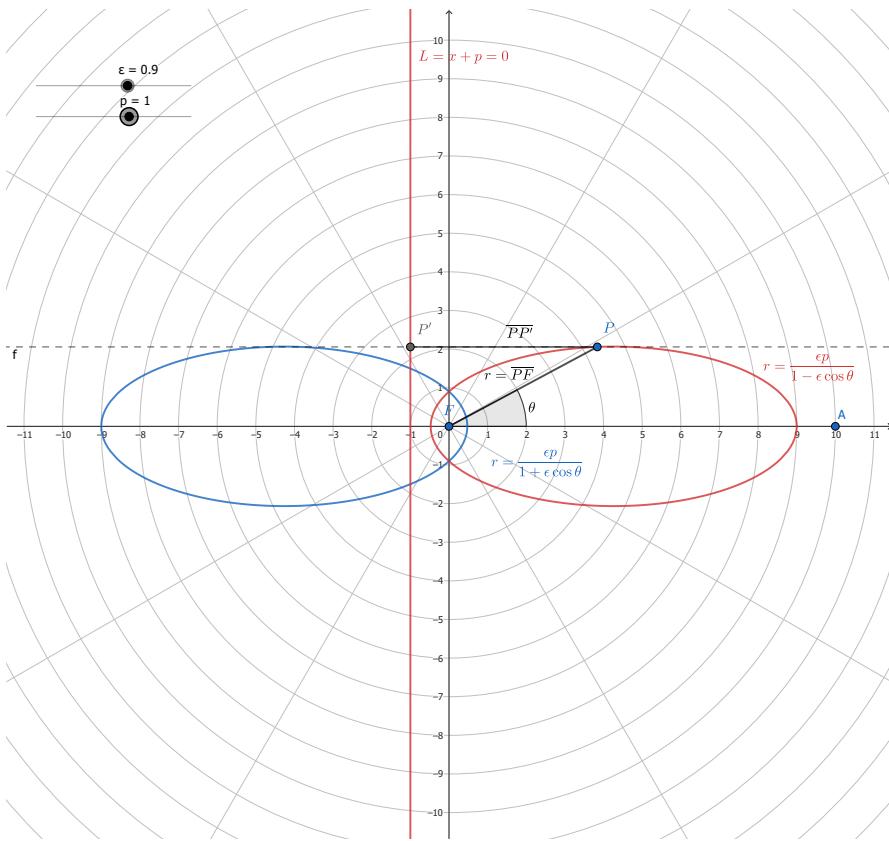


Figure 21.6: polar conic sections: ellipse

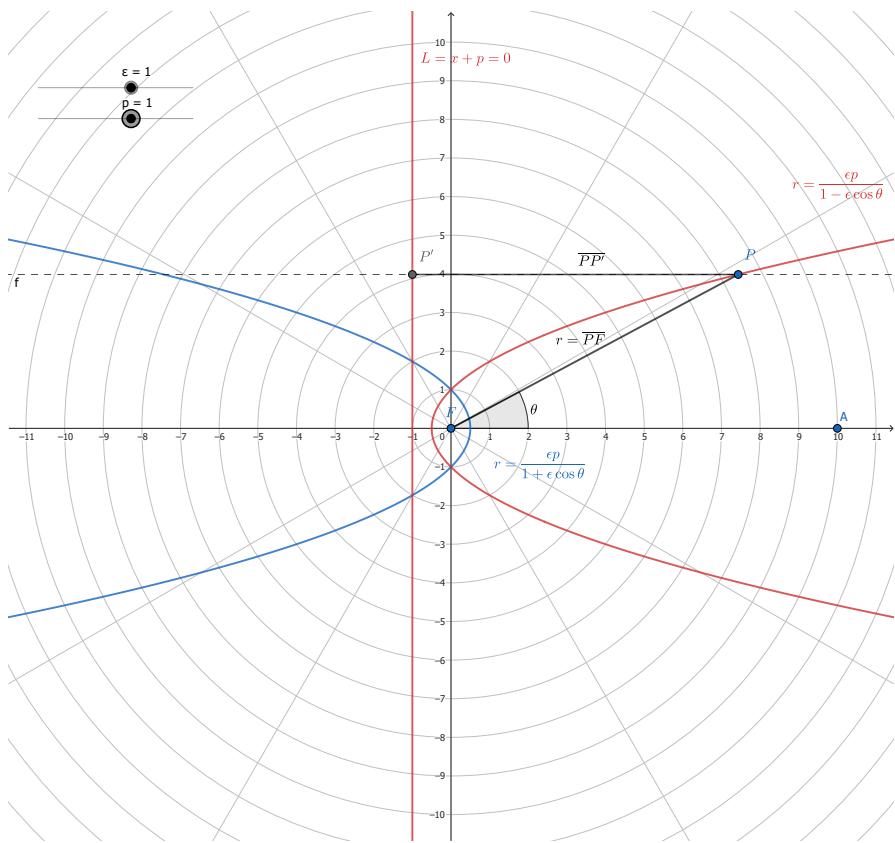


Figure 21.7: polar conic sections: parabola

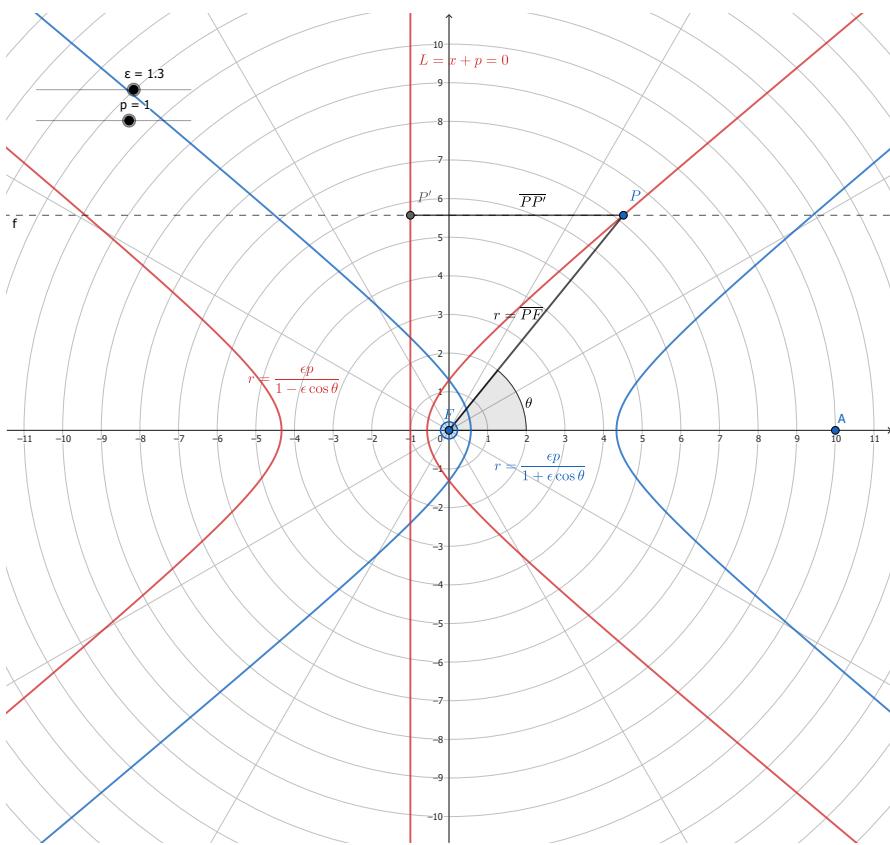


Figure 21.8: polar conic sections: hyperbola

21.7 homogeneous coordinate

X homogeneous coordinate

[homogeneous coordinate](#) O: HTML, X: PDF becoming web link

O homogeneous coordinate^[??]

X homogeneous coordinate

X homogeneous coordinate^[??]

<https://ccjou.wordpress.com/2013/05/24/> /

$$(x \ y) \begin{pmatrix} a & b/2 \\ b/2 & c \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = (x \ y \ 1) \begin{pmatrix} a & b/2 & 0 \\ b/2 & c & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = (x \ y \ 1) \begin{pmatrix} a & b/2 & 0 \\ b/2 & c & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}$$

$$\begin{aligned} (d \ e) \begin{pmatrix} x \\ y \end{pmatrix} &= (x \ y \ 1) \begin{pmatrix} \alpha & \beta & \gamma \\ \delta & \epsilon & \zeta \\ \eta & \theta & \kappa \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = (x \ y \ 1) \begin{pmatrix} \alpha x + \beta y + \gamma \\ \delta x + \epsilon y + \zeta \\ \eta x + \theta y + \kappa \end{pmatrix}, \begin{cases} \gamma + \eta = d \\ \zeta + \theta = e \end{cases} \\ &= (x \ y \ 1) \begin{pmatrix} 0 & 0 & \gamma \\ 0 & 0 & \zeta \\ \eta & \theta & 0 \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = (x \ y \ 1) \begin{pmatrix} 0 & 0 & d/2 \\ 0 & 0 & e/2 \\ d/2 & e/2 & 0 \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} \end{aligned}$$

$$\begin{aligned} 0 &= ax^2 + bxy + cy^2 + dx + ey + f \\ &= (x \ y) \begin{pmatrix} a & b/2 \\ b/2 & c \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + (d \ e) \begin{pmatrix} x \\ y \end{pmatrix} + f = x^\top Ax + b^\top x + f \\ &= (x \ y \ 1) \begin{pmatrix} a & b/2 & d/2 \\ b/2 & c & e/2 \\ d/2 & e/2 & f \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = (x^\top \ 1) M \begin{pmatrix} x \\ 1 \end{pmatrix}, M = \begin{pmatrix} a & b/2 & d/2 \\ b/2 & c & e/2 \\ d/2 & e/2 & f \end{pmatrix} \end{aligned}$$

$$\begin{aligned} 0 &= ax^2 + bxy + cy^2 + dx + ey + f \\ &= (x \ y) \begin{pmatrix} a & b/2 \\ b/2 & c \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + (d \ e) \begin{pmatrix} x \\ y \end{pmatrix} + f = x^\top Ax + b^\top x + f \\ &= (x \ y \ 1) \begin{pmatrix} a & b/2 & d/2 \\ b/2 & c & e/2 \\ d/2 & e/2 & f \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = (x^\top \ 1) M \begin{pmatrix} x \\ 1 \end{pmatrix}, M = \begin{pmatrix} a & b/2 & d/2 \\ b/2 & c & e/2 \\ d/2 & e/2 & f \end{pmatrix} \end{aligned}$$

https://en.wikipedia.org/wiki/Matrix_representation_of_conic_sections

$$\begin{aligned} 0 &= Q = Ax^2 + Bxy + Cy^2 + Dx + Ey + F \\ &= [x \ y \ 1] \begin{bmatrix} A & B/2 & D/2 \\ B/2 & C & E/2 \\ D/2 & E/2 & F \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = x_h^\top A_Q x_h \\ &= [x \ y] \begin{bmatrix} A & B/2 \\ B/2 & C \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + [D \ E] \begin{bmatrix} x \\ y \end{bmatrix} + F = x^\top A_{Q,33} x + b^\top x + F \end{aligned}$$

Chapter 22

distance from a point to a line

Theorem 22.1.

$$\begin{cases} P = P(x_0, y_0) \\ L = L(x, y) = Ax + By + C = 0, A^2 + B^2 \neq 0 \end{cases}$$
$$d(P, L) = \frac{|Ax_0 + By_0 + C|}{\sqrt{A^2 + B^2}}$$

https://en.wikipedia.org/wiki/Distance_from_a_point_to_a_line

<https://highscope.ch.ntu.edu.tw/wordpress/?p=47407>

<https://web.math.sinica.edu.tw/mathmedia/HTMLArticle18.jsp?mID=40312>

Proofs:

22.1 by shortest $\overline{PP'}$

$$\begin{aligned} P' &= P'(x, y) \in L = Ax + By + C = 0 \\ \Rightarrow y &= \frac{-1}{B}(Ax + C) \end{aligned}$$

$$\begin{aligned} \overline{PP'}^2(x, y) &= (x_0 - x)^2 + (y_0 - y)^2 \\ &= (x_0 - x)^2 + \left(y_0 - \frac{-1}{B}(Ax + C)\right)^2 \\ &= (x - x_0)^2 + \left(\frac{A}{B}x + \frac{C}{B} + y_0\right)^2 = \overline{PP'}^2(x) \end{aligned}$$

$$\begin{aligned}
0 &= \frac{\partial}{\partial x} \overline{PP'}^2(x) = 2(x - x_0) + 2\left(\frac{A}{B}x + \frac{C}{B} + y_0\right)\frac{A}{B} \\
&= \frac{2}{B^2}(B^2(x - x_0) + A^2x + AC + ABy_0) \\
&= \frac{2}{B^2}[(A^2 + B^2)x - (B^2x_0 - ABy_0 - AC)] \\
x &= \frac{B^2x_0 - ABy_0 - AC}{A^2 + B^2}
\end{aligned}$$

or by completing the square to find x .

$$\begin{aligned}
&\overline{PP'}^2 \left(x = \frac{B^2x_0 - ABy_0 - AC}{A^2 + B^2} \right) \\
&= \left(\frac{B^2x_0 - ABy_0 - AC}{A^2 + B^2} - x_0 \right)^2 + \left(\frac{A}{B} \frac{B^2x_0 - ABy_0 - AC}{A^2 + B^2} + \frac{C}{B} + y_0 \right)^2 \\
&= \left(\frac{-A^2x_0 - ABy_0 - AC}{A^2 + B^2} \right)^2 + \left(\frac{A(B^2x_0 - ABy_0 - AC) + C(A^2 + B^2) + B(A^2 + B^2)y_0}{B(A^2 + B^2)} \right)^2 \\
&= \left(\frac{-A(Ax_0 + By_0 + C)}{A^2 + B^2} \right)^2 + \left(\frac{AB^2x_0 + B^3y_0 + B^2C}{B(A^2 + B^2)} \right)^2 \\
&= \frac{A^2(Ax_0 + By_0 + C)^2}{(A^2 + B^2)^2} + \frac{B^2(Ax_0 + By_0 + C)^2}{(A^2 + B^2)^2} \\
&= \frac{(Ax_0 + By_0 + C)^2}{A^2 + B^2} \\
\overline{PP'} &= \overline{PP'} \left(x = \frac{B^2x_0 - ABy_0 - AC}{A^2 + B^2} \right) = \frac{|Ax_0 + By_0 + C|}{\sqrt{A^2 + B^2}}
\end{aligned}$$

22.2 by perpendicular foot

$$y = \frac{-A}{B}x - \frac{C}{B} = \frac{-1}{B}(Ax + C), \text{ if } B \neq 0$$

$$L_{\perp} : \left(y = \frac{B}{A}x + K \right) \perp \left(y = \frac{-A}{B}x - \frac{C}{B} \right) : L$$

$$L_{\perp} = L_{\perp}(x, y) = Bx - Ay + K = 0$$

$$P = P(x_0, y_0) \in L_{\perp} = B(x - x_0) - A(y - y_0) = 0$$

$$L_{\perp} = Bx - Ay - (Bx_0 - Ay_0) = 0$$

perpendicular foot = foot of the perpendicular P'

$$\begin{aligned}
P' \in (L_{\perp} \cap L) &= \begin{cases} L = Ax + By + C = 0 \\ L_{\perp} = Bx - Ay - (Bx_0 - Ay_0) = 0 \end{cases} \\
&= \begin{cases} Ax + By = -C \\ Bx - Ay = Bx_0 - Ay_0 \end{cases} \\
P' = P'(x, y) &= \left(\frac{\begin{vmatrix} -C & B \\ Bx_0 - Ay_0 & -A \end{vmatrix}}{\begin{vmatrix} A & B \\ B & -A \end{vmatrix}}, \frac{\begin{vmatrix} A & -C \\ B & Bx_0 - Ay_0 \end{vmatrix}}{\begin{vmatrix} A & B \\ B & -A \end{vmatrix}} \right) \\
&= \left(\frac{\begin{vmatrix} C & B \\ -Bx_0 + Ay_0 & -A \end{vmatrix}}{\begin{vmatrix} A & -B \\ B & A \end{vmatrix}}, \frac{\begin{vmatrix} A & C \\ B & -Bx_0 + Ay_0 \end{vmatrix}}{\begin{vmatrix} A & -B \\ B & A \end{vmatrix}} \right) \\
&= \left(\frac{B^2x_0 - ABy_0 - AC}{A^2 + B^2}, \frac{-ABx_0 + A^2y_0 - BC}{A^2 + B^2} \right)
\end{aligned}$$

$$\begin{aligned}
d(P, L) &= \overline{PP'} \\
&= \left\| (x_0, y_0) - \left(\frac{B^2x_0 - ABy_0 - AC}{A^2 + B^2}, \frac{-ABx_0 + A^2y_0 - BC}{A^2 + B^2} \right) \right\| \\
&= \sqrt{\left(x_0 - \frac{B^2x_0 - ABy_0 - AC}{A^2 + B^2} \right)^2 + \left(y_0 - \frac{-ABx_0 + A^2y_0 - BC}{A^2 + B^2} \right)^2} \\
&= \sqrt{\left(\frac{A^2x_0 + ABy_0 + AC}{A^2 + B^2} \right)^2 + \left(\frac{ABx_0 + B^2y_0 + BC}{A^2 + B^2} \right)^2} \\
&= \sqrt{\frac{A^2(Ax_0 + By_0 + C)^2 + B^2(Ax_0 + By_0 + C)^2}{(A^2 + B^2)^2}} = \sqrt{\frac{(Ax_0 + By_0 + C)^2}{A^2 + B^2}} \\
&= \frac{|Ax_0 + By_0 + C|}{\sqrt{A^2 + B^2}}
\end{aligned}$$

22.3 by normal vector

$$\begin{cases} \vec{n} = (A, B) \perp L = Ax + By + C = 0 \\ \vec{PP'} = P' - P = (x - x_0, y - y_0) \end{cases}$$

$$P \ L \ d(P, L) \ L \ P' \ \vec{PP'} \ L \ \vec{n}$$

$$\begin{aligned}
\vec{PP'} \cdot \vec{n} &= \left\| \vec{PP'} \right\| \left\| \vec{n} \right\| \cos \theta \\
\left| \vec{PP'} \cdot \vec{n} \right| &= \left\| \vec{PP'} \right\| \left\| \vec{n} \right\| |\cos \theta| \\
\left\| \vec{PP'} \right\| |\cos \theta| &= \left| \vec{PP'} \cdot \hat{n} \right| = \frac{\left| \vec{PP'} \cdot \vec{n} \right|}{\left\| \vec{n} \right\|} = \frac{|(x - x_0, y - y_0) \cdot (A, B)|}{\|(A, B)\|} \\
&= \frac{|A(x - x_0) + B(y - y_0)|}{\sqrt{A^2 + B^2}} = \frac{|-Ax_0 - By_0 + Ax + By|}{\sqrt{A^2 + B^2}} \\
\frac{Ax + By + C = 0}{Ax + By = -C} &= \frac{|-Ax_0 - By_0 - C|}{\sqrt{A^2 + B^2}} = \frac{|Ax_0 + By_0 + C|}{\sqrt{A^2 + B^2}}
\end{aligned}$$

PDF LaTeX \usepackage{fdsymbol} to have \overrightharpoon vector; however, there are too many side effects, including ugly mathptmx \sum , ...

```

\usepackage{fdsymbol} % vector over accent, but will use mathptmx
% replace the rather ugly mathptmx \sum operator with the equivalent Computer Modern one
\let\sum\relax
\DeclareSymbolFont{CMlargesymbols}{OMX}{cmex}{m}{n}
\DeclareMathSymbol{\sum}{\mathop}{CMlargesymbols}{"50}

```

22.4 by Cauchy inequality

$$\begin{aligned}
Ax + By + C &= 0 \\
Ax + By &= -C \\
(Ax + By) - (Ax_0 + By_0) &= -C - (Ax_0 + By_0) \\
A(x - x_0) + B(y - y_0) &= -(Ax_0 + By_0 + C) \\
\overline{PP'}^2 &= (x_0 - x)^2 + (y_0 - y)^2 \\
[A^2 + B^2] \overline{PP'}^2 &= [A^2 + B^2] [(x_0 - x)^2 + (y_0 - y)^2] \\
&\geq [A(x - x_0) + B(y - y_0)]^2 \\
&= [-(Ax_0 + By_0 + C)]^2 = (Ax_0 + By_0 + C)^2 \\
\overline{PP'}^2 &\geq \frac{(Ax_0 + By_0 + C)^2}{A^2 + B^2} \\
\overline{PP'} &\geq \frac{|Ax_0 + By_0 + C|}{\sqrt{A^2 + B^2}}
\end{aligned}$$

Chapter 23

real symmetric matrix diagonalizable

<https://ccjou.wordpress.com/2011/02/09/> /

<https://tex.stackexchange.com/questions/30619/what-is-the-best-symbol-for-vector-matrix-transpose>

Theorem 23.1.

$$\left\{ \begin{array}{l} \left\{ \begin{array}{ll} A \in \mathcal{M}_{n \times n}(\mathbb{R}) & \text{real matrix} \\ A^\top = A & \text{symmetric matrix} \end{array} \right. \\ Ax = \lambda x \end{array} \right. \quad \begin{array}{ll} \text{real symmetric matrix} & \\ \downarrow & \\ \left\{ \begin{array}{ll} \lambda \in \mathbb{C} & \text{complex eigenvalue} \\ 0 \neq x \in \mathbb{C}^n & \text{complex eigenvector} \end{array} \right. & \end{array}$$
$$\left\{ \begin{array}{ll} \lambda \in \mathbb{R} & \text{real eigenvalue (1)} \\ x \in \mathbb{R}^n & \text{real eigenvector (2)} \end{array} \right.$$

Proof. (1)

$$\begin{aligned}
Ax &= \lambda x \\
\bar{A}\bar{x} &= \overline{Ax} = \overline{\lambda x} = \bar{\lambda}\bar{x} \\
\bar{x}^\top \bar{A}^\top &= (\bar{A}\bar{x})^\top = (\bar{\lambda}\bar{x})^\top = \bar{\lambda}\bar{x}^\top \\
\bar{x}^\top A &\stackrel{\text{symmetric}}{=} \bar{x}^\top A^\top \stackrel{\text{real}}{=} \\
\bar{x}^\top A &= \bar{\lambda}\bar{x}^\top \\
\lambda\bar{x}^\top x &= \bar{x}^\top (\lambda x) \stackrel{Ax=\lambda x}{\stackrel{\cdot x}{=}} \bar{x}^\top Ax = \bar{\lambda}\bar{x}^\top x \\
\lambda\bar{x}^\top x &= \bar{\lambda}\bar{x}^\top x \\
(\lambda - \bar{\lambda})\bar{x}^\top x &= 0 \wedge \begin{cases} \bar{x}^\top x = \sum_{i=1}^n |x_i|^2 \\ x \neq 0 \end{cases} \Rightarrow \bar{x}^\top x \neq 0 \\
\lambda - \bar{\lambda} &= 0 \\
\lambda = \bar{\lambda} &\Leftrightarrow \lambda \in \mathbb{R}
\end{aligned}$$

□

Proof. (1) fast concept

$$\begin{aligned}
(\bar{A}\bar{x})^\top x &= (\bar{x}^\top \bar{A}^\top) x \stackrel{\text{symmetric}}{=} (\bar{x}^\top \bar{A}) x = \bar{x}^\top (\bar{A}x) \\
(L) &= (\bar{A}\bar{x})^\top x = \bar{x}^\top (\bar{A}x) = (R) \\
(L) &= (\bar{A}\bar{x})^\top x \stackrel{Ax=\lambda x}{\stackrel{Ax=\lambda x}{=}} (\bar{\lambda}\bar{x})^\top x = \bar{\lambda}\bar{x}^\top x \\
(R) &= \bar{x}^\top (\bar{A}x) \stackrel{\text{real}}{=} \bar{x}^\top (Ax) \stackrel{Ax=\lambda x}{\stackrel{Ax=\lambda x}{=}} \bar{x}^\top (\lambda x) = \lambda\bar{x}^\top x \\
\bar{\lambda}\bar{x}^\top x &= (\bar{A}\bar{x})^\top x = \bar{x}^\top (\bar{A}x) = \lambda\bar{x}^\top x \\
\bar{\lambda}\bar{x}^\top x &= \lambda\bar{x}^\top x
\end{aligned}$$

□

Proof. (2)

???

$$N(A - \lambda I) \quad (A - \lambda I -) \quad \mathbb{R}^n \quad x \in N(A - \lambda I)$$

□

Theorem 23.2.

$$\begin{cases}
\begin{cases}
A \in \mathcal{M}_{n \times n}(\mathbb{R}) & \text{real matrix} \\
A^\top = A & \text{symmetric matrix}
\end{cases} & \text{real symmetric matrix} \\
Ax = \lambda x & \text{??} \begin{cases}
\lambda \in \mathbb{R} & \text{real eigenvalue} \\
x \in \mathbb{R}^n & \text{real eigenvector}
\end{cases} \\
\begin{cases}
Ax_1 = \lambda_1 x_1 & (e_1) \\
Ax_2 = \lambda_2 x_2 & (e_2)
\end{cases} & \lambda_1 \neq \lambda_2
\end{cases}$$

↓
 $x_1^\top x_2 = 0 \Leftrightarrow x_1 \perp x_2$

Proof. (1)

$$\begin{aligned}
& Ax_2 = \lambda_2 x_2 \\
& x_1^\top Ax_2 \stackrel{x_1^\top}{=} x_1^\top \lambda_2 x_2 = \lambda_2 x_1^\top x_2 = (1) \\
& Ax_1 = \lambda_1 x_1 \\
& x_1^\top A^\top = (Ax_1)^\top = (\lambda_1 x_1)^\top = \lambda_1 x_1^\top \\
& x_1^\top A^\top = \lambda_1 x_1^\top \\
& x_1^\top Ax_2 \stackrel{\text{symmetric}}{=} x_1^\top A^\top x_2 \stackrel{x_2}{=} \lambda_1 x_1^\top x_2 = (2) \\
& \lambda_2 x_1^\top x_2 \stackrel{(1)}{=} x_1^\top Ax_2 \stackrel{(2)}{=} \lambda_1 x_1^\top x_2 \\
& \lambda_2 x_1^\top x_2 = \lambda_1 x_1^\top x_2 \\
& (\lambda_2 - \lambda_1) x_1^\top x_2 = 0 \wedge \lambda_1 \neq \lambda_2 \\
& x_1^\top x_2 = 0
\end{aligned}$$

□

Proof. (1) fast concept

$$\begin{aligned}
(Ax_1)^\top x_2 &= (x_1^\top A^\top) x_2 \stackrel{\text{symmetric}}{=} (x_1^\top A) x_2 = x_1^\top (Ax_2) \\
(L) &= (Ax_1)^\top x_2 = x_1^\top (Ax_2) = (R) \\
(L) &= (Ax_1)^\top x_2 \stackrel{(e_1)}{=} (\lambda_1 x_1)^\top x_2 = \lambda_1 x_1^\top x_2 \\
(R) &= x_1^\top (Ax_2) \stackrel{(e_2)}{=} x_1^\top (\lambda_2 x_2) = \lambda_2 x_1^\top x_2 \\
\lambda_1 x_1^\top x_2 &= (Ax_1)^\top x_2 = x_1^\top (Ax_2) = \lambda_2 x_1^\top x_2 \\
\lambda_1 x_1^\top x_2 &= \lambda_2 x_1^\top x_2
\end{aligned}$$

□

Theorem 23.3.

$$\begin{cases}
 \begin{cases}
 A \in \mathcal{M}_{n \times n}(\mathbb{R}) & \text{real matrix} \\
 A^\top = A & \text{symmetric matrix}
 \end{cases} & \text{real symmetric matrix} \\
 \begin{cases}
 Ax_1 = \lambda x_1 \\
 x_2^\top x_1 = 0 \Leftrightarrow x_2 \perp x_1
 \end{cases} & \begin{array}{l} (e) \\ (o) \end{array}
 \end{cases}$$

\Downarrow

$$Ax_2 \perp x_1 \Leftrightarrow (Ax_2)^\top x_1 = 0$$

Proof.

$$\begin{aligned}
 (Ax_2)^\top x_1 &= (x_2^\top A^\top) x_1 \stackrel{\text{symmetric}}{=} (x_2^\top A) x_1 \\
 &= x_2^\top (Ax_1) \stackrel{(e)}{=} x_2^\top (\lambda x_1) \\
 &= \lambda x_2^\top x_1 \stackrel{(o)}{=} \lambda \cdot 0 = 0
 \end{aligned}$$

$$(Ax_2)^\top x_1 = 0 \Leftrightarrow Ax_2 \perp x_1$$

□

Chapter 24

tangent half-angle formula

https://en.wikipedia.org/wiki/Tangent_half-angle_formula

<https://zh.wikipedia.org/zh-tw/>

Chapter 25

homogeneous coordinate

<https://youtu.be/EKN7dTJ4ep8?si=8woajZxbqPfEXhdK&t=2263>

<https://youtu.be/1z1S2kQKXD8?si=71o339yBtIQYhWtj&t=3082>

Chapter 26

Archimedean property

26.1 integer Archimedean property

26.2 rational Archimedean property

<https://math.stackexchange.com/questions/3699023/proof-the-the-field-of-rational-numbers-has-the-archimedean-property>

<https://math.stackexchange.com/questions/1919829/proving-the-archimedean-properties-of-rational-numbers>

26.3 real Archimedean property

Chapter 27

MatPlotLib / matplotlib

- tikzplotlib^[??]: Python^[??] matplotlib^[??] export to TikZ^[??] .tex

27.1 Timothy H. Wu

- API = application programming interface
 - functional^[??]
 - object-oriented^[??]
 - * figure
 - * axes
 - * subplot

https://matplotlib.org/stable/tutorials/introductory/quick_start.html

<https://pbpython.com/effective-matplotlib.html>

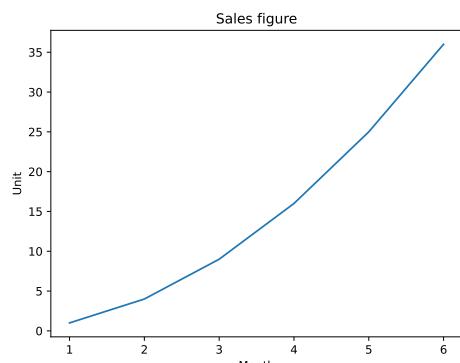
<https://tex.stackexchange.com/questions/84847/can-i-use-webp-images-in-latex>

You probably need to convert the image to png.

27.1.1 funcitonal API

```
import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
                     ← 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
plt.title('Sales figure')
plt.xlabel('Month')
plt.ylabel('Unit')
plt.plot(a1, a2) # this doesn't
                 ← actually show the plot.
# plt.show() This is automatically
                 ← called for Jupyter notebook.
```



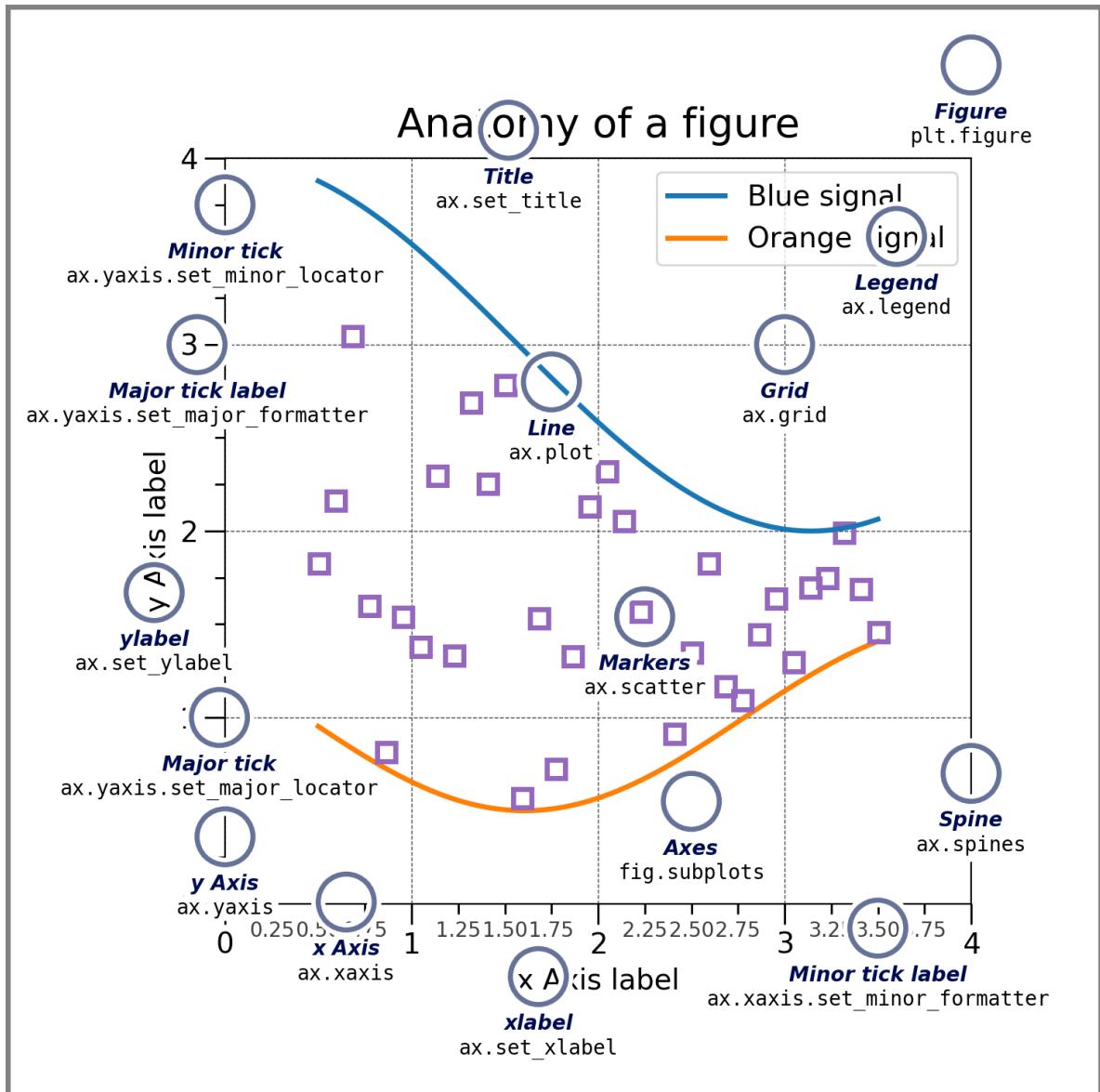


Figure 27.1: matplotlib figure anatomy

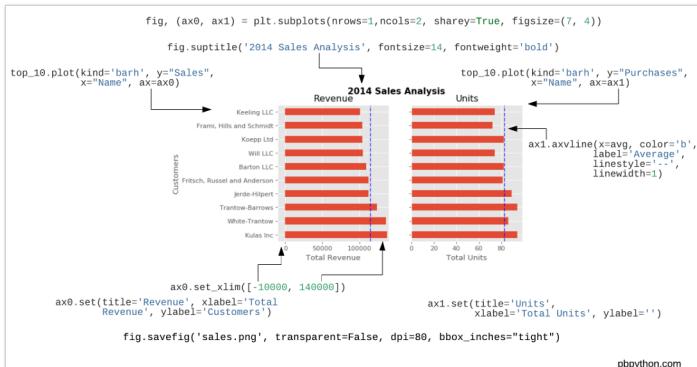


Figure 27.2: matplotlib subplot anatomy

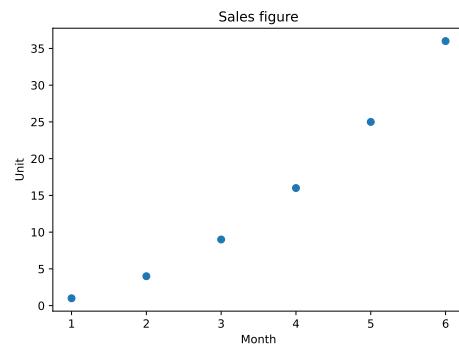
To plot a scatterplot, call `scatter()` instead of `plot()`.

```

import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
    ↵ 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
plt.title('Sales figure')
plt.xlabel('Month')
plt.ylabel('Unit')
plt.scatter(a1, a2) # instead of
    ↵ plot.plot(), use scatter() to show
    ↵ scatter plot

```

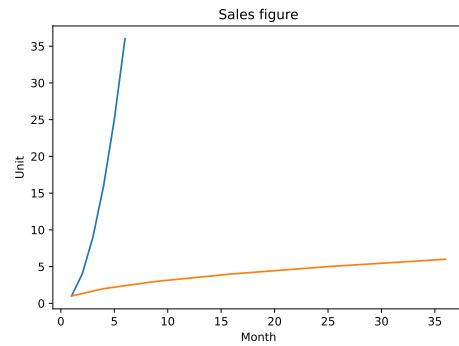


```

import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
    ↵ 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
plt.title('Sales figure')
plt.xlabel('Month')
plt.ylabel('Unit')
plt.plot(a1, a2)
plt.plot(a2, a1)

```

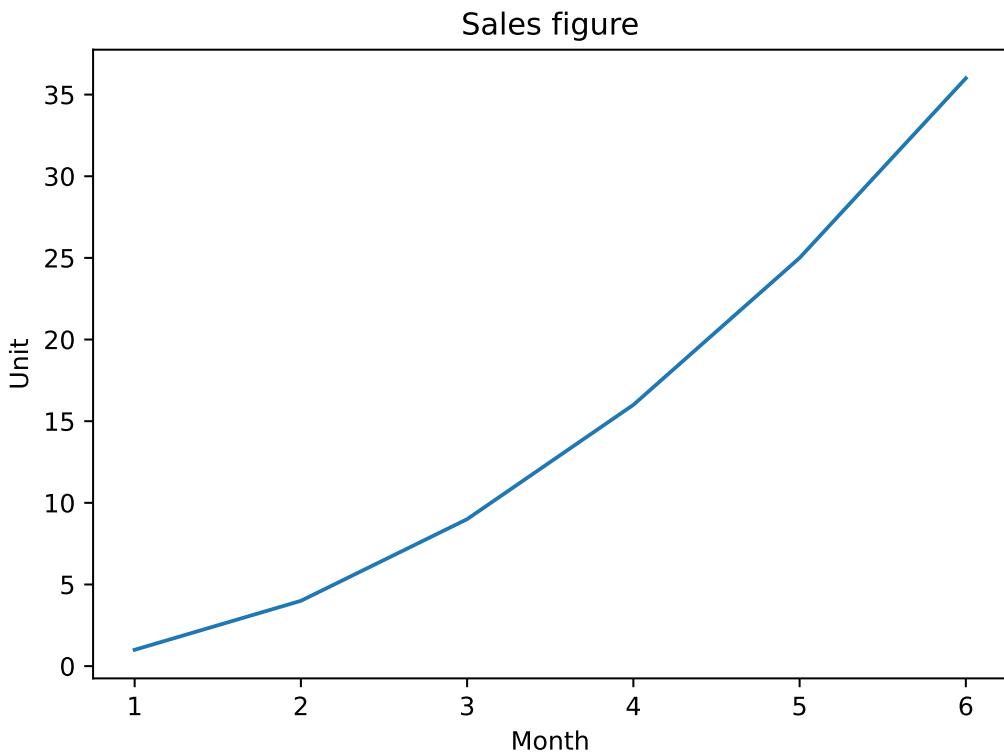


The behavior of the functional API is stateful. What's stateful? An example is when you read a text file. When you `open()` a text file to read, the library read the next line every time you call `readline()`. It remembers where you left off, despite the fact that you do

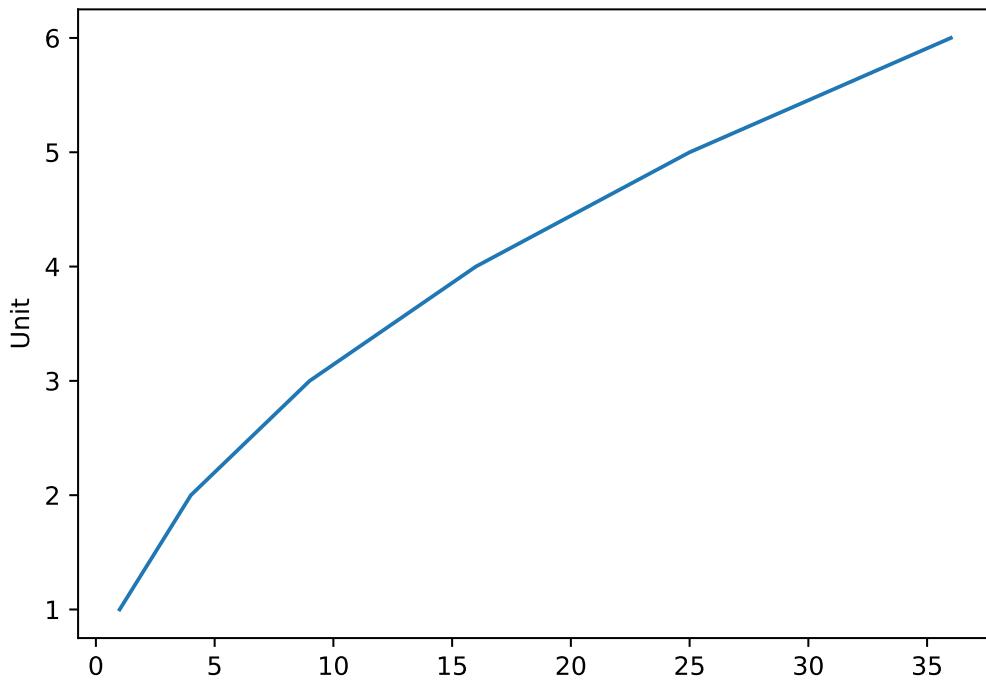
not give it the position to read from. This behavior of the library is called **stateful**. The way we've used Matplotlib is also **stateful**. And everytime, `plot.show()` is called (and it automatically gets called on cell ends), some state about plots is reset. We can see that here:

```
import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4, 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
plt.title('Sales figure')
plt.xlabel('Month')
plt.ylabel('Unit')
plt.plot(a1, a2)
```



```
plt.plot(a2, a1)
plt.ylabel('Unit')
```



It makes two graphs instead of one. Also note that `ylabel()` was called after `plot()`, and it is still shown before `plot.show()` but `Sales Figure` plot title and other labels don't show up on this graph. Because every time `plot.show()` is called, things are reset. This is a `stateful API` we're using. The functional APIs are used when you plot Matplotlib by calling on `pyplot` module level API (module level functions).

27.1.2 object-oriented API

In object-oriented API, we're getting two type of objects. One is `Figure`, the other one is `Axes`. `Figure` is the *canvas* of the plot. In English, `axes` is the plural form of `axis`. We're talking about the axis in x axis and y axis. Since one `plot` consists of both axis, in Matplotlib the object that represents one plot is called `Axes`. Since it's an object. We'll call it "a" axes.

```
import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4, 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure()
print("fig is of type:", type(fig))

## fig is of type: <class 'matplotlib.figure.Figure'>
```

```
ax1 = fig.add_axes([0, 0, 1, 1]) # [left, bottom, width, height]
print("ax1 is of type:", type(ax1))
# ax1.plot(a1, a2)
```

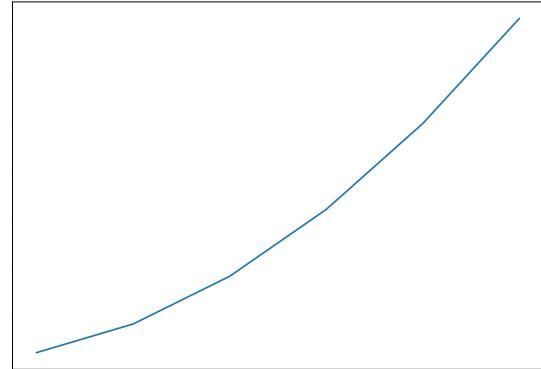
```
## ax1 is of type: <class 'matplotlib.axes._axes.Axes'>
```

1. Call `figure()` to get a Figure type
2. Call `add_axes()` to get a `ax1` type `ax1 = fig.add_axes([0, 0, 1, 1]) # [left, bottom, width, height]`

- The list given to `add_axes()` is the rectangular region of where to show the plot:
 - Bottom left corner at $x=0$, $y=0$, width and height of both 1, 1

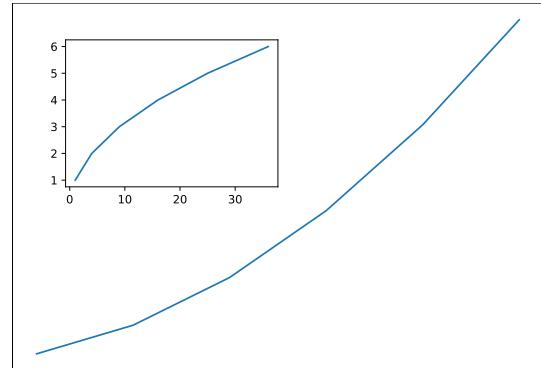
```
import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
                     ↵ 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure()
# print("fig is of type:", type(fig))
ax1 = fig.add_axes([0, 0, 1, 1]) #
                     ↵ [left, bottom, width, height]
# print("ax1 is of type:", type(ax1))
ax1.plot(a1, a2)
```



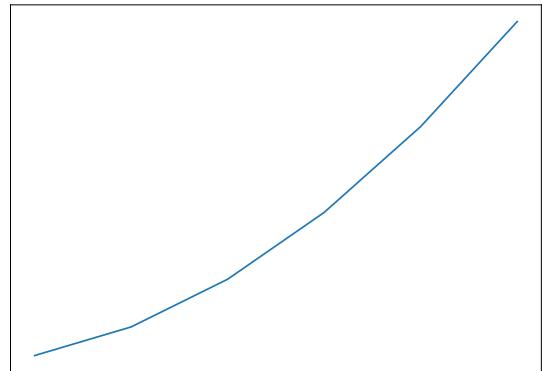
```
import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
                     ↵ 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure()
ax1 = fig.add_axes([0, 0, 1, 1])
ax1.plot(a1, a2)
ax2 = fig.add_axes([0.1, 0.5, .4, .4])
ax2.plot(a2, a1)
```



```
import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
↪ 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure()
ax = fig.add_axes([0, 0, 1, 1])
ax.plot(a1, a2)
ax.set_xlabel('Time')
ax.set_ylabel('Unit')
ax.set_title('Sales figure')
# alternatively:
# ax.set(xlabel='Time', ylabel='Unit',
↪ title='Sales figure')
```



27.1.2.1 Configure the figure size and DPI

Get image size for the figure object. 6 by 4 is the default.

```
fig.get_size_inches()
```

```
import matplotlib.pyplot as plt

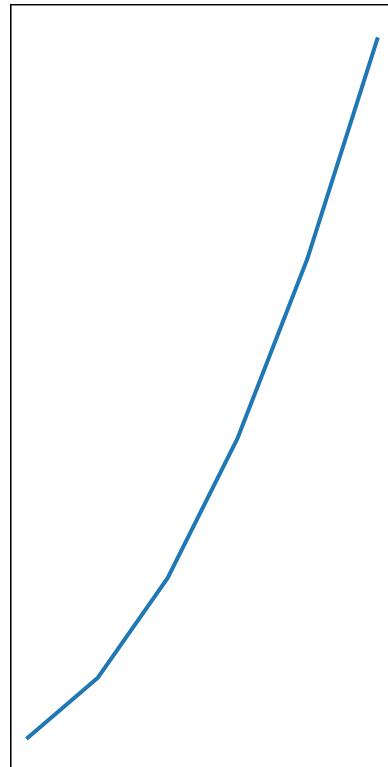
fig = plt.figure()
fig.get_size_inches()
```

```
## array([6.5, 4.5])
```

```
fig = plt.figure(figsize=(2, 4))
```

```
import matplotlib.pyplot as plt

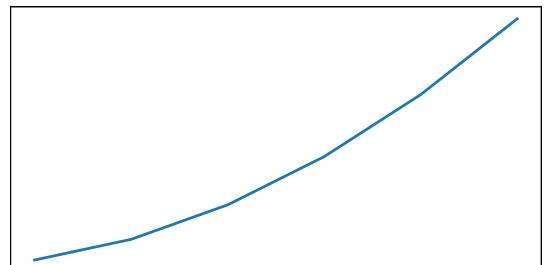
a1 = list(range(1, 7)) # [1, 2, 3, 4,
↪ 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure(figsize=(2, 4))
# you can also set after getting the
↪ figure
# fig.set_size_inches((12, 2))
ax = fig.add_axes([0, 0, 1, 1])
ax.plot(a1, a2)
```



```
fig.set_size_inches((4, 2))

import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
↪ 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure()
# you can also set after getting the
↪ figure
fig.set_size_inches((4, 2))
ax = fig.add_axes([0, 0, 1, 1])
ax.plot(a1, a2)
```



DPI = dots per inch

Get image DPI for the figure object. 100 is the default here.

```
fig.get_dpi()
```

```
import matplotlib.pyplot as plt

fig = plt.figure()
fig.get_dpi()
```

```
## 100.0
```

```
import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4, 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure()
# you can also set after getting the figure
fig.set_size_inches((12, 2))
ax = fig.add_axes([0, 0, 1, 1])
ax.plot(a1, a2)
plt.title('Sales figure')
fig.get_dpi()
```

```
## 100.0
```

27.1.2.2 subplot

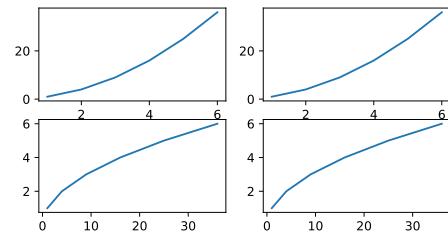
```
import matplotlib.pyplot as plt

# Subplots handles add_axes for you according to the number of rows and columns
fig, axes = plt.subplots(nrows=2, ncols=2, figsize=(6, 3))
# axes is a numpy array, you can use it like using a list.
print(axes)

## [[<Axes: > <Axes: >]
##  [<Axes: > <Axes: >]]
```

```
import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
# 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
# Subplots handles add_axes for you
# according to the number of rows
# and columns
fig, axes = plt.subplots(nrows=2,
# ncols=2, figsize=(6, 3))
# axes is a numpy array, you can use
# it like using a list.
# print(axes)
axes[0][0].plot(a1, a2)
axes[0][1].plot(a1, a2)
axes[1][0].plot(a2, a1)
axes[1][1].plot(a2, a1)
```

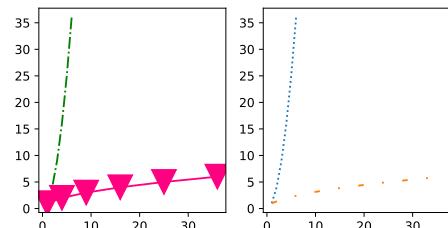


27.1.2.3 color and linestyle

- Color
 - <https://matplotlib.org/stable/tutorials/colors/colors.html>
- line-style (ls)
 - https://matplotlib.org/stable/gallery/lines_bars_and_markers/linestyles.html
- marker
 - https://matplotlib.org/stable/api/markers_api.html
- linewidth (lw)

```
import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
↪ 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
# Subplots handles add_axes for you
↪ according to the number of rows
↪ and columns
fig, axes = plt.subplots(nrows=1,
↪ ncols=2, figsize=(6, 3))
# axes is a numpy array
axes[0].plot(a1, a2, color='green',
↪ linestyle='-.')
axes[0].plot(a2, a1, color=(1, 0,
↪ 0.5), marker='v', markersize=20)
axes[1].plot(a1, a2,
↪ linestyle='dotted')
axes[1].plot(a2, a1, linestyle=(0, (3,
↪ 10, 1, 10)))
```



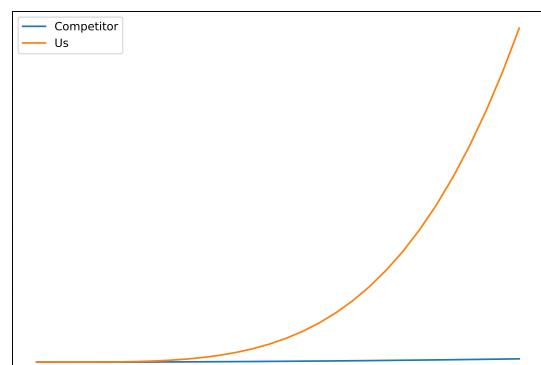
27.1.2.4 other inputs

- NumPy array
- Pandas series

27.1.2.5 legend

```
import matplotlib.pyplot as plt
import numpy as np

x = np.linspace(0, 10, 30)
y = x * x
fig = plt.figure()
ax = fig.add_axes([0, 0, 1, 1])
line1 = ax.plot(x, y,
↪ label="Competitor")
line2 = ax.plot(x, y**2, label="Us")
ax.legend()
```



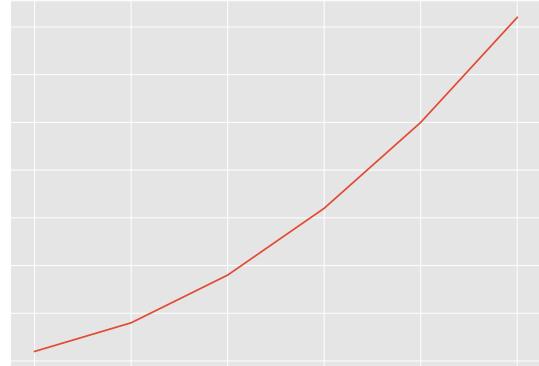
27.1.2.6 customize style

predefined styles

```
import matplotlib.pyplot as plt
print(plt.style.available)
```

```
## ['Solarize_Light2', '_classic_test_patch', '_mpl-gallery', '_mpl-gallery-nogrid', 'bmh'
```

```
import matplotlib.pyplot as plt
a1 = list(range(1, 7)) # [1, 2, 3, 4,
# 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure()
plt.style.use('ggplot')
ax = fig.add_axes([0, 0, 1, 1])
ax.plot(a1, a2)
```



restore default style

```
import matplotlib.pyplot as plt
plt.style.use('default') # But strangely enough figure size gets changed still
```

```
import matplotlib.pyplot as plt
plt.rcParams["figure.figsize"] = (6, 4)
plt.rcParams["figure.dpi"] = 100
```

27.1.2.7 save to file

`savefig` saves image to file. We also set the `bbox_inches` parameter to `tight` to make sure the image doesn't get out of the image bound.

save to .png

```
import matplotlib.pyplot as plt
a1 = list(range(1, 7)) # [1, 2, 3, 4, 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure()
ax = fig.add_axes([0, 0, 1, 1])
ax.plot(a1, a2)
fig.savefig('out.png', bbox_inches = 'tight')
```

save to .pdf

```
import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4, 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure()
ax = fig.add_axes([0, 0, 1, 1])
ax.plot(a1, a2)
fig.savefig('out.pdf', bbox_inches = 'tight')
```

27.1.3 Seaborn

- Kimberly Fessel

- visually explained
- Seaborn
- Matplotlib
- Pandas
- iPyWidgets

- Seaborn
 - figure-level plot
 - axes-level plot

R or RStudio run Python with installing packages or modules by using `reticulate`, R package and directly using Anaconda `conda` environment for convenience, instead of `virtualenv`

https://rstudio.github.io/reticulate/articles/python_packages.html

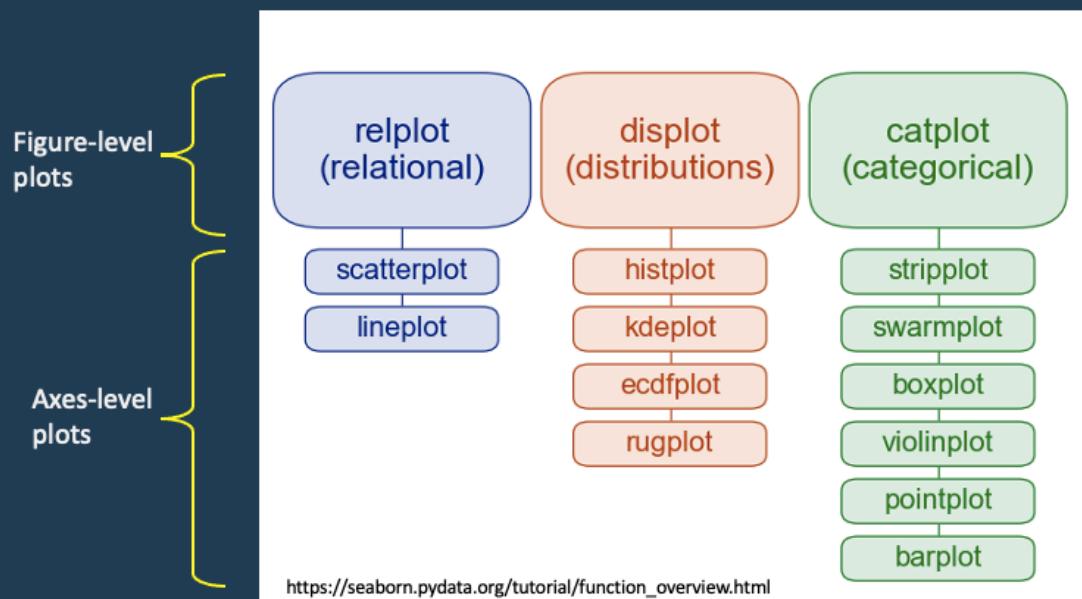
```
library(reticulate)
```

```
## Warning: package 'reticulate' was built under R version 4.2.3
```

```
conda_list()
```

##	name	python
## 1	base	D:\\Anaconda3\\python.exe
## 2	fiftyone	D:\\Anaconda3\\envs\\fiftyone\\python.exe
## 3	keras	D:\\Anaconda3\\envs\\keras\\python.exe
## 4	labelme	D:\\Anaconda3\\envs\\labelme\\python.exe
## 5	manim	D:\\Anaconda3\\envs\\manim\\python.exe
## 6	mmyolo	D:\\Anaconda3\\envs\\mmyolo\\python.exe
## 7	r-reticulate	D:\\Anaconda3\\envs\\r-reticulate\\python.exe
## 8	rsconnect-jupyter	D:\\Anaconda3\\envs\\rsconnect-jupyter\\python.exe
## 9	sandbox	D:\\Anaconda3\\envs\\sandbox\\python.exe
## 10	sandbox-3.9	D:\\Anaconda3\\envs\\sandbox-3.9\\python.exe

Three main type of Seaborn plots



Yes, that correspond to Matplotlib's concept of figure and axes

Figure 27.3: seaborn plot type

```
use_condaenv(condaenv = 'sandbox-3.9')

## install Seaborn
# conda_install("r-reticulate", "seaborn")

## import Seaborn (it will be automatically discovered in "r-reticulate")
seaborn <- import("seaborn")
```

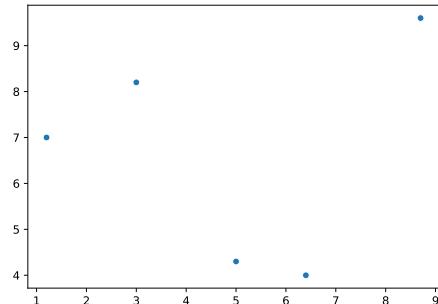
27.1.3.1 basic

```
import matplotlib.pyplot as plt # need it sometimes
import seaborn as sns

sns.set_theme() # set the default theme
```

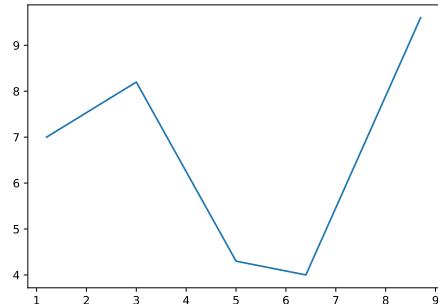
```
import seaborn as sns

x = [3, 5, 1.2, 8.7, 6.4]
y = [8.2, 4.3, 7, 9.6, 4]
sns.scatterplot(x=x, y=y)
```



```
import seaborn as sns

x = [3, 5, 1.2, 8.7, 6.4]
y = [8.2, 4.3, 7, 9.6, 4]
sns.lineplot(x=x, y=y)
```



27.1.3.2 data frame

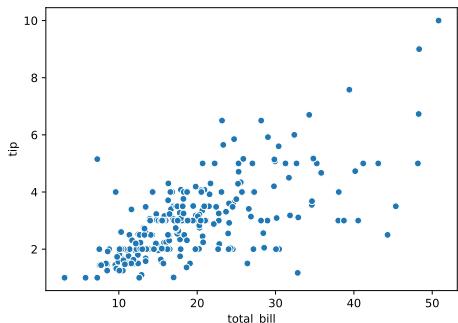
```
sns.load_dataset
```

```
import seaborn as sns
tips = sns.load_dataset("tips")
tips
```

	total_bill	tip	sex	smoker	day
## 0	16.99	1.01	Female	No	Su
## 1	10.34	1.66	Male	No	Su
## 2	21.01	3.50	Male	No	Su
## 3	23.68	3.31	Male	No	Su
## 4	24.59	3.61	Female	No	Su
##
## 239	29.03	5.92	Male	No	Sa
## 240	27.18	2.00	Female	Yes	Sa
## 241	22.67	2.00	Male	Yes	Sa
## 242	17.82	1.75	Male	No	Sa
## 243	18.78	3.00	Female	No	Thu
##					
## [244 rows x 7 columns]					

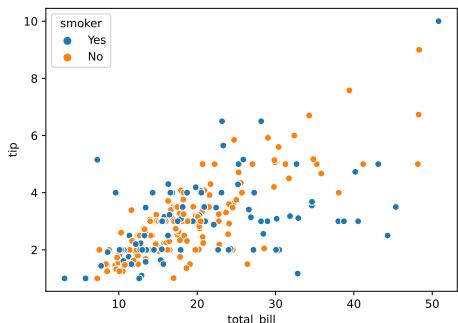
data

```
import seaborn as sns
tips = sns.load_dataset("tips")
sns.scatterplot(data=tips,
                 x='total_bill',
                 y='tip')
```



hue

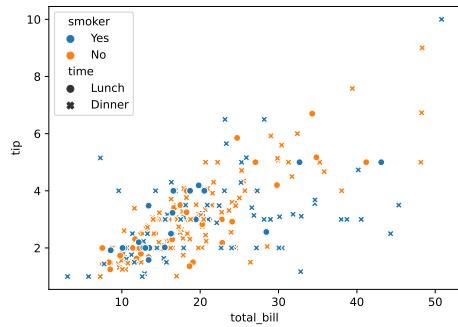
```
import seaborn as sns
tips = sns.load_dataset("tips")
sns.scatterplot(data=tips,
                 x='total_bill',
                 y='tip',
                 hue='smoker')
```



style

```
import seaborn as sns

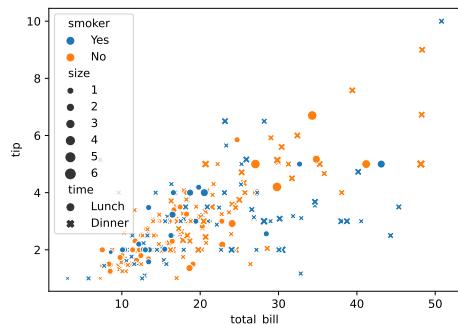
tips = sns.load_dataset("tips")
sns.scatterplot(data=tips,
                 x='total_bill',
                 y='tip',
                 hue='smoker',
                 style='time')
```



size

```
import seaborn as sns

tips = sns.load_dataset("tips")
sns.scatterplot(data=tips,
                 x='total_bill',
                 y='tip',
                 hue='smoker',
                 style='time',
                 size='size')
```



- Legend is covering up the graph, it's getting out of hand. Let's tune the range of x
- `sns.scatterplot()` actually returns something that resembles Matplotlib axis. So we use a Matplotlib axis function:

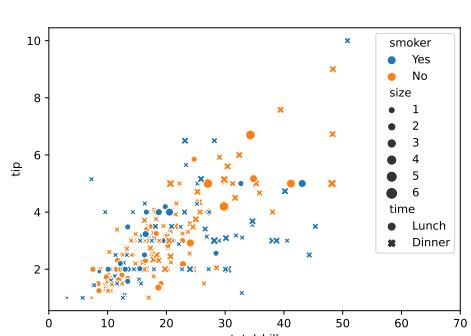
```
ax = sns.scatterplot(...)
```

<https://stackoverflow.com/questions/26597116/seaborn-plots-not-showing-up>

```
import matplotlib.pyplot as plt
import seaborn as sns

tips = sns.load_dataset("tips")
ax = sns.scatterplot(data=tips,
                     x='total_bill',
                     y='tip',
                     hue='smoker',
                     style='time',
                     size='size')

ax.set_xlim(0, 70)
# alternatively:
# ax.set(xlim=(0, 70))
plt.show()
```



27.1.3.3 axis-level plot and figure-level plot

```
sns.relplot
```

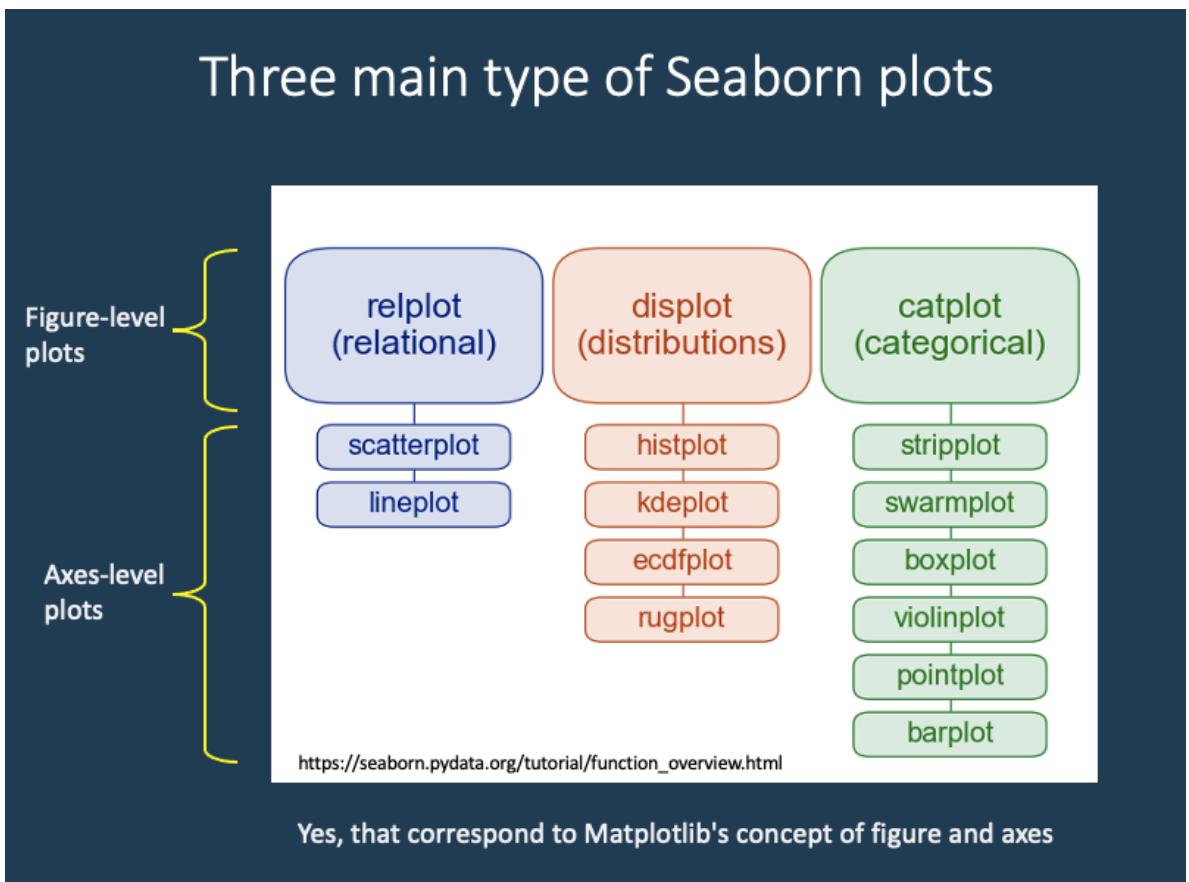


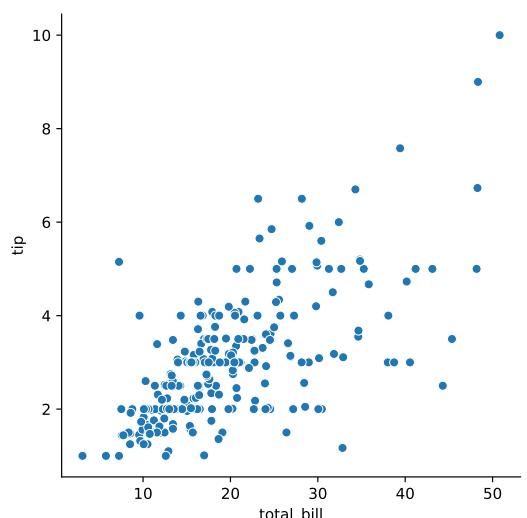
Figure 27.4: seaborn plot type

```

import seaborn as sns

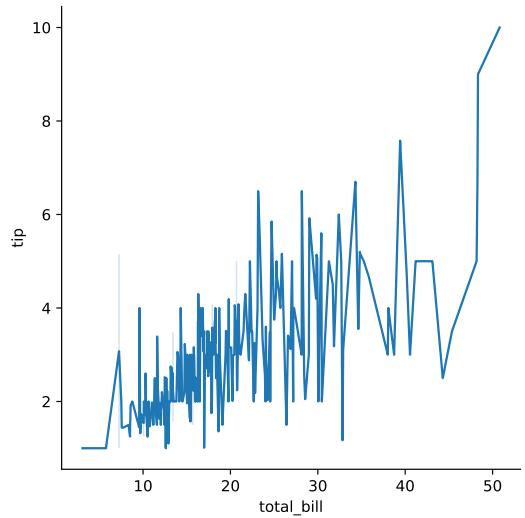
tips = sns.load_dataset("tips")
sns.relplot(kind='scatter',
            data=tips,
            x='total_bill',
            y='tip')

```



```
import seaborn as sns

tips = sns.load_dataset("tips")
sns.relplot(kind='line',
            data=tips,
            x='total_bill',
            y='tip')
```



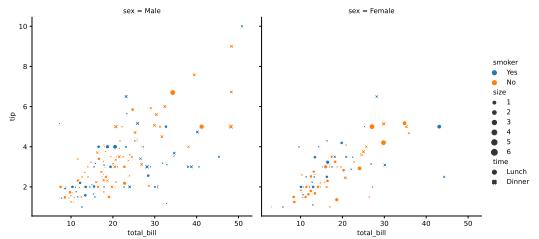
With figure-level plot, we can draw more than one plot (one `axes`).

Here we specify that different `sex` be on different column by specifying `col=sex`.

`col=sex`

```
import seaborn as sns

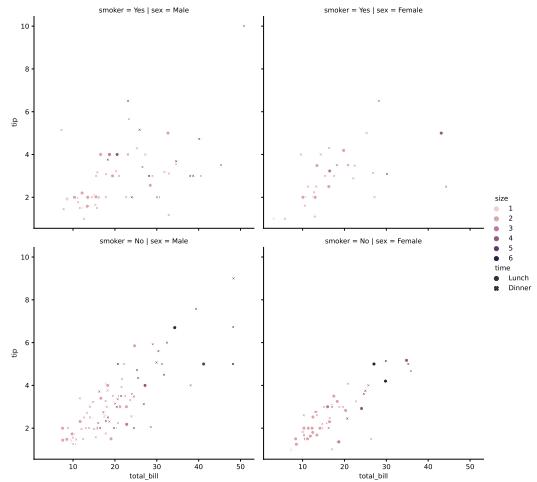
tips = sns.load_dataset("tips")
sns.relplot(kind='scatter',
            data=tips,
            x='total_bill',
            y='tip',
            hue='smoker',
            style='time',
            size='size',
            col='sex')
```



`col=sex row=smoker`

```
import seaborn as sns

tips = sns.load_dataset("tips")
sns.relplot(kind='scatter',
            data=tips,
            x='total_bill',
            y='tip',
            style='time',
            hue='size',
            row='smoker',
            col='sex')
```



27.1.3.4 accessing figure and axes objects

Recall that Seaborn uses Matplotlib to draw the graphics. So underneath the Seaborn library, you can still access Matplotlib's figure object and axes objects if necessary. The call to figure-level plot returns an object.

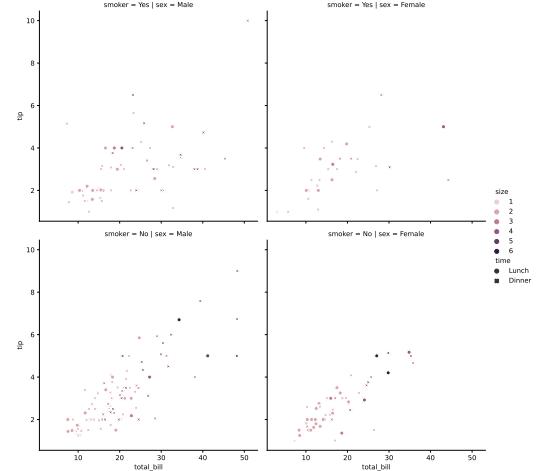
```
import seaborn as sns

tips = sns.load_dataset("tips")
g = sns.relplot(kind='scatter',
                 data=tips,
                 x='total_bill',
                 y='tip',
                 style='time',
                 hue='size',
                 row='smoker',
                 col='sex')

print(type(g))
print(type(g.fig)) # g.fig gets you
                   # the Figure
g.fig
```

```
## <class 'seaborn.axisgrid.FacetGrid'>
```

```
## <class 'matplotlib.figure.Figure'>
```



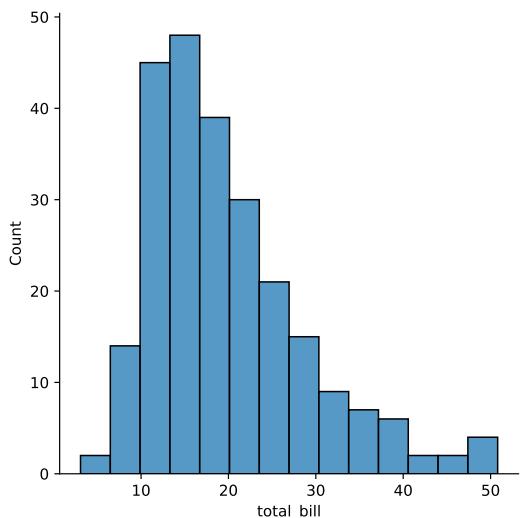
27.1.3.5 distribution plot

```
sns.displot
```

27.1.3.5.1 histogram

```
import seaborn as sns

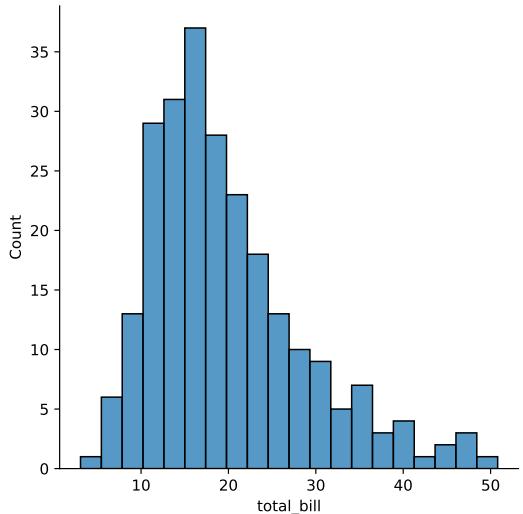
tips = sns.load_dataset("tips")
sns.displot(kind='hist',
            data=tips,
            x='total_bill')
```



bins

```
import seaborn as sns

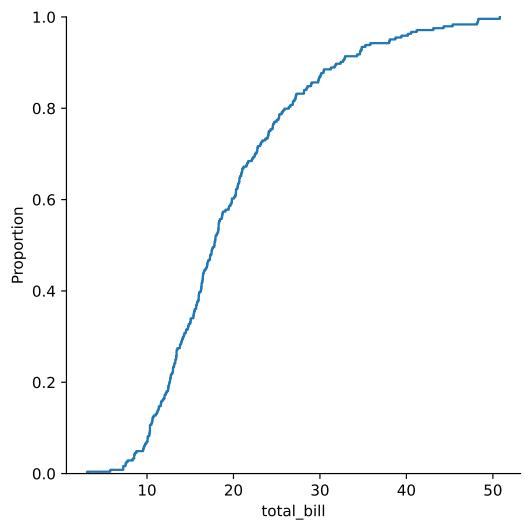
tips = sns.load_dataset("tips")
sns.displot(kind='hist', bins=20,
            data=tips,
            x='total_bill')
```



27.1.3.5.2 ECDF = empirical cumulative distrutive function

```
import seaborn as sns

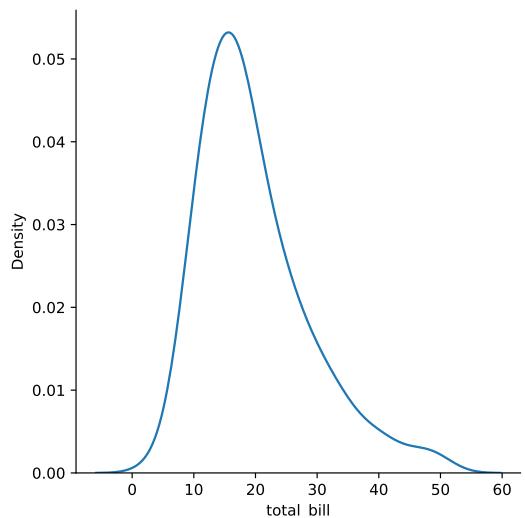
tips = sns.load_dataset("tips")
sns.displot(kind='ecdf',
            data=tips,
            x='total_bill')
```



27.1.3.5.3 KDE = kernel density estimation

```
import seaborn as sns

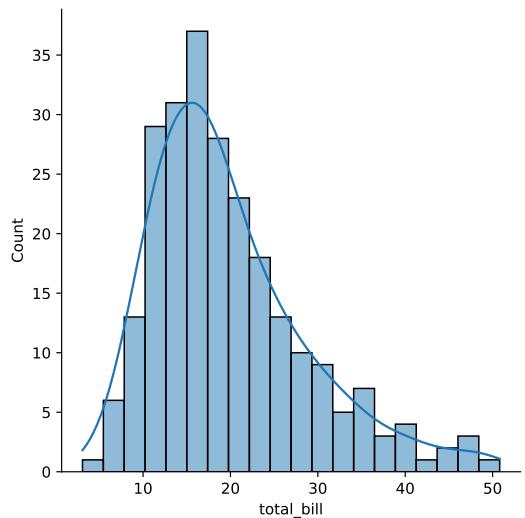
tips = sns.load_dataset("tips")
sns.displot(kind='kde',
            data=tips,
            x='total_bill')
```



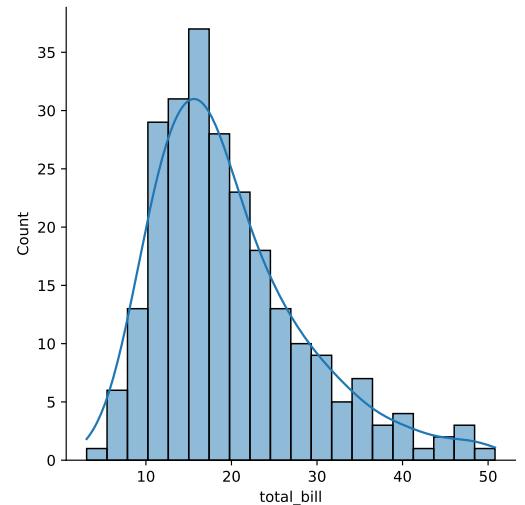
histogram with KDE

```
import seaborn as sns

tips = sns.load_dataset("tips")
sns.displot(kind='hist', bins=20,
            kde=True,
            data=tips,
            x='total_bill')
```



'% This file was created with tikzplotlib'



TikZ / `tikzpicture` with PGFplots `axis` by transforming Matplotlib-based Seaborn plot to .tex via Python package `tikzplotlib`

`xlabel={total_bill}`, changed to `xlabel={total bill}`, without `_` in text

`X ylabel={Count}`, changed to `ylabel={Count}:` not necessary to be changed, the problem is `_` in xlabel name

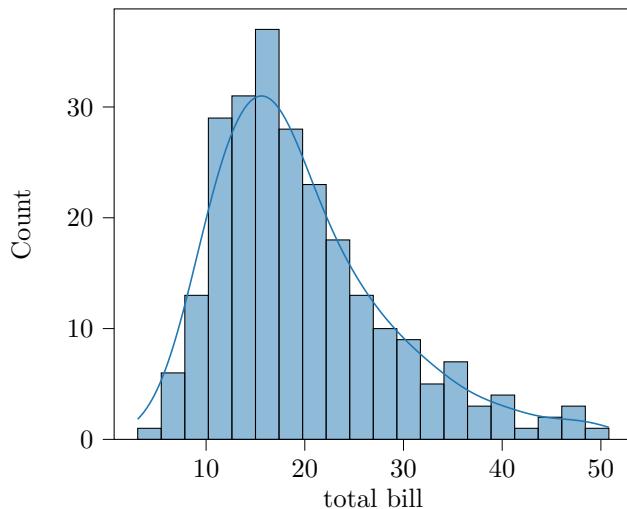
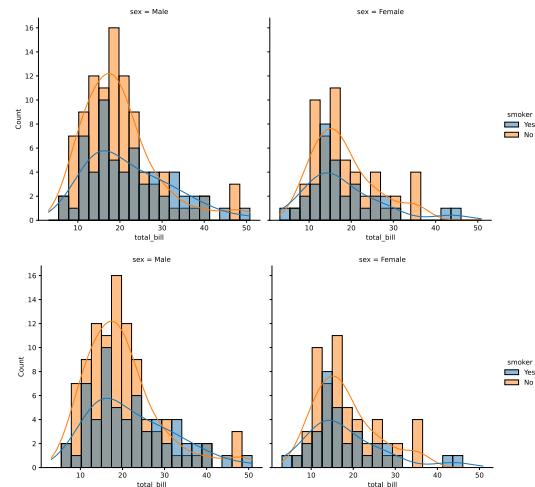


Figure 27.5: tikzplotlib

```
import seaborn as sns

tips = sns.load_dataset("tips")
sns.displot(kind='hist', bins=20,
            kde='true',
            data=tips,
            x='total_bill',
            hue='smoker',
            col='sex'
            )
```



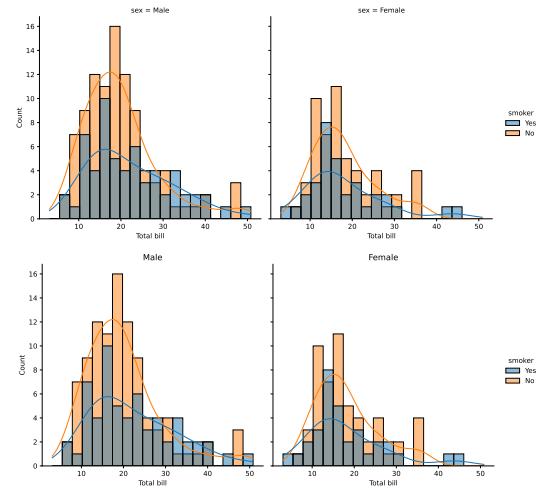
Let's customize the label and title.

```

import seaborn as sns

tips = sns.load_dataset("tips")
g = sns.displot(kind='hist', bins=20,
                 kde=True,
                 data=tips,
                 x='total_bill',
                 hue='smoker',
                 col='sex'
)
g.set(xlabel='Total bill')
g.axes[0][0].set(title='Male')
g.axes[0][1].set(title='Female')
g.fig

```

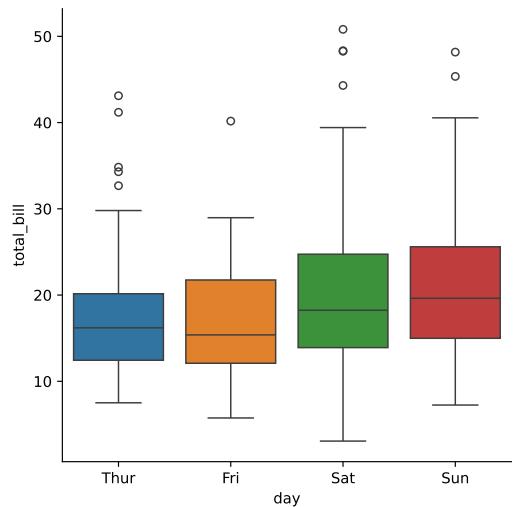
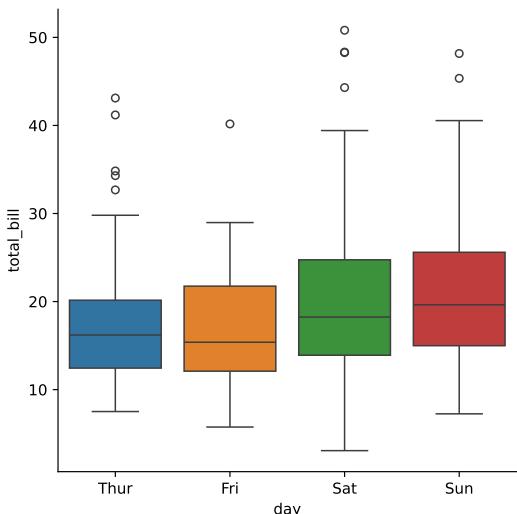


27.1.3.6 categorical plot

`sns.catplot`

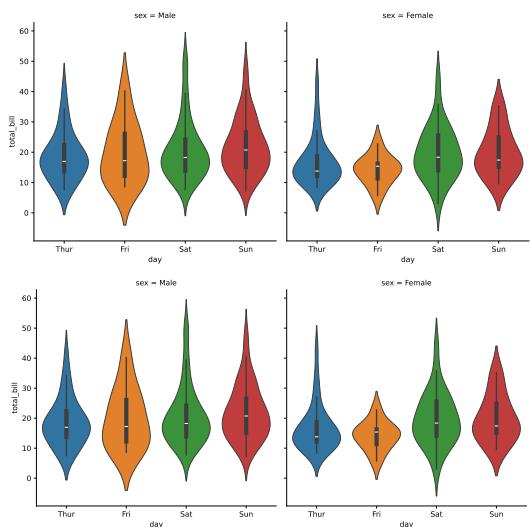
```
import seaborn as sns

tips = sns.load_dataset("tips")
sns.catplot(kind='box',
            data=tips,
            x="day", hue="day",
            y="total_bill"
            )
```



```
import seaborn as sns

tips = sns.load_dataset("tips")
sns.catplot(kind='violin',
            data=tips,
            x="day", hue="day",
            y="total_bill",
            col='sex'
            )
```



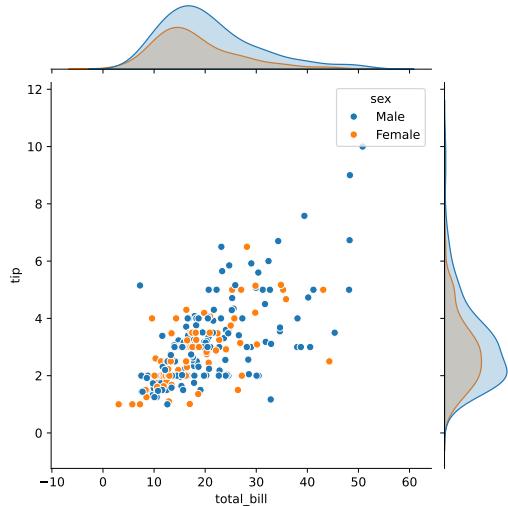
27.1.3.7 joint plot

```
sns.jointplot
```

```
import matplotlib.pyplot as plt
import seaborn as sns

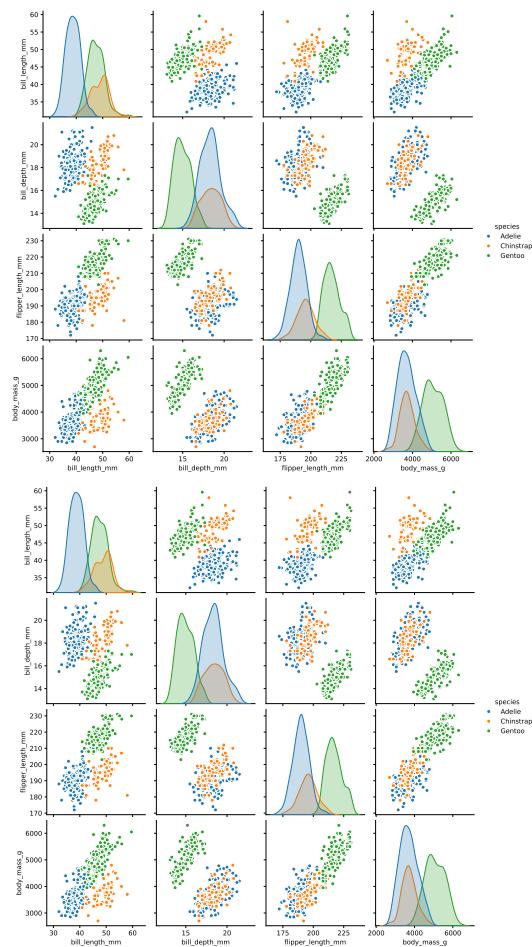
tips = sns.load_dataset("tips")
sns.jointplot(data=tips,
               x="total_bill",
               y="tip",
               hue='sex'
              )
plt.show()
```

```
## <seaborn.axisgrid.JointGrid object at 0x0000000000000000>
```



27.1.3.8 pair plot

```
sns.pairplot
```



```
import seaborn as sns

penguins =
    sns.load_dataset("penguins")
sns.pairplot(data=penguins,
             hue='species')
```

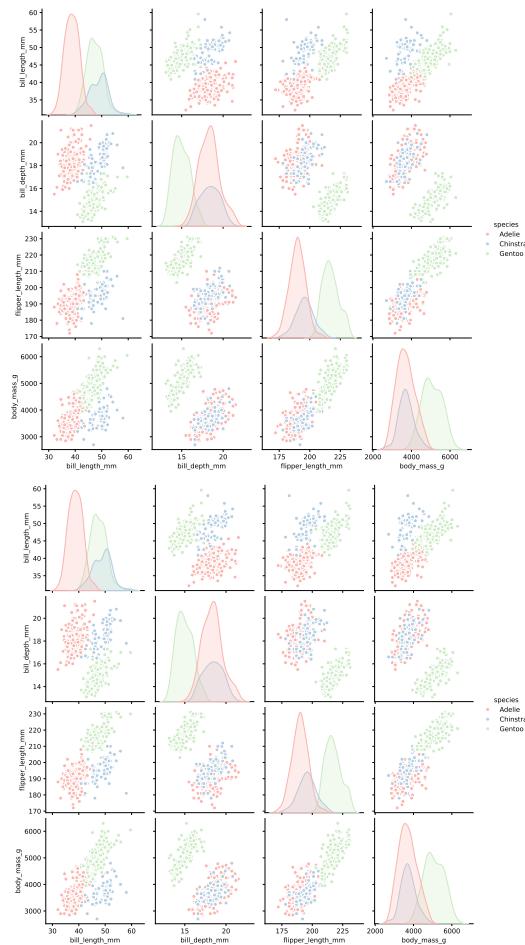
27.1.3.9 palette

Changing the color with Matplotlib's color

A list of color: <https://matplotlib.org/stable/tutorials/colors/colormaps.html>

```
import seaborn as sns

penguins =
    sns.load_dataset("penguins")
sns.pairplot(data=penguins,
              hue='species',
              palette='Pastel1')
```



27.1.3.10 volcano plot

27.1.3.11 heatmap

27.2 export

27.2.1 .svg

<https://stackoverflow.com/questions/24525111/how-can-i-get-the-output-of-a-matplotlib-plot-as-an-svg>

```
import matplotlib.pyplot as plt
import seaborn as sns

penguins = sns.load_dataset("penguins")
sns.pairplot(data=penguins,
              hue='species')

plt.savefig("test.svg")
# plt.savefig("test.svg", dpi=1200)
```

27.2.2 .eps

<https://stackoverflow.com/questions/16183462/saving-images-in-python-at-a-very-high-quality>

The PostScript backend does not support transparency; partially transparent artists will be rendered opaque.

```
import matplotlib.pyplot as plt
import seaborn as sns

penguins = sns.load_dataset("penguins")
sns.pairplot(data=penguins,
              hue='species')

plt.savefig("test.eps")
# plt.savefig("test.eps", dpi=1200)
```


Chapter 28

survival analysis

28.1 Python package `tableone`

28.2 Python package `lifelines`

Chapter 29

Manim

29.1 VSCode extension: Manim Sideview

<https://marketplace.visualstudio.com/items?itemName=Rickaym.manim-sideview>

ffmpeg.exe placed in the same folder with .py

VSCode Ctrl + Shift + P: open Mobject gallery

29.2 installation

<https://docs.manim.community/en/stable/installation.html>

29.2.1 Conda

conda install -c conda-forge manim

29.3 quickstart

<https://docs.manim.community/en/stable/tutorials/quickstart.html>

https://www.w3schools.com/tags/att_video_autoplay.asp

https://www.w3schools.com/tags/att_video_loop.asp

```
from manim import *

class CreateCircle(Scene):
    def construct(self):
        circle = Circle()  # create a
        ↪ circle
        circle.set_fill(PINK,
        ↪ opacity=0.5)  # set the color and
        ↪ transparency
        self.play(Create(circle))  #
        ↪ show the circle on screen
```

```
manim -pql scene.py CreateCircle
```

Chapter 30

ggplot2

<https://bookdown.org/xiangyun/msg/system.html#chap:system>

Modern Statistical Graphics section 5.1

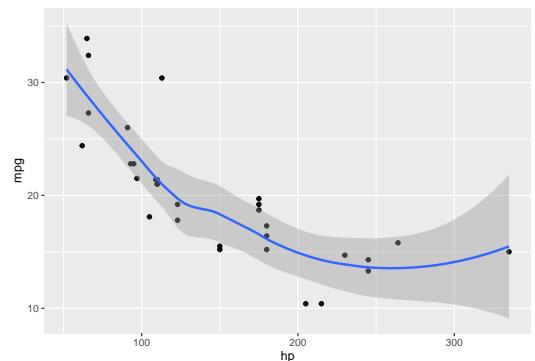
- <https://www.rdocumentation.org/> to search function
- ggplot2
 - <https://ggplot2.tidyverse.org/index.html> to search ggplot2 function
 - panel = layer
 - * geom = geometric objects / geometry = element
 - element
 - * statistic
 - * scale
 - * coordinate system
 - * facet

Warning: package 'ggplot2' was built under R version 3.6.3

`geom_smooth()` using formula = 'y ~ x'

```
library(ggplot2)

p <- ggplot(aes(x = hp, y = mpg), data
  ←  = mtcars) +
  geom_point() # layer of scatterplot
p + geom_smooth(method = "loess") #
  ← add layer of smooth
```



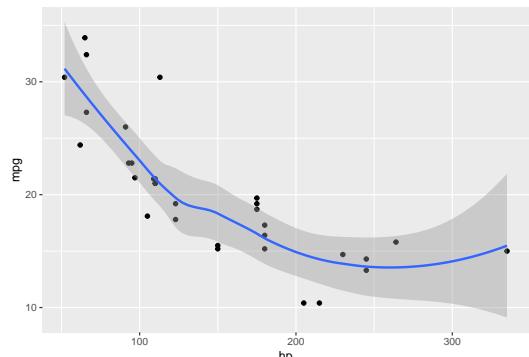
30.1 geom

<https://bookdown.org/xiangyun/msg/system.html#section-13>

```
## `geom_smooth()` using formula = 'y ~ x'
```

```
library(ggplot2)

ggplot(aes(x = hp, y = mpg), data =
  mtcars) +
  geom_point() +
  geom_smooth(method = "loess")
```



points https://ggplot2.tidyverse.org/reference/geom_point.html?q=geom_point#null

`geom_point`

smoothed conditional means https://ggplot2.tidyverse.org/reference/geom_smooth.html?q=geom_sm#null

Aids the eye in seeing patterns in the presence of overplotting. `geom_smooth()` and `stat_smooth()` are effectively aliases: they both use the same arguments. Use `stat_smooth()` if you want to display the results with a non-standard geom.

`geom_smooth`

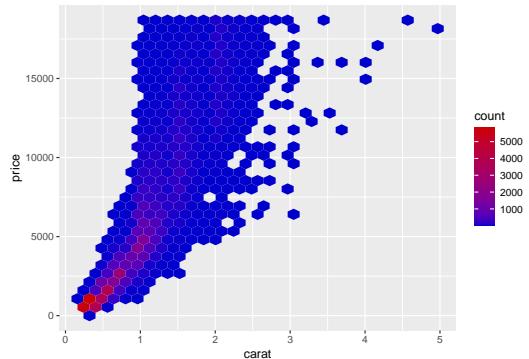
`stat_smooth`

`method` Smoothing method (function) to use, accepts either NULL or a character vector, e.g. "lm", "glm", "gam", "loess" or a function, e.g. MASS::rlm or mgcv::gam, `stats::lm`, or `stats::loess`. "auto" is also accepted for backwards compatibility. It is equivalent to NULL.

```
# install.packages("hexbin")
```

```
library(ggplot2)

ggplot(aes(x = carat, y = price), data
  = diamonds) +
  geom_hex() +
  scale_fill_gradient(low = "blue3",
  high = "red3")
```

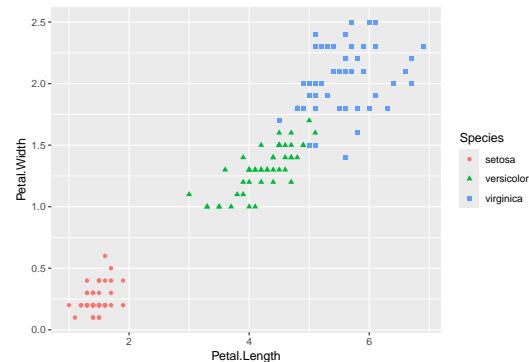


gradient color scales https://ggplot2.tidyverse.org/reference/scale_gradient.html?q=scale_fill_gradient#ref-usage

https://ggplot2.tidyverse.org/reference/scale_gradient.html?q=scale_fill_gradient#ref-examples

```
library(ggplot2)

ggplot(aes(x = Petal.Length, y =
           Petal.Width), data = iris) +
  geom_point(aes(color = Species,
                 shape = Species))
```

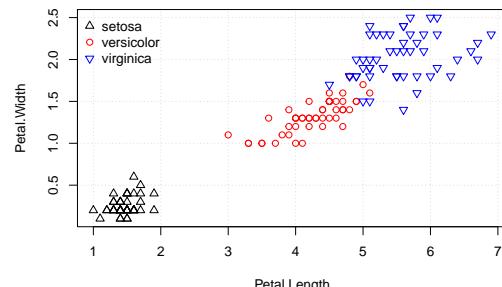


basic plot system

<https://bookdown.org/xiangyun/msg/elements.html#sec:points>

```
# iris species converted to type
#   integer 1, 2, 3 for further using
#   vectors
idx <- as.integer(iris[["Species"]])
plot(iris[, 3:4],
      pch = c(24, 21, 25)[idx],
      col = c("black", "red",
             "blue")[idx], panel.first =
      grid())
)
legend("topleft",
       legend = levels(iris[["Species"]]),
       col = c("black", "red", "blue"), pch
       = c(24, 21, 25), bty = "n"
)
```

plot <https://www.rdocumentation.org/packages/graphics/versions/3.6.2/topics/plot.default>



pch a vector of **plotting characters** or symbols: see [points](#).

col The **colors** for lines and points. Multiple colors can be specified so that each point can be given its own color. If there are fewer colors than points they are recycled in the standard fashion. Lines will all be plotted in the first colour specified.

panel.first an ‘expression’ to be evaluated after the plot axes are set up but before any plotting takes place. This can be useful for drawing **background grids** or **scatterplot smooths**. Note that this works by lazy evaluation: passing this argument from other plot methods may well not work since it may be evaluated too early.

legend <https://www.rdocumentation.org/packages/graphics/versions/3.6.2/topics/legend>

bty the **type of box** to be drawn around the legend. The allowed values are “o” (the default) and “n”.

<https://stackoverflow.com/questions/10108073/plot-legends-without-border-and-with-white-background>

Use option **bty = "n"** in legend to remove the box around the legend.

legend a character or expression vector of length ≥ 1 to appear in the legend. Other objects will be coerced by [as.graphicsAnnot](#)

30.1.1 basic plot system decomposition

```
##      Sepal.Length Sepal.Width Petal.Length  
## 1          5.1         3.5      1.4  
## 2          4.9         3.0      1.4  
## 3          4.7         3.2      1.3  
## 4          4.6         3.1      1.5  
## 5          5.0         3.6      1.4  
## 6          5.4         3.9      1.7  
## 7          4.6         3.4      1.4  
## 8          5.0         3.4      1.5  
## 9          4.4         2.9      1.4  
## 10         4.9         3.1      1.5  
## 11         5.4         3.7      1.5  
## 12         4.8         3.4      1.6  
## 13         4.8         3.0      1.4  
## 14         4.3         3.0      1.1  
## 15         5.8         4.0      1.2  
## 16         5.7         4.4      1.5  
## 17         5.4         3.9      1.3  
## 18         5.1         3.5      1.4  
## 19         5.7         3.8      1.7  
## 20         5.1         3.8      1.5  
## 21         5.4         3.4      1.7  
## 22         5.1         3.7      1.5  
## 23         4.6         3.6      1.0  
## 24         5.1         3.3      1.7  
## 25         4.8         3.4      1.9  
## 26         5.0         3.0      1.6  
## 27         5.0         3.4      1.6  
## 28         5.2         3.5      1.5  
## 29         5.2         3.4      1.4  
## 30         4.7         3.2      1.6  
## 31         4.8         3.1      1.6  
## 32         5.4         3.4      1.5  
## 33         5.2         4.1      1.5  
## 34         5.5         4.2      1.4  
## 35         4.9         3.1      1.5  
## 36         5.0         3.2      1.2  
## 37         5.5         3.5      1.3  
## 38         4.9         3.6      1.4  
## 39         4.4         3.0      1.3  
## 40         5.1         3.4      1.5  
## 41         5.0         3.5      1.3  
## 42         4.5         2.3      1.3  
## 43         4.4         3.2      1.3  
## 44         5.0         3.5      1.6  
## 45         5.1         3.8      1.9  
## 46         4.8         3.0      1.4  
## 47         5.1         3.8      1.6  
## 48         4.6         3.2      1.4  
## 49         5.3         3.7      1.5  
## 50         5.0         3.3      1.4  
## 51         7.0         3.2      4.7  
## 52         6.4         3.2      4.5  
## 53         6.9         3.1      4.9
```

```
iris$Species
```

```
## [1] setosa      setosa      setosa      setosa      se
## [7] setosa      setosa      setosa      setosa      se
## [13] setosa     setosa      setosa      setosa      se
## [19] setosa     setosa      setosa      setosa      se
## [25] setosa     setosa      setosa      setosa      se
## [31] setosa     setosa      setosa      setosa      se
## [37] setosa     setosa      setosa      setosa      se
## [43] setosa     setosa      setosa      setosa      se
## [49] setosa     setosa      setosa      versicolor ve
## [55] versicolor versicolor versicolor versicolor ve
## [61] versicolor versicolor versicolor versicolor ve
## [67] versicolor versicolor versicolor versicolor ve
## [73] versicolor versicolor versicolor versicolor ve
## [79] versicolor versicolor versicolor versicolor ve
## [85] versicolor versicolor versicolor versicolor ve
## [91] versicolor versicolor versicolor versicolor ve
## [97] versicolor versicolor versicolor versicolor ve
## [103] virginica virginica virginica virginica vi
## [109] virginica virginica virginica virginica vi
## [115] virginica virginica virginica virginica vi
## [121] virginica virginica virginica virginica vi
## [127] virginica virginica virginica virginica vi
## [133] virginica virginica virginica virginica vi
## [139] virginica virginica virginica virginica vi
## [145] virginica virginica virginica virginica vi
## Levels: setosa versicolor virginica
```

```
iris[["Species"]]
```

```
## [1] setosa      setosa      setosa      setosa      se
## [7] setosa      setosa      setosa      setosa      se
## [13] setosa     setosa      setosa      setosa      se
## [19] setosa     setosa      setosa      setosa      se
## [25] setosa     setosa      setosa      setosa      se
## [31] setosa     setosa      setosa      setosa      se
## [37] setosa     setosa      setosa      setosa      se
## [43] setosa     setosa      setosa      setosa      se
## [49] setosa     setosa      setosa      versicolor ve
## [55] versicolor versicolor versicolor ve
## [61] versicolor versicolor versicolor ve
## [67] versicolor versicolor versicolor ve
## [73] versicolor versicolor versicolor ve
## [79] versicolor versicolor versicolor ve
## [85] versicolor versicolor versicolor ve
## [91] versicolor versicolor versicolor ve
## [97] versicolor versicolor versicolor ve
## [103] virginica virginica virginica vi
## [109] virginica virginica virginica vi
## [115] virginica virginica virginica vi
## [121] virginica virginica virginica vi
## [127] virginica virginica virginica vi
## [133] virginica virginica virginica vi
## [139] virginica virginica virginica vi
## [145] virginica virginica virginica vi
## [151] virginica virginica virginica vi
## Levels: setosa versicolor virginica
```

```
as.integer(iris[["Species"]])
```

```
levels(iris[["Species"]]) ## [1] "setosa"      "versicolor" "virginica"
```

```
idx <- as.integer(iris[["Species"]])  
c(24, 21, 25)[idx]  
  
## [26] 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24  
## [51] 21 21 21 21 21 21 21 21 21 21 21 21 21 21 21  
## [76] 21 21 21 21 21 21 21 21 21 21 21 21 21 21 21  
## [101] 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25  
## [126] 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25
```

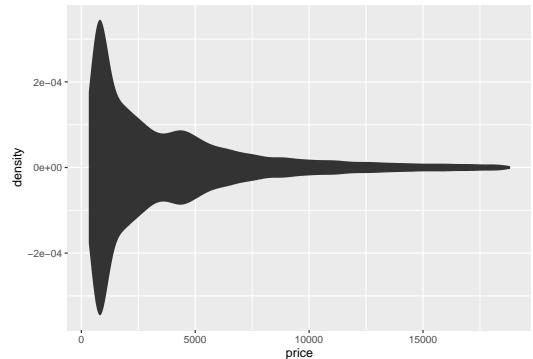
30.2 statistic

<https://bookdown.org/xiangyun/msg/system.html#section-14>

```
## Warning: The dot-dot notation (`..density..`)
## i Please use `after_stat(density)` instead
## This warning is displayed once every 8 hours
## Call `lifecycle::last_lifecycle_warnings()`
## generated.
```

```
library(ggplot2)

ggplot(diamonds, aes(x = price)) +
  stat_density(aes(ymax = ..density..,
                  ymin = -..density..),
               geom = "ribbon", position =
                 "identity"
  )
```



smoothed density estimates https://ggplot2.tidyverse.org/reference/geom_density.html

Computes and draws kernel density estimate, which is a smoothed version of the histogram. This is a useful alternative to the histogram for continuous data that comes from an underlying smooth distribution.

`geom_density`

`stat_density`

https://ggplot2.tidyverse.org/reference/geom_density.html#ref-examples

30.3 scale

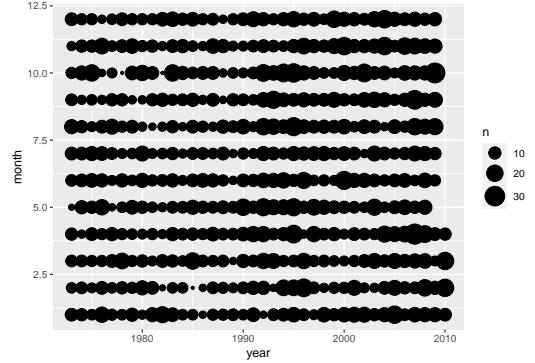
ggplot2

<https://bookdown.org/xiangyun/msg/system.html#section-15>

```
## Warning: package 'ggplot2' was built under R version 3.6.3
## Warning: The dot-dot notation (`...n...`) will be removed in lifecycle 1.0.0.
## i Please use `after_stat(n)` instead.
## This warning is displayed once every 8 hours.
## Call `lifecycle::last_lifecycle_warnings()` to see it again.
## generated.
```

```
library(ggplot2)

data(quake6, package = "MSG")
ggplot(quake6, aes(x = year, y =
  month)) +
  stat_sum(aes(size = ..n..)) +
  scale_size(range = c(1, 8))
```



count overlapping points https://ggplot2.tidyverse.org/reference/geom_count.html?q=stat_sum#ref-usage

This is a variant `geom_point()` that counts the number of observations at each location, then maps the count to point area. It useful when you have discrete data and overplotting.

`geom_count`

`stat_sum`

https://ggplot2.tidyverse.org/reference/geom_count.html?q=stat_sum#ref-examples

scales for area or radius https://ggplot2.tidyverse.org/reference/scale_size.html?q=scale_size#null

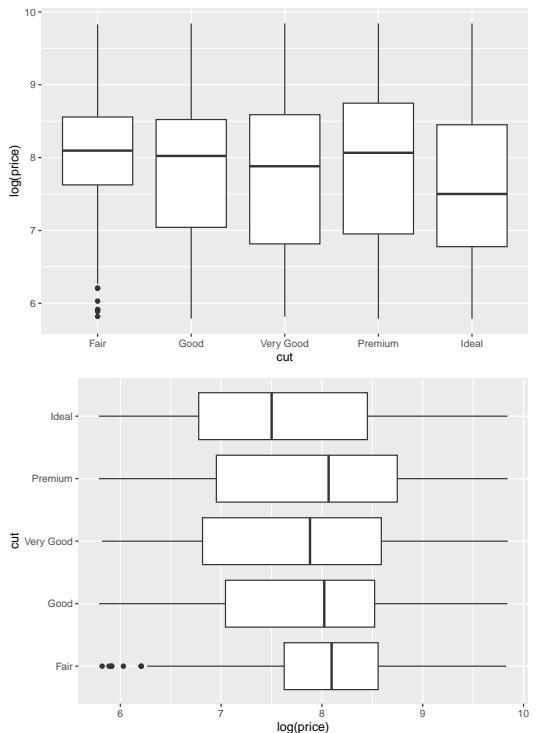
`scale_size`

30.4 coordinate system

<https://bookdown.org/xiangyun/msg/system.html#section-16>

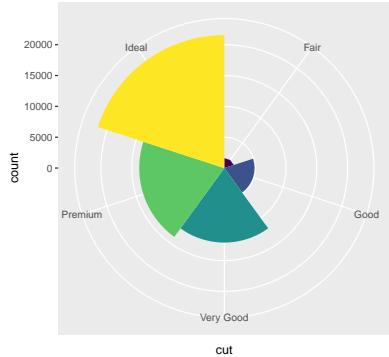
```
library(ggplot2)

p <- ggplot(aes(x = cut, y =
  log(price)), data = diamonds) +
  geom_boxplot()
p
p + coord_flip()
```



```
library(ggplot2)

ggplot(aes(x = cut, fill = cut), data
  = diamonds) +
  coord_polar() +
  geom_bar(width = 1, show.legend =
    FALSE)
```

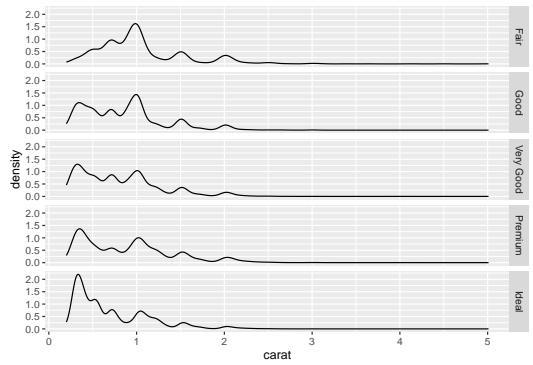


30.5 facet

<https://bookdown.org/xiangyun/msg/system.html#subsec:facet>

```
library(ggplot2)

ggplot(aes(x = carat), data =
  diamonds) +
  geom_density() +
  facet_grid(cut ~ .)
```

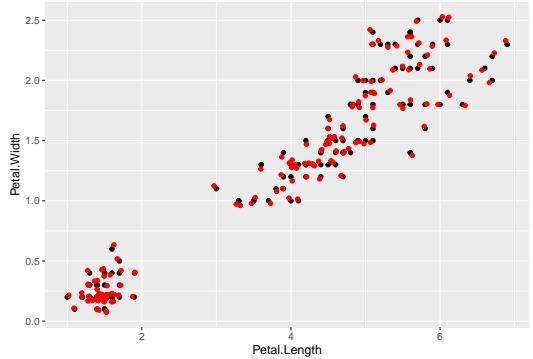


30.6 jitter

<https://bookdown.org/xiangyun/msg/system.html#section-17>

```
library(ggplot2)

ggplot(aes(x = Petal.Length, y =
  Petal.Width), data = iris) +
  geom_point() +
  geom_jitter(color = "red")
```



30.7 font

<https://bookdown.org/xiangyun/msg/system.html#subsec:font>

Chapter 31

notational system for design

? p.51

NSD = notational system for design

?

31.1 graphic notation

? p.51

- X : treatment or exposure to an agent or an event of interest
- P : **placebo**, i.e. blank treatment or exposure, or standard treatment, or exposure as an active control
- O : **observation** or process of measurement
- R : **randomization**, i.e. random assignment of research subjects to separate treatment or exposure groups
- subscript
 - g : **groups**
 - k : **kinds** of treatments, exposures, or placebos
 - t : **time** or sequential order

<https://tex.stackexchange.com/questions/591882/citation-within-a-latex-figure-caption-in-rmarkdown>

```
(ref:rudolph) *nice* cite: [@Lam94].  
(ref:campbell1963) *nice* cite: [@campbell1963].  
(ref:campbell1963) ([@campbell1963]  
(ref:campbell1963) \ [@campbell1963]  
? ?
```

31.2 pre-experimental design

? p.6

	Sources of Invalidity											
	Internal				External							
	History	Maturat	Testing	Instrumentation	Regression	Selection	Mortality	Interaction of Selection and Maturat, etc.	Interaction of Testing and X	Interaction of Selection and X	Reactive Arrangements	Multiple-X Interference
<i>Pre-Experimental Designs:</i>												
1. One-Shot Case Study	-	-				-	-			-		
	X	O										
2. One-Group Pretest-Posttest Design	-	-	-	-	?	+	+	-	-	-	-	?
	O	X	O									
3. Static-Group Comparison	+	?	+	+	+	-	-	-		-		
	X	O										
<i>True Experimental Designs:</i>												
4. Pretest-Posttest Control Group Design	+	+	+	+	+	+	+	+	-	?	?	?
	R	O	X	O								
	R	O										
	R		X	O								
	R		O									
5. Solomon Four-Group Design	+	+	+	+	+	+	+	+	+	?	?	?
	R	O	X	O								
	R	O										
	R		X	O								
	R		O									
6. Posttest-Only Control Group Design	+	+	+	+	+	+	+	+	+	?	?	?
	R		X	O								
	R											

Figure 31.1: pre- and true experimental designs (? p.8)

31.2.1 one-shot case study

X O

31.2.2 one-group pretest-posttest design

O X O

paired t test

? p.62

$O \quad X \quad O$
 $O_t \quad X \quad O_t$
 $O_0 \quad X \quad O_1$

$O \quad X \quad O$
 $O_{gt} \quad X_g \quad O_{gt}$
 $O_{10} \quad X \quad O_{11}$

	Sources of Invalidity											
	Internal							External				
	History	Maturity	Testing	Instrumentation	Regression	Selection	Mortality	Interaction of Selection and Maturation, etc.	Interaction of Testing and X	Interaction of Selection and X	Reactive Arrangements	Multiple-X Interference
<i>Quasi-Experimental Designs:</i>												
7. Time Series <i>O O O O X O O O O</i>	-	+	+	?	+	+	+	+	-	?	?	
8. Equivalent Time Samples Design <i>X₁O X₂O X₃O, etc.</i>	+	+	+	+	+	+	+	+	-	?	-	-
9. Equivalent Materials Samples Design <i>M_aX₁O M_bX₂O M_cX₃O, etc.</i>	+	+	+	+	+	+	+	+	-	?	?	-
10. Nonequivalent Control Group Design <i>O X O</i> <i>O-----O</i>	+	+	+	+	?	+	+	-	-	?	?	
11. Counterbalanced Designs <i>X₁O X₂O X₁O X₂O</i> <i>X₂O X₁O X₂O X₁O</i> <i>X₃O X₄O X₃O X₄O</i> <i>X₄O X₃O X₄O X₃O</i>	+	+	+	+	+	+	+	?	?	?	-	
12. Separate-Sample Pretest-Posttest Design <i>R O (X)</i> <i>R X O</i>	-	-	+	?	+	+	-	-	+	+	+	
12a. <i>R O (X)</i> <i>R X O</i> <i>R O (X)</i> <i>R X O</i>	+	-	+	?	+	+	-	+	+	+	+	
12b. <i>R O₁ (X)</i> <i>R O₂ (X)</i> <i>R X O₁</i> <i>R X O₂</i>	-	+	+	?	+	+	-	?	+	+	+	
12c. <i>R O₁ X O₂</i> <i>R X O₂</i>	-	-	+	?	+	+	+	-	+	+	+	

Figure 31.2: quasi-experimental designs (? p.40)

	Sources of Invalidity										
	Internal					External					
	History	Maturity	Testing	Instrumentation	Regression	Selection	Mortality	Selection and Maturation, etc.	Interaction of Testing and X	Interaction of Selection and X	Reactive Arrangements
<i>Quasi-Experimental Designs</i>											
<i>Continued:</i>											
13. Separate-Sample Pretest-Posttest Control Group Design	+ + + + + + -								+ + +		
$R \begin{matrix} O \\ (X) \end{matrix}$											
$R \begin{matrix} X \\ O \end{matrix}$											
$\overline{R \begin{matrix} O \\ X \end{matrix}}$											
$R \begin{matrix} O \\ O \end{matrix}$											
13a. $\left\{ \begin{array}{l} R \begin{matrix} O \\ (X) \end{array} \\ R \begin{matrix} X \\ O \end{matrix} \\ \hline R' \begin{matrix} O \\ (X) \end{matrix} \\ R \\ R \begin{matrix} O \\ X \end{matrix} \\ R \\ R \begin{matrix} O \\ O \end{matrix} \\ \hline R' \begin{matrix} O \\ R \end{matrix} \\ R \\ R \begin{matrix} O \\ O \end{matrix} \\ R \\ R \begin{matrix} O \\ O \end{matrix} \end{array} \right.$	+ + + + + + + + +								+ + +		
14. Multiple Time-Series	+ + + + + + + + +								- - ?		
$O \begin{matrix} O \\ O \end{matrix} \begin{matrix} O \\ O \end{matrix}$											
15. Institutional Cycle Design											
Class A $X \bar{O}_1$											
Class B ₁ $R O_2 \begin{matrix} X \\ O_3 \end{matrix}$											
Class B ₂ $R \begin{matrix} X \\ O_4 \end{matrix}$											
Class C $O_5 \begin{matrix} X \\ O_6 \end{matrix}$											
^a Gen. Pop. Con. Cl. B O_6											
^a Gen. Pop. Con. Cl. C O_7											
$O_2 < O_1 \}$	+ - + + ? - ?								+ ? +		
$O_6 < O_1 \}$											
$O_2 < O_4$	- - - ? ? + +								- ? +		
$O_2 < O_4$											
$O_6 = O_7 \}$	- - + ? ? + ?										
$O_{2g} = O_{2o} \}$	+ -										
16. Regression Discontinuity	+ + + ? + + ? +								+ - + +		

• General Population Controls for Class B, etc.

Figure 31.3: quasi-experimental designs continued (? p.56)

31.2.3 static-group comparison

$$\begin{array}{ccc} X & O \\ X_g & O_{gt} \\ X & O_{11} \\ & O_{21} \end{array}$$

$$\begin{array}{ccc} X & O \\ X_g & O_{gt} \\ X & O_{11} \\ & O_{01} \end{array}$$

31.3 true experimental design

? p.13

31.3.1 posttest-only control group design

basic experimental design

two-sample t test

? p.53

$$\begin{array}{ccc} R & X & O \\ R & & O \end{array}$$

or, with a placebo or an active control,

$$\begin{array}{ccc} R & X & O \\ R & P & O \end{array}$$

$$R \quad X_g \quad O_{gt}$$

$$\begin{array}{cccc} R & X_g = X_1 = X & O_{gt} = O_{11} \\ R & X_g = X_2 = \emptyset & O_{gt} = O_{21} \end{array}$$

or, with a placebo or an active control

$$\begin{array}{cccc} R & X_g = X_1 = X & O_{gt} = O_{11} \\ R & X_g = X_2 = P & O_{gt} = O_{21} \end{array}$$

$$\begin{array}{lll} R & X & O_{11} \\ R & & O_{21} \end{array}$$

or, with a placebo or an active control

$$\begin{array}{lll} R & X & O_{11} \\ R & P & O_{21} \end{array}$$

$$\begin{array}{lll} R & X_g & O_{gt} \\ R & X & O_{11} \\ R & P & O_{21} \end{array}$$

$$\begin{array}{lll} R & X & O \\ R & X_g & O_{gt} \\ R & X & O_{11} \\ R & P & O_{21} \end{array}$$

31.3.2 pretest-posttest control group design

$$\begin{array}{llll} R & O & X & O \\ R & O_{gt} & X_g & O_{gt} \\ R & O_{10} & X & O_{11} \\ R & O_{20} & & O_{21} \end{array}$$

31.3.3 Solomon four-group design

? p.52

Solomon 4-group design = pretest-posttest + posttest-only control group design

$$\begin{array}{llll} R & O_{gt} & X_g & O_{gt} \\ R & O_{10} & X & O_{11} \\ R & O_{20} & & O_{21} \\ R & & X & O_{31} \\ R & & & O_{41} \end{array}$$

$$\begin{array}{llll} R & O & X & O \\ R & O_{gt} & X_g & O_{gt} \\ R & O_{10} & X & O_{11} \\ R & O_{20} & & O_{21} \\ R & & X & O_{31} \\ R & & & O_{41} \end{array}$$

31.4 quasi-experimental design

? p.34

31.5 correlational and ex post facto designs

? p.64

31.6 graphic notation, advanced

? p.74

- X : treatment or exposure to an agent or an event of interest
- P : **placebo**, i.e. blank treatment or exposure, or standard treatment, or exposure as an active control
- O : **observation** or process of measurement
- R : **randomization**, i.e. random assignment of research subjects to separate treatment or exposure groups
- subscript
 - $_g$: **groups**
 - $_k$: **kinds** of treatments, exposures, or placebos
 - $_t$: **time** or sequential order
- V : **variable(s)**
 - $B(V)$: **blocking** by the variable(s)
 - $M(V)$: **matching** by the variable(s)
 - $S(V)$: **stratifying** by the variable(s)
 - $L(V/L)$: **limiting** to the level(s) of the variable(s)
- M^* : research **material(s)** selected
- -: cohort

Chapter 32

design of experiment

experimental design = experiment design = design of experiments = DoE

? p.72

question-design-analysis loop

32.1 notational system for design^[??]

graphic notation, advanced^[??]

32.2 terminology

- population
 - sample
 - * subsample
- unit
 - experimental unit
 - * response
 - * block: group of similar experimental unit (? p.74)
 - observational unit / measurement unit ¹
- replication (? p.76): an independent observation of the treatment (? p.74)
 - treatment replication: experimental-unit-to-experimental-unit variation
 - measurement replication = subsample: measurement-to-measurement variation
- replicate
 - experimental replicate
 - biological replicate
 - technical replicate

¹<https://passel2.unl.edu/view/lesson/2e09f0055f13/6>

? p.73

Y_{ij} : the response observed from the j^{th} experimental unit assigned to the i^{th} treatment

μ_i : the mean response to the i^{th} treatment

\mathcal{E}_{ij} : the noise from other possible natural variation or nonrandom and random error

$$Y_{ij} = \mu_i + \mathcal{E}_{ij}, \begin{cases} i \in \mathbb{N} \cap [1, n_i] & \mathbb{N} \ni n_i \text{ treatments} \\ j \in \mathbb{N} \cap [1, n_j] & \mathbb{N} \ni n_j \text{ experimental units per treatment} \end{cases}$$

Each treatment has n_j experimental units, so there are totally $n_i n_j$ experimental units.

If experimental units cannot be homogeneous, we can try to

- stratify them
- group them, and measure group to group variation
- block them

here n_j blocks each with n_i experimental units where **each treatment occurs once in each block**

$$\begin{aligned} Y_{ij} &= \mu_i + \mathcal{E}_{ij} \\ &= \mu_i + b_j + \mathcal{E}_{ij}^*, \begin{cases} i \in \mathbb{N} \cap [1, n_i] & \mathbb{N} \ni n_i \text{ experimental units per block} \\ j \in \mathbb{N} \cap [1, n_j] & \mathbb{N} \ni n_j \text{ blocks} \end{cases} \end{aligned}$$

where

$$\mathcal{E}_{ij} = b_j + \mathcal{E}_{ij}^*$$

i.e. the variation between groups or blocks of experimental units has been identified and isolated from \mathcal{E}_{ij}^* , which represents the variability of experimental units within a block. By isolating the block effect from the experimental units, the within-block variation can be used to compare treatment effects, which involves computing the estimated standard errors of contrasts of the treatments.

$$\begin{aligned} Y_{ij} - Y_{i'j} &= (\mu_i + b_j + \mathcal{E}_{ij}^*) \\ &\quad - (\mu_{i'} + b_j + \mathcal{E}_{i'j}^*) \\ &= (\mu_i - \mu_{i'}) + (\mathcal{E}_{ij}^* - \mathcal{E}_{i'j}^*) \end{aligned}$$

which does not depend on the block effect b_j or free of block effects. The result of this difference is that the variance of the difference of two treatment responses within a block depends on the within-block variation among the experimental units and not the between-block variation.

32.2.1 replication vs. subsample

It is very important to distinguish between a **subsample** and a **replication** since the error variance estimated from between subsamples is in general considerably smaller than the error variance estimated from replications or between experimental units. (? p.77)

<https://www.researchgate.net/post/What-is-Experimental-Unit-Replicate-Total-sample-size-treatment-size>

32.2.2 replication vs. repeated measurements

32.2.3 replication, replicate

32.2.3.1 technical replicate, biological replicate

https://www.youtube.com/watch?v=c_cpl5YsBV8

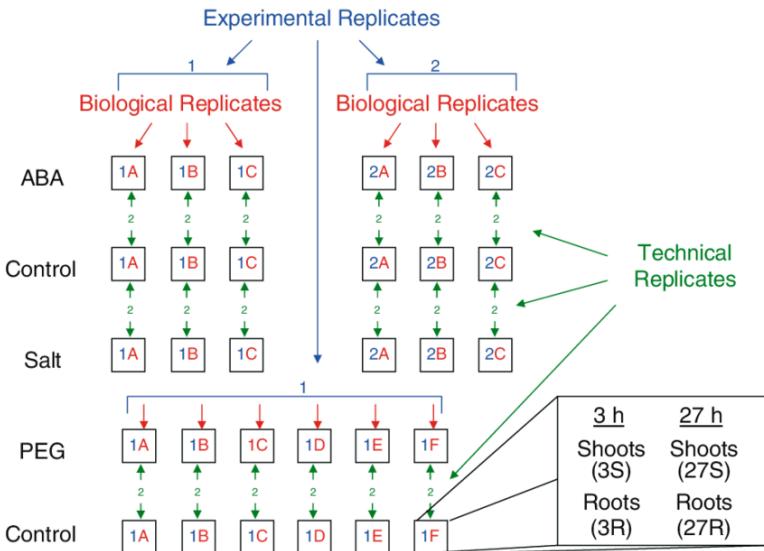


Figure 32.1: experimental, biological, technical replicates (?)

32.2.4 Latin square design

LSD = Latin square design

? p.505~507

<https://tex.stackexchange.com/questions/501671/how-to-get-math-mode-curly-braces-in-tikz>

```
\usepackage{pgfplots} in engine.opts=list(extra.preamble=c("\usepackage{pgfplots}"))
\usetikzlibrary{decorations}
```

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + \varepsilon_{ijk}, \begin{cases} i \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ treatments} \\ j \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ rows} \\ k \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ columns} \end{cases}$$

$p = 4$ columns			
$p = 4$ rows			
A	B	C	D
B	C	D	A
C	D	A	B
D	A	B	C

$p = |\{A, B, C, D\}| = 4$ treatments

Figure 32.2: Latin square example

$$\mathcal{E}_{ijk} \stackrel{\text{i.i.d.}}{\sim} n(0, \sigma^2)$$

ρ_i : i^{th} row

κ_j : j^{th} column

τ_k : k^{th} treatment

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + \mathcal{E}_{ijk}, \begin{cases} i \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ treatments} \\ j \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ rows} \\ k \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ columns} \end{cases}$$

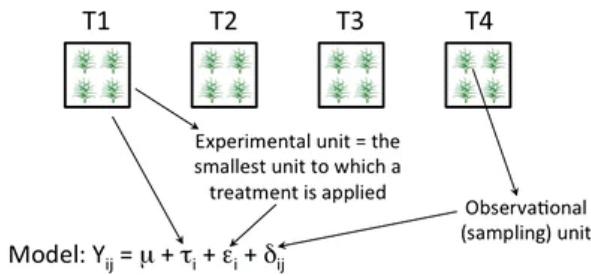
$$= \mu + \rho_i + \kappa_j + \tau_k + \mathcal{E}_{ijk}, \begin{cases} i \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ rows} \\ j \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ columns} \\ k \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ treatments} \end{cases}$$

32.2.5 model assumption and experimental unit, measurement/observational unit

$$Y_{ijk} = \mu + \tau_i + \beta_j + \epsilon_{ij} + \Delta_{ijk}$$

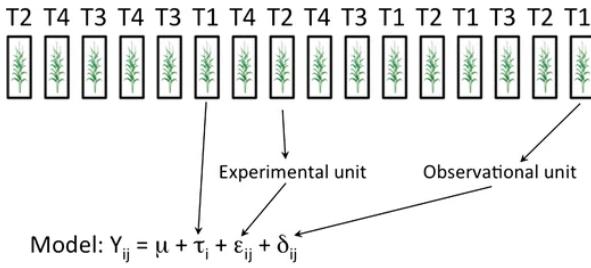
32.3 experiment structure

32.3.1 treatment structure



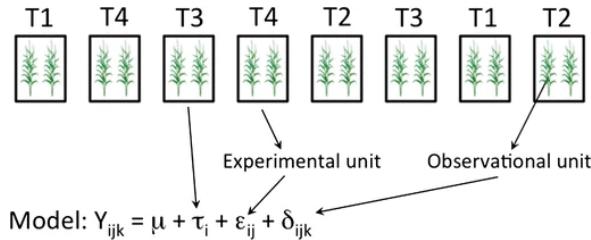
ANOVA Source of variation	df
Treatments + Experimental error	3 (fixed)
Observational error	12

Figure 32.3: model assumption and experimental unit 1 (? fig.1)



ANOVA Source of variation	df
Treatments	3 (fixed)
Error (experimental + observational)	12

Figure 32.4: model assumption and experimental unit 2 (? fig.2)



ANOVA Source of variation	df
Treatments	3 (fixed)
Experimental error	4
Observational error	8

Figure 32.5: model assumption and experimental unit 3 (? fig.3)

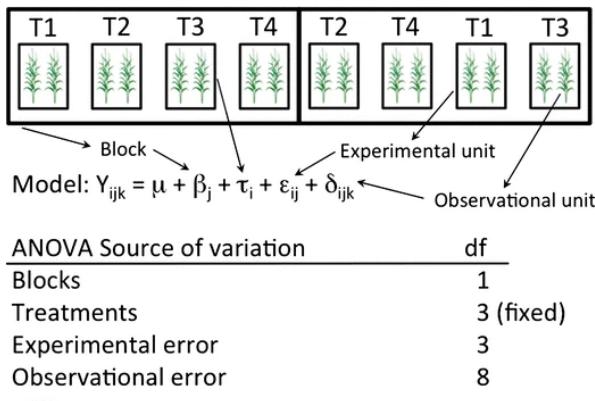


Figure 32.6: model assumption and experimental unit 4 (? fig.4)

- 1-way treatment structure
- 2-way treatment structure
- factorial arrangement treatment structure
- *fractional* factorial arrangement treatment structure
- factorial arrangement with one or more controls

32.3.2 design structure

? p.77

- CRD = completely randomized design
- RCBD = randomized complete block design
 - ? why not called CRBD = completely randomized block design
- LSD = Latin square design[??]
- IBD = incomplete block design
 - BIBD = balanced IBD
- various combinations and generalizations

32.3.3 size of experimental unit

- split-plot design
 - split-split-plot design
 - split-split-split-plot design
- repeated measures design
 - cross-over design
 - change-over design
- nested design = hierarchical design
- variations and combinations
 - SSEU = several sizes of experimental units

32.4 approach to experimentation

? p.75

- approach to experimentation
 - best-guess approach
 - one-factor-at-a-time approach = OFAT
 - factorial approach

32.5 sample size estimation

32.6 statistical analysis plan

32.7 protocol

? p.95

- study objective
- study endpoint
 - primary endpoint
 - secondary endpoint(s)
- experimental unit(s)
- treatment structure^[??]
- design structure^[??]
- potential confounder(s)
- randomization
- blinding
- chance reduction
- sample size estimation^[??]
- data collection
- data management system
- statistical analysis plan^[??]
- DSMB / DSMC = data and safety monitoring board / committee

32.8 DoE course with six sigma and Minitab

<https://zhuanlan.zhihu.com/p/265914617>

<https://www.zhihu.com/question/416312693/answer/1426399810>

32.8.1 evolution

- Fisher
- Rao

Chapter 33

quine

```
s = 's = %r\nprint(s%%s)'  
print(s%s)
```

```
## s = 's = %r\nprint(s%%s)'  
## print(s%s)
```

This snippet is a clever example of a quine. A quine is a computer program that takes no input and produces a copy of its own source code as its output. The given code in Python is written to print its own source when executed. Let's break it down:

`s = 's = %r\nprint(s%%s)'`: This line defines a string `s` that contains a format string. `%r` is a placeholder that gets replaced with the `repr()` of the argument provided to the `%` operator, which in this case will be the string `s` itself. This means it will insert the string representation of `s` into the format string at `%r`.

`print(s%s)`: This line prints the result of `s%s`. Here, the `%` operator is used to format the string `s` with itself. The `%s` inside the print statement is replaced by the string `s`, leading to the entire string being printed out, including the print statement itself.

This is because the format operation replaces `%r` with the representation of the string `s`, and `%%` is a way to escape the `%` sign in format strings, resulting in a single `%` in the output. This output is exactly the same as the source code, making it a quine.

33.1 `%r`

The `%r` in Python string formatting represents the “representation” of a value, which is typically the way you would see it if you were to type it into a Python interpreter. It uses the `repr()` function to convert the value to a string. This is useful for debugging, among other things, because it shows strings with quotes around them and escapes special characters. Essentially, `%r` gives you the “developer’s view” of what a variable looks like.

Here's a simple example to illustrate `%r` versus `%s` in string formatting:

```
my_str = "Hello, World!\nNew line character is represented with \\n"
print("Using %s: %s" % my_str)
```

```
## Using %s: Hello, World!
## New line character is represented with \n
```

```
print("Using %%r: %r" % my_str)
```

```
## Using %r: 'Hello, World!\nNew line character is represented with \\n'
```

In this example:

The `%s` specifier tells Python to convert the object using `str()`, which is designed to be readable and outputs the string `"Hello, World!\nNew line character is represented with \n"`, interpreting the escape character `\n` as a newline.

The `%r` specifier tells Python to convert the object using `repr()`, which aims to generate output that could be used to recreate the object, outputting the string `'Hello, World!\nNew line character is represented with \\n'`, preserving the actual escape characters in the output.

Notice how `%r` preserves the string exactly as it is, including the quotes and escaped characters, making it clear it's a string and showing the escape sequence explicitly.

Chapter 34

quaternion

34.1 TaylorCatAlice

https://en.wikipedia.org/wiki/Blackboard_bold

34.1.1 complex / dionion / bionion

$$\begin{aligned} c &= a + bi = a + ib, \begin{cases} c \in \mathbb{C} \\ i^2 = -1 \\ a, b \in \mathbb{R} \Leftrightarrow \langle a, b \rangle \in \mathbb{R}^2 \end{cases} \\ z &= x + yi = x + iy, \begin{cases} z \in \mathbb{C} \\ i^2 = -1 \\ x, y \in \mathbb{R} \Leftrightarrow \langle x, y \rangle \in \mathbb{R}^2 \end{cases} \\ &= \sqrt{x^2 + y^2} \left(\frac{x}{\sqrt{x^2 + y^2}} + \frac{y}{\sqrt{x^2 + y^2}} i \right) = r (\cos \theta + i \sin \theta) = re^{i\theta} \end{aligned}$$

Also see complex group representation^[??].

34.1.2 trionion / triernion / triplex / ternion

<https://zh.wikipedia.org/zh-tw/%E4%B8%89%E5%85%83%E6%95%B8>

<https://math.stackexchange.com/questions/1784166/why-are-there-no-triernions-3-dimensional-analogue-of-complex-numbers-quate>

<https://math.stackexchange.com/questions/32100/is-there-a-third-dimension-of-numbers/4453131>

$$\begin{aligned}
t &= a + bi + cj = a + ib + jc, \begin{cases} t \in \mathbb{T} \\ i^2 = -1 \\ j^2 = -1 \end{cases} \\
w &= x + yi + zj = x + iy + jz, \begin{cases} w \in \mathbb{T} \\ i^2 = -1 \\ j^2 = -1 \end{cases} \\
&= \sqrt{x^2 + y^2 + z^2} \left(\frac{x}{\sqrt{x^2 + y^2 + z^2}} + \frac{y}{\sqrt{x^2 + y^2 + z^2}}i + \frac{z}{\sqrt{x^2 + y^2 + z^2}}j \right) = ?
\end{aligned}$$

$$\begin{cases} A(BC) = (AB)C & (a) \text{ associativity} \\ A(B+C) = AB+AC & (d) \text{ distributivity} \end{cases}$$

$$\begin{aligned}
\mathbb{T} \ni ij &= X + Yi + Zj \in \mathbb{T} \\
-ij &= (i^2)j \stackrel{(a)}{=} i(ij) = i(X + Yi + Zj) \stackrel{(d)}{=} -Y + Xi + Zij \\
ij &= \frac{Y}{Z} - \frac{X}{Z}i - \frac{1}{Z}j \Rightarrow \begin{cases} X = \frac{Y}{Z} \\ Y = -\frac{X}{Z} \\ Z = -\frac{1}{Z} \end{cases} \Rightarrow Z^2 = -1 \Rightarrow Z \notin \mathbb{R} \\
-ij &= i(j^2) \stackrel{(a)}{=} (ij)j = (X + Yi + Zj)j \stackrel{(d)}{=} -Z + Xj + Yij \\
ij &= \frac{Z}{Y} - \frac{1}{Y}i - \frac{X}{Y}j \Rightarrow \begin{cases} X = \frac{Z}{Y} \\ Y = -\frac{1}{Y} \\ Z = -\frac{X}{Y} \end{cases} \Rightarrow Y^2 = -1 \Rightarrow Y \notin \mathbb{R}
\end{aligned}$$

34.1.3 quaternion

<https://en.wikipedia.org/wiki/Quaternion>

$$\begin{aligned}
q &= a + bi + cj + dk = a + ib + jc + kd, \begin{cases} q \in \mathbb{H} \\ a, b, c, d \in \mathbb{R} \Leftrightarrow \langle a, b, c, d \rangle \in \mathbb{R}^4 \end{cases} \\
w &= t + xi + yj + zk = t + ix + jy + kz, \begin{cases} w \in \mathbb{H} \\ t, x, y, z \in \mathbb{R} \Leftrightarrow \langle t, x, y, z \rangle \in \mathbb{R}^4 \end{cases} \\
&= ?
\end{aligned}$$

The quaternion set is denoted \mathbb{H} for Sir R.W. **Hamilton**, because he suddenly and strikingly realized

$$\begin{cases} ij = k \\ k \in \mathbb{H} \end{cases} \Rightarrow ij \in \mathbb{H} \text{ for closure property}$$

for the sake of rigorosity, see group theory^[??]

$$k^2 = -1$$

$$\begin{aligned} ij &= k \\ ijk &= i(jk) \stackrel{(a)}{=} (ij)k = kk = k^2 = -1 \\ kij &= (ki)j \stackrel{(a)}{=} k(ij) = kk = k^2 = -1 \end{aligned}$$

$$\begin{aligned} ij &= k \\ -j &= (i^2)j \stackrel{(a)}{=} i(ij) = ik \\ -i &= i(j^2) \stackrel{(a)}{=} (ij)j = kj \\ -j &= (i^2)j \stackrel{(a)}{=} i(ij) = ik \\ 1 &= -j^2 = j(-j) = j(ik) \stackrel{(a)}{=} (ji)k \\ k &= [1]k = [(ji)k]k \stackrel{(a)}{=} (ji)(k^2) = (ji)(-1) \\ -k &= ji \\ -i &= i(j^2) \stackrel{(a)}{=} (ij)j = kj \\ 1 &= (-i)i = (kj)i \stackrel{(a)}{=} k(ji) = kji \\ 1 &= kji \end{aligned}$$

There is no more commutativity^[??], i.e.

$$AB \not\equiv BA$$

but

$$AB + BA = 0 \Leftrightarrow AB = -BA$$

satisfying anticommutativity^[??].

$$\begin{aligned} \begin{cases} ij = k \\ ji = -k \end{cases} &\Leftrightarrow ji = -k = -ij \\ &\Rightarrow ji = -ij \\ &\Leftrightarrow ij + ji = 0 \end{aligned}$$

$$\begin{cases} kij = -1 \\ kji = 1 \end{cases} \Leftrightarrow kij = -1 = -kji$$

$$\Rightarrow kij = -kji$$

$$\Leftrightarrow kij + kji = 0$$

$$q = a + bi + cj + dk = a + ib + jc + kd, \begin{cases} q \in \mathbb{H} \\ i^2 = j^2 = k^2 = -1 = ijk \Rightarrow ij = k \\ a, b, c, d \in \mathbb{R} \end{cases} \Leftrightarrow \langle a, b, c, d \rangle \in \mathbb{R}^4$$

$$= w = t + xi + yj + zk = t + ix + jy + kz, \begin{cases} w \in \mathbb{H} \\ i^2 = j^2 = k^2 = -1 = ijk \Rightarrow ij = k \\ t, x, y, z \in \mathbb{R} \end{cases} \Leftrightarrow \langle t, x, y, z \rangle \in \mathbb{R}^4$$

$$= t + (i \ j \ k) \begin{pmatrix} x \\ y \\ z \end{pmatrix} = x_0 + (i \ j \ k) \begin{pmatrix} x \\ y \\ z \end{pmatrix} = x_0 + (e_1 \ e_2 \ e_3) \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = x_0 + x, \begin{cases} e_1 = i = i \\ e_2 = j = j \\ e_3 = k = k \end{cases}$$

.	1	i	j	k
1	1	i	j	k
i	i	-1	k	-j
j	j	-k	-1	i
k	k	j	-i	-1

.	1	i	j	k	-1	-i	-j	-k
1	1	i	j	k				
i	i	-1	k	-j				
j	j	-k	-1	i				
k	k	j	-i	-1				
-1								
-i								
-j								
-k								

Figure 34.1: quaternion basis group table

34.1.3.1 true origin of (dot product & cross product) / (inner product & outer product)

product of two pure imaginary quaternions

.	1	-1	i	-i	j	-j	k	-k
1								
-1								
i								
-i								
j								
-j								
k								
-k								

Figure 34.2: quaternion basis group table 2

$$\begin{aligned}
x_1 x_2 &= (x_{11}i + x_{12}j + x_{13}k)(x_{21}i + x_{22}j + x_{23}k) \\
&= x_{11}x_{21}i^2 + x_{11}x_{22}ij + x_{11}x_{23}ik \\
&\quad + x_{12}x_{21}ji + x_{12}x_{22}j^2 + x_{12}x_{23}jk \\
&\quad + x_{13}x_{21}ki + x_{13}x_{22}kj + x_{13}x_{23}k^2 \\
&= -(x_{11}x_{21} + x_{12}x_{22} + x_{13}x_{23}) \\
&\quad + (x_{12}x_{23} - x_{13}x_{22})jk + (x_{13}x_{21} - x_{11}x_{23})ki + (x_{11}x_{22} - x_{12}x_{21})ij \\
&= -(x_{11}x_{21} + x_{12}x_{22} + x_{13}x_{23}) \\
&\quad + (x_{12}x_{23} - x_{13}x_{22})i + (x_{13}x_{21} - x_{11}x_{23})j + (x_{11}x_{22} - x_{12}x_{21})k \\
&= - (x_1 \cdot x_2) + (x_1 \times x_2), \begin{cases} x_1 \cdot x_2 = x_{11}x_{21} + x_{12}x_{22} + x_{13}x_{23} \\ x_1 \times x_2 = \begin{vmatrix} i & j & k \\ x_{11} & x_{12} & x_{13} \\ x_{21} & x_{22} & x_{23} \end{vmatrix} \end{cases} \\
&= - x_1 \cdot x_2 + x_1 \times x_2
\end{aligned}$$

product of two general quaternions / ordinary quaternions

$$\begin{aligned}
q_1 q_2 &= (q_{10} + q_{11}\mathbf{i} + q_{12}\mathbf{j} + q_{13}\mathbf{k})(q_{20} + q_{21}\mathbf{i} + q_{22}\mathbf{j} + q_{23}\mathbf{k}) \\
&= (x_{10} + x_1)(x_{20} + x_2), \quad \begin{cases} x_{i\mu} = q_{i\mu} & \mu \in \{0\} \cup (\mathbb{N} \cap [1, 3]) \\ x_i = x_{ij}e_j & i, j \in \mathbb{N} \cap [1, 3], \begin{cases} e_1 = \mathbf{i} \\ e_2 = \mathbf{j} \\ e_3 = \mathbf{k} \end{cases} \end{cases} \\
&= x_{10}x_{20} + x_{10}x_2 + x_{20}x_1 + x_1x_2 \\
&= x_{10}x_{20} + x_{10}x_2 + x_{20}x_1 - x_1 \cdot x_2 + x_1 \times x_2 \\
&= (x_{10}x_{20} - x_1 \cdot x_2) + (x_{10}x_2 + x_{20}x_1 + x_1 \times x_2) \\
x_{10}x_{20} - x_1 \cdot x_2 &= (q_{10} \quad q_{11} \quad q_{12} \quad q_{13}) \begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix} \begin{pmatrix} q_{20} \\ q_{21} \\ q_{22} \\ q_{23} \end{pmatrix} = q_1^\mu \eta_{\mu\nu} q_2^\nu \\
&= (q_{10} \quad q_{11} \quad q_{12} \quad q_{13}) \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} q_{20} \\ q_{21} \\ q_{22} \\ q_{23} \end{pmatrix} = q_1^\top H q_2, H = [\eta_{\mu\nu}]_{4 \times 4} = \eta_{\mu\nu}
\end{aligned}$$

$$\begin{aligned}
q_1 q_2 &= (x_{10}x_{20} - x_1 \cdot x_2) + (x_{10}x_2 + x_{20}x_1 + x_1 \times x_2) \\
QP &= (Q_0 P_0 - Q \cdot P) + (Q_0 P + P_0 Q + Q \times P)
\end{aligned}$$

$$ab = (a_0 b_0 - a \cdot b) + (a_0 b + b_0 a + a \times b)$$

Minkowski metric tensor

$$\eta = H = [\eta_{\mu\nu}]_{4 \times 4} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} = \begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix} = \eta_{\mu\nu}$$

and quaternions as 4-vectors or four-vectors

$$q_1^\top = (q_{10} \quad q_{11} \quad q_{12} \quad q_{13})$$

$$q_2 = \begin{pmatrix} q_{20} \\ q_{21} \\ q_{22} \\ q_{23} \end{pmatrix}$$

34.1.3.2 commutativity vs. anticommutativity

34.1.3.2.1 commutativity = =

$$AB = BA \Leftrightarrow AB - BA = 0$$

$$AB = BA \Rightarrow AB \equiv BA$$

34.1.3.2.2 anticommutativity = =

$$AB + BA = 0 \Leftrightarrow AB = -BA$$

$$AB = -BA \Rightarrow AB \neq BA$$

34.1.3.3 bracket**34.1.3.3.1 self-invented bracket** =**34.1.3.3.1.1 commutative bracket** =

$$[X, Y] = \frac{XY - YX}{2}$$

34.1.3.3.1.2 anticommutative bracket =

$$\{X, Y\} = \frac{XY + YX}{2}$$

34.1.3.3.2 Poisson bracket https://en.wikipedia.org/wiki/Poisson_bracket**34.1.3.3.3 Lagrange bracket****34.1.3.3.4 Lie bracket****34.1.3.4 triple product**

product = double product

$$ab = (a_0 b_0 - a \cdot b) + (a_0 b + b_0 a + a \times b)$$

pure imaginary

$$\begin{aligned} ab &= (a_0 b_0 - a \cdot b) + (a_0 b + b_0 a + a \times b) \\ &\stackrel{\begin{cases} a_0 = 0 \\ b_0 = 0 \end{cases}}{=} (00 - a \cdot b) + (0b + 0a + a \times b) \\ &= -a \cdot b + a \times b \end{aligned}$$

pure imaginary product can get both (real & imaginary) / (scalar & vector) parts

$$ab = ab = -a \cdot b + a \times b, \begin{cases} a = 0 + a = a \\ b = 0 + b = b \end{cases}$$

triple product

https://en.wikipedia.org/wiki/Triple_product

pure imaginary

$$\begin{cases} a = 0 + a = a \\ b = 0 + b = b \\ c = 0 + c = c \end{cases}$$

$$\begin{aligned} abc &= abc = (ab)c = (-a \cdot b + a \times b)c \\ &= a(bc) = a(-b \cdot c + b \times c) \end{aligned}$$

$$\begin{aligned} abc &= (ab)c = (-a \cdot b + a \times b)c \\ &= -(a \cdot b)c + (a \times b)c \\ &= -(a \cdot b)c + (-(a \times b) \cdot c + (a \times b) \times c) \\ &= [-(a \times b) \cdot c] + [(a \times b) \times c - (a \cdot b)c] \\ &= a(bc) = a(-b \cdot c + b \times c) \\ &= -a(b \cdot c) + a(b \times c) \\ &= -a(b \cdot c) + (-a \cdot (b \times c) + a \times (b \times c)) \\ &= [-a \cdot (b \times c)] + [a \times (b \times c) - a(b \cdot c)] \end{aligned}$$

by comparing (real & imaginary) / (scalar & vector) parts,

$$\begin{aligned} &\begin{cases} -(a \times b) \cdot c = -a \cdot (b \times c) \\ (a \times b) \times c - (a \cdot b)c = a \times (b \times c) - a(b \cdot c) \end{cases} \\ \Rightarrow &\begin{cases} (a \times b) \cdot c = a \cdot (b \times c) \\ (a \times b) \times c - (a \cdot b)c = a \times (b \times c) - a(b \cdot c) \end{cases} \quad (s) \quad (v) \end{aligned}$$

permutation

$$\sigma = \begin{pmatrix} x_1 & x_2 & \dots \\ \sigma(x_1) & \sigma(x_2) & \dots \end{pmatrix}$$

$$\begin{pmatrix} a & b & c \\ a & b & c \end{pmatrix}, \begin{pmatrix} a & b & c \\ b & c & a \end{pmatrix}, \begin{pmatrix} a & b & c \\ c & a & b \end{pmatrix}, \begin{pmatrix} a & b & c \\ a & c & b \end{pmatrix}, \begin{pmatrix} a & b & c \\ b & a & c \end{pmatrix}, \begin{pmatrix} a & b & c \\ c & b & a \end{pmatrix}$$

$$(s) \Rightarrow \begin{cases} (a \times b) \cdot c = a \cdot (b \times c) & \begin{pmatrix} a & b & c \\ a & b & c \end{pmatrix}, s_1 \\ (b \times c) \cdot a = b \cdot (c \times a) & \begin{pmatrix} a & b & c \\ b & c & a \end{pmatrix}, s_2 \\ (c \times a) \cdot b = c \cdot (a \times b) & \begin{pmatrix} a & b & c \\ c & a & b \end{pmatrix}, s_3 \\ (b \times a) \cdot c = b \cdot (a \times c) & \begin{pmatrix} a & b & c \\ b & a & c \end{pmatrix}, s_4 \\ (a \times c) \cdot b = a \cdot (c \times b) & \begin{pmatrix} a & b & c \\ a & c & b \end{pmatrix}, s_5 \\ (c \times b) \cdot a = c \cdot (b \times a) & \begin{pmatrix} a & b & c \\ c & b & a \end{pmatrix}, s_6 \end{cases}$$

$\stackrel{\cdot \text{ commutative}}{\Rightarrow} (a \times b) \cdot c \stackrel{s_1}{=} (b \times c) \cdot a \stackrel{s_2}{=} (c \times a) \cdot b \stackrel{s_3}{=} (a \times b) \cdot c$
 $\stackrel{\times \text{ anticommutative}}{\equiv} - (b \times a) \cdot c \stackrel{s_6}{=} - (c \times b) \cdot a \stackrel{s_5}{=} - (a \times c) \cdot b \stackrel{s_4}{=} - (b \times a) \cdot c$
 $\Leftrightarrow a \cdot (b \times c) = b \cdot (c \times a) = c \cdot (a \times b)$
 $= -a \cdot (c \times b) = -b \cdot (a \times c) = -c \cdot (b \times a)$

$$\begin{aligned}
 (v) \Rightarrow & \left\{ \begin{array}{ll} (a \times b) \times c - (a \cdot b)c = a \times (b \times c) - a(b \cdot c) & \begin{pmatrix} a & b & c \\ a & b & c \end{pmatrix}, v_1 \\ (b \times c) \times a - (b \cdot c)a = b \times (c \times a) - b(c \cdot a) & \begin{pmatrix} a & b & c \\ b & c & a \end{pmatrix}, v_2 \\ (c \times a) \times b - (c \cdot a)b = c \times (a \times b) - c(a \cdot b) & \begin{pmatrix} a & b & c \\ c & a & b \end{pmatrix}, v_3 \\ (b \times a) \times c - (b \cdot a)c = b \times (a \times c) - b(a \cdot c) & \begin{pmatrix} a & b & c \\ b & a & c \end{pmatrix}, v_4 \\ (a \times c) \times b - (a \cdot c)b = a \times (c \times b) - a(c \cdot b) & \begin{pmatrix} a & b & c \\ a & c & b \end{pmatrix}, v_5 \\ (c \times b) \times a - (c \cdot b)a = c \times (b \times a) - c(b \cdot a) & \begin{pmatrix} a & b & c \\ c & b & a \end{pmatrix}, v_6 \end{array} \right. \\
 \Rightarrow & \left\{ \begin{array}{ll} -Z - C = X - A & v_1 \\ -X - A = Y - B & v_2 \\ -Y - B = Z - C & v_3 \\ Z - C = -Y - B & v_4 \\ Y - B = -X - A & v_5 \\ X - A = -Z - C & v_6 \end{array} \right., \left\{ \begin{array}{ll} \cdot \text{ and scalar-vector product} & \text{commutative} \\ \times & \text{anticommutative} \end{array} \right. , \\
 & \left\{ \begin{array}{ll} X = a \times (b \times c) = -(b \times c) \times a = -a \times (c \times b) = (c \times b) \times a \\ Y = b \times (c \times a) = -(c \times a) \times b = -b \times (a \times c) = (a \times c) \times b \\ Z = c \times (a \times b) = -(a \times b) \times c = -c \times (b \times a) = (b \times a) \times c \\ A = a(b \cdot c) = a(c \cdot b) = (c \cdot b)a = (b \cdot c)a \\ B = b(c \cdot a) = b(a \cdot c) = (a \cdot c)b = (c \cdot a)b \\ C = c(a \cdot b) = c(b \cdot a) = (b \cdot a)c = (a \cdot b)c \end{array} \right. \\
 \Rightarrow & \left\{ \begin{array}{ll} -Z - C = X - A & v_1 = v_6 \\ -X - A = Y - B & v_2 = v_5 \\ -Y - B = Z - C & v_3 = v_4 \end{array} \right. \Leftrightarrow \left\{ \begin{array}{ll} Z + X = A - C & X + Y = B - A \\ X + Y = B - A & Y + Z = C - B \\ Y + Z = C - B & Z + X = A - C \end{array} \right. \Leftrightarrow \left\{ \begin{array}{ll} X + Y = B - A \\ Y + Z = C - B \\ Z + X = A - C \end{array} \right. \\
 \Leftrightarrow & \left\{ \begin{array}{ll} 2(X + Y + Z) = 0 & \Rightarrow X + Y + Z = 0 \\ Y + Z = C - B & \Rightarrow X = B - C \Leftrightarrow a \times (b \times c) = b(c \cdot a) - c(a \cdot b) \text{ "back cab"} \\ Z + X = A - C & \Rightarrow Y = C - A \Leftrightarrow b \times (c \times a) = c(a \cdot b) - a(b \cdot c) \\ X + Y = B - A & \Rightarrow Z = A - B \Leftrightarrow c \times (a \times b) = a(b \cdot c) - b(c \cdot a) \end{array} \right.
 \end{aligned}$$

34.1.3.5 differential operator

https://en.wikipedia.org/wiki/Differential_operator

34.1.3.5.1 4-differential operator 4-differential operator / four-differential operator = d'Alembert operator

$$\begin{aligned}
D &= \frac{\partial}{\partial t} + i \frac{\partial}{\partial x} + j \frac{\partial}{\partial y} + k \frac{\partial}{\partial z} = \partial_t + i \partial_x + j \partial_y + k \partial_z \\
&= \frac{\partial}{\partial t} + i \frac{\partial}{\partial x} + j \frac{\partial}{\partial y} + k \frac{\partial}{\partial z} = \partial_t + i \partial_x + j \partial_y + k \partial_z \\
&= \frac{\partial}{\partial x_0} + e_1 \frac{\partial}{\partial x_1} + e_2 \frac{\partial}{\partial x_2} + e_3 \frac{\partial}{\partial x_3} = \partial_0 + e_i \partial_i = \partial_0 + \nabla
\end{aligned}$$

$$D = \partial_0 + i \partial_1 + j \partial_2 + k \partial_3 = \partial_0 + \nabla = D_0 + \mathbf{D}$$

34.1.3.5.2 nabla nabla = spatial differential operator = 3-differential operator / three-differential operator

$$\nabla = e_i \partial_i = \sum_{i=1}^3 e_i \partial_i = \sum_{i=1}^3 e_i \frac{\partial}{\partial x_i} = \begin{pmatrix} \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \end{pmatrix}^\top = \begin{pmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} \end{pmatrix}$$

34.1.3.5.3 Laplace operator Laplace operator = Laplacian

$$\Delta = \nabla^2 = \nabla \cdot \nabla = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

34.1.3.5.4 d'Alembert operator

$$\square = \square_c = \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial z^2} = \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \Delta = \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \nabla^2$$

$$\square_1 = \square_{c=1} = \frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial z^2} = \frac{\partial^2}{\partial t^2} - \Delta = \frac{\partial^2}{\partial t^2} - \nabla^2$$

34.1.3.6 electromagnetism

Maxwell

34.1.3.6.1 4-potential electromagnetic 4-potential / four-potential

$$A = A_0 + i A_1 + j A_2 + k A_3 = A_0 + A$$

4-differential operator^[??]

$$D = \partial_0 + i \partial_1 + j \partial_2 + k \partial_3 = \partial_0 + \nabla = D_0 + \mathbf{D}$$

$$QP = (Q_0 P_0 - Q \cdot P) + (Q_0 P + P_0 Q + Q \times P)$$

commutative bracket^[??]

$$\begin{aligned}
 [\mathbf{D}, A] &= \frac{\mathbf{D}A - A\mathbf{D}}{2} \\
 2[\mathbf{D}, A] &= \mathbf{D}A - A\mathbf{D} \\
 &= (\partial_0 + i\partial_1 + j\partial_2 + k\partial_3)(A_0 + iA_1 + jA_2 + kA_3) \\
 &\quad - (A_0 + iA_1 + jA_2 + kA_3)(\partial_0 + i\partial_1 + j\partial_2 + k\partial_3) \\
 \mathbf{D}A &= (\mathbf{D}_0 A_0 - \mathbf{D} \cdot A) + (\mathbf{D}_0 A + A_0 \mathbf{D} + \mathbf{D} \times A) \\
 &= (\mathbf{D}_0 A_0 - \mathbf{D} \cdot A) + (\mathbf{D}_0 A + \mathbf{D} A_0 + \mathbf{D} \times A) \\
 &= \mathbf{D}_0 (A_0 + A) - \mathbf{D} \cdot A + \mathbf{D} A_0 + \mathbf{D} \times A \\
 &= \mathbf{D}_0 A - \mathbf{D} \cdot A + \mathbf{D} A_0 + \mathbf{D} \times A \\
 &= \partial_0 A - \nabla \cdot A + \nabla A_0 + \nabla \times A \\
 \mathbf{AD} &= (A_0 \mathbf{D}_0 - A \cdot \mathbf{D}) + (A_0 \mathbf{D} + \mathbf{D}_0 A + A \times \mathbf{D}) \\
 &= (\mathbf{D}_0 A_0 - \mathbf{D} \cdot A) + (\mathbf{D} A_0 + \mathbf{D}_0 A - \mathbf{D} \times A) \\
 &= (\mathbf{D}_0 A_0 - \mathbf{D} \cdot A) + (\mathbf{D}_0 A + \mathbf{D} A_0 - \mathbf{D} \times A) \\
 &= \mathbf{D}_0 (A_0 + A) - \mathbf{D} \cdot A + \mathbf{D} A_0 - \mathbf{D} \times A \\
 &= \mathbf{D}_0 A - \mathbf{D} \cdot A + \mathbf{D} A_0 - \mathbf{D} \times A \\
 &= \partial_0 A - \nabla \cdot A + \nabla A_0 - \nabla \times A
 \end{aligned}$$

$$\begin{aligned}
 \mathbf{DA} &= \mathbf{D}_0 A - \mathbf{D} \cdot A + \mathbf{D} A_0 + \mathbf{D} \times A = \partial_0 A - \nabla \cdot A + \nabla A_0 + \nabla \times A \\
 \mathbf{AD} &= \mathbf{D}_0 A - \mathbf{D} \cdot A + \mathbf{D} A_0 - \mathbf{D} \times A = \partial_0 A - \nabla \cdot A + \nabla A_0 - \nabla \times A
 \end{aligned}$$

$$\begin{aligned}
 \mathbf{DA} - \mathbf{AD} &= 2\mathbf{D} \times A = 2\nabla \times A \\
 [\mathbf{D}, A] &= \frac{\mathbf{DA} - \mathbf{AD}}{2} = \mathbf{D} \times A = \nabla \times A
 \end{aligned}$$

anticommutative bracket^[??]

$$\begin{aligned}
 \mathbf{DA} + \mathbf{AD} &= 2(\mathbf{D}_0 A - \mathbf{D} \cdot A + \mathbf{D} A_0) = 2(\partial_0 A - \nabla \cdot A + \nabla A_0) \\
 \{\mathbf{D}, A\} &= \frac{\mathbf{DA} + \mathbf{AD}}{2} = \mathbf{D}_0 A - \mathbf{D} \cdot A + \mathbf{D} A_0 = \partial_0 A - \nabla \cdot A + \nabla A_0
 \end{aligned}$$

commutation and anticommutation on differential operator and any quaternion

$$\begin{aligned}
 [\mathbf{D}, Q] &= \nabla \times Q \\
 \{\mathbf{D}, Q\} &= \partial_0 Q - \nabla \cdot Q + \nabla Q_0
 \end{aligned}$$

or more evident

$$\begin{aligned}
 [\mathbf{D}, Q] &= \nabla \times Q \\
 \{\mathbf{D}, Q\} &= \partial_0 Q - \nabla \cdot Q + \nabla Q_0 \\
 &= \partial_0 (Q_0 + Q) - \nabla \cdot Q + \nabla Q_0 \\
 &= (\partial_0 Q_0 - \nabla \cdot Q) + (\partial_0 Q + \nabla Q_0) \\
 &= \left(\frac{\partial Q_0}{\partial t} - \nabla \cdot Q \right) + \left(\frac{\partial Q}{\partial t} + \nabla Q_0 \right)
 \end{aligned}$$

34.1.3.6.2 Maxwell compromise for both quaternion and 3-vector electric potential and vector potential

$$A = A_0 + +iA_1 + jA_2 + kA_3 = A_0 + A = U + A$$

electric quaternion and electric field

$$\begin{aligned} E &= -\{\mathbf{D}, \mathbf{A}\} \\ &= -(\partial_0 A - \nabla \cdot A + \nabla A_0) \\ &= -\partial_0 A + \nabla \cdot A - \nabla A_0 \\ &= -\partial_t (U + A) + \nabla \cdot A - \nabla U \\ &= -\frac{\partial U}{\partial t} + \nabla \cdot A - \nabla U - \frac{\partial A}{\partial t} \\ &= E_0 + E, \begin{cases} E_0 = -\frac{\partial U}{\partial t} + \nabla \cdot A \\ E = -\nabla U - \frac{\partial A}{\partial t} \end{cases} \quad \text{electric field 3-vector} \end{aligned}$$

magnetic field

$$B = [\mathbf{D}, \mathbf{A}] = \nabla \times \mathbf{A} = \begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ A_1 & A_2 & A_3 \end{vmatrix} = B$$

Work on time? Yes.

$$qE = qE_0 + qE = qE_0 + F_E$$

force equivalent on time

$$qE_0$$

$$\begin{cases} E = -\{\mathbf{D}, \mathbf{A}\} = E_0 + E \\ B = +[\mathbf{D}, \mathbf{A}] = B_0 + B = 0 + B = B \quad B_0 = 0 \end{cases}$$

for any quaternion commutating and anticommutating with differential operator

$$\begin{aligned} [\mathbf{D}, Q] &= \nabla \times Q \\ \{\mathbf{D}, Q\} &= \partial_0 Q - \nabla \cdot Q + \nabla Q_0 \\ &= \partial_0 (Q_0 + Q) - \nabla \cdot Q + \nabla Q_0 \\ &= (\partial_0 Q_0 - \nabla \cdot Q) + (\partial_0 Q + \nabla Q_0) \\ &= \left(\frac{\partial Q_0}{\partial t} - \nabla \cdot Q \right) + \left(\frac{\partial Q}{\partial t} + \nabla Q_0 \right) \end{aligned}$$

$$\left\{ \begin{array}{l} [\mathbf{D}, \mathbf{E}] = \nabla \times \mathbf{E} = (0) + (\nabla \times \mathbf{E}) \\ \{\mathbf{D}, \mathbf{E}\} = (\partial_0 E_0 - \nabla \cdot \mathbf{E}) + (\partial_0 \mathbf{E} + \nabla E_0) = \left(\frac{\partial E_0}{\partial t} - \nabla \cdot \mathbf{E} \right) + \left(\frac{\partial \mathbf{E}}{\partial t} + \nabla E_0 \right) \\ [\mathbf{D}, \mathbf{B}] = \nabla \times \mathbf{B} = (0) + (\nabla \times \mathbf{B}) \\ \{\mathbf{D}, \mathbf{B}\} = (\partial_0 B_0 - \nabla \cdot \mathbf{B}) + (\partial_0 \mathbf{B} + \nabla B_0) \stackrel{B_0=0}{=} -\nabla \cdot \mathbf{B} + \partial_0 \mathbf{B} = (-\nabla \cdot \mathbf{B}) + \left(\frac{\partial \mathbf{B}}{\partial t} \right) \end{array} \right.$$

by comparing (real & imaginary) / (scalar & vector) parts,

Maxwell equations without source terms

$$\begin{aligned} & \left\{ \begin{array}{l} [\mathbf{D}, \mathbf{B}] = +\{\mathbf{D}, \mathbf{E}\} \Leftrightarrow (0) + (\nabla \times \mathbf{B}) = \left(\frac{\partial E_0}{\partial t} - \nabla \cdot \mathbf{E} \right) + \left(\frac{\partial \mathbf{E}}{\partial t} + \nabla E_0 \right) \\ [\mathbf{D}, \mathbf{E}] = -\{\mathbf{D}, \mathbf{B}\} \Leftrightarrow (0) + (\nabla \times \mathbf{E}) = (-\nabla \cdot \mathbf{B}) + \left(\frac{\partial \mathbf{B}}{\partial t} \right) \end{array} \right. \\ & \Leftrightarrow \left\{ \begin{array}{l} \frac{\partial E_0}{\partial t} - \nabla \cdot \mathbf{E} = 0 \quad \Leftrightarrow \nabla \cdot \mathbf{E} = \frac{\partial E_0}{\partial t} \\ \frac{\partial \mathbf{E}}{\partial t} + \nabla E_0 = \nabla \times \mathbf{B} \quad \Leftrightarrow \nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \nabla E_0 \\ -\nabla \cdot \mathbf{B} = 0 \quad \Leftrightarrow \nabla \cdot \mathbf{B} = 0 \\ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E} \quad \Leftrightarrow \nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t} \end{array} \right. \end{aligned}$$

34.1.3.7 Joule heat vs. Thomson heat (Kelvin heat?)

The Lord Kelvin = William Thomson

34.1.3.7.1 thermoelectric effect thermoelectric effect = Seebeck effect = Peltier effect = Thomson effect

34.1.3.8 source term

$$J = J_0 + iJ_1 + jJ_2 + kJ_3 = J_0 + J = \rho + J$$

Maxwell equations with source terms

$$\begin{aligned} & \left\{ \begin{array}{l} [\mathbf{D}, \mathbf{B}] = J + \{\mathbf{D}, \mathbf{E}\} \Leftrightarrow (0) + (\nabla \times \mathbf{B}) = \left(\rho + \frac{\partial E_0}{\partial t} - \nabla \cdot \mathbf{E} \right) + \left(J + \frac{\partial \mathbf{E}}{\partial t} + \nabla E_0 \right) \\ [\mathbf{D}, \mathbf{E}] = 0 - \{\mathbf{D}, \mathbf{B}\} \Leftrightarrow (0) + (\nabla \times \mathbf{E}) = (-\nabla \cdot \mathbf{B}) + \left(\frac{\partial \mathbf{B}}{\partial t} \right) \end{array} \right. \\ & \Leftrightarrow \left\{ \begin{array}{l} \rho + \frac{\partial E_0}{\partial t} - \nabla \cdot \mathbf{E} = 0 \quad \Leftrightarrow \nabla \cdot \mathbf{E} = \rho + \frac{\partial E_0}{\partial t} \\ J + \frac{\partial \mathbf{E}}{\partial t} + \nabla E_0 = \nabla \times \mathbf{B} \quad \Leftrightarrow \nabla \times \mathbf{B} = J + \frac{\partial \mathbf{E}}{\partial t} + \nabla E_0 \\ -\nabla \cdot \mathbf{B} = 0 \quad \Leftrightarrow \nabla \cdot \mathbf{B} = 0 \\ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E} \quad \Leftrightarrow \nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t} \end{array} \right. \end{aligned}$$

34.1.4 quaternion group

https://en.wikipedia.org/wiki/Quaternion_group

group theory^[??]

or please first see quaternion group representation^[??].

34.1.5 octonion

34.2 3Blue1Brown

34.2.1 Ben Eater

<https://eater.net/quaternions/video/intro>

<https://eater.net/quaternions>

34.2.2 3B1B

34.2.3 Sutrabla

<https://www.newscientist.com/article/mg20427391-600-alices-adventures-in-algebra-wonderland-solved/>

<https://threejs.org/>

34.3 CCJou: LA Revelation

<https://ccjou.wordpress.com/2014/04/21/>

Chapter 35

DICOM

35.1 Innolitics: DICOM Standard Browser

<https://dicom.innolitics.com/ciods>

<https://dicom.innolitics.com/ciods/parametric-map/parametric-map-multi-frame-functional-groups/52009229/0048021a/0040072a>

35.2 David Clunie: Medical Image Format Site

<https://www.dclunie.com/>

Chapter 36

tendon pathophysiology

Mark E. Schweitzer, MD

36.1 histology

Chapter 37

group theory

[https://en.wikipedia.org/wiki/Group_\(mathematics\)](https://en.wikipedia.org/wiki/Group_(mathematics))

37.1 matrix group

subset of two-by-two matrices at least excluding zero matrix

$$\mathcal{M} = (\mathcal{M}, \cdot) \subset (\mathcal{M}_{2 \times 2}(\mathbb{C}) - \{0\}, \cdot) = \mathcal{M}_{2 \times 2}(\mathbb{C}) - \left\{ \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \right\}$$

matrix multiplication

$$\begin{aligned} & \forall \langle M_1, M_2 \rangle \in \mathcal{M}^2, \exists M_1 M_2 \in \mathcal{M} [M_1 M_2 = M_1 \cdot M_2] \\ \Leftrightarrow & \cdot : \mathcal{M} \times \mathcal{M} = \mathcal{M}^2 \rightarrow \mathcal{M} \\ \Leftrightarrow & \cdot : \mathcal{M} \times \mathcal{M} \rightarrow \mathcal{M} \\ \Leftrightarrow & \mathcal{M} \times \mathcal{M} \xrightarrow{\cdot} \mathcal{M} \\ \Leftrightarrow & \mathcal{M}^2 \xrightarrow{\cdot} \mathcal{M} \end{aligned}$$

matrix group

$$\begin{cases} \forall \langle M_1, M_2, M_3 \rangle \in \mathcal{M}^3 [M_1 (M_2 M_3) = (M_1 M_2) M_3] & \text{associativity} \\ \exists I = I_2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \in \mathcal{M}, \forall M \in \mathcal{M} [IM = M] & \text{left unit element} \\ \forall M \in \mathcal{M}, \exists M^{-1} \in \mathcal{M} [M^{-1} M = I] & \text{left inverse (element)} \end{cases}$$

$\Rightarrow \mathcal{M} = (\mathcal{M}, \cdot)$ is a matrix group

37.2 group definition and basic theorem

[https://en.wikipedia.org/wiki/Group_\(mathematics\)#Elementary_consequences_of_the_group_axioms](https://en.wikipedia.org/wiki/Group_(mathematics)#Elementary_consequences_of_the_group_axioms)

Definition 37.1 (group). group definition by a set and a binary operation on the set

$$\left\{ \begin{array}{l} \circ : G \times G = G^2 \rightarrow G \\ \forall \langle g_1, g_2, g_3 \rangle \in G^3 [g_1 \circ (g_2 \circ g_3) = (g_1 \circ g_2) \circ g_3] \\ \exists e \in G, \forall g \in G [e \circ g = g] \\ \forall g \in G, \exists g^{-1} \in G [g^{-1} \circ g = e] \end{array} \right. \begin{array}{l} \text{binary operation} \\ \text{associativity} \\ \text{left unit element} \\ \text{left inverse (element)} \end{array}$$

$\Leftrightarrow G = (G, \circ)$ is a group

Theorem 37.1. group left inverses equal right inverses

Proof:

□

37.3 complex group representation

37.3.1 complex basis group

$$\begin{aligned} G &= \{1, i, -1, -i\} \\ &= \{i^0, i^1, i^2, i^3\} \end{aligned}$$

$$\begin{aligned} \forall \langle g_1, g_2 \rangle \in G^2, \exists g_1 g_2 \in G [g_1 g_2 = g_1 \cdot g_2] \\ \Leftrightarrow : G \times G = G^2 \rightarrow G \end{aligned}$$

<https://tex.stackexchange.com/questions/627708/tikz-how-to-put-tables-within-arbitrarily-placed-nodes>

.	1	i	-1	-i
1	1	i	-1	-i
i	i	-1	-i	1
-1	-1	-i	1	i
-i	-i	1	i	-1

.	1	i	-1	-i
1	1	i	-1	-i
i	i	-1	-i	1
-1	-1	-i	1	i
-i	-i	1	i	-1

Figure 37.1: complex basis group table

37.3.2 $\mathbb{C} \rightarrow \mathcal{M}_{2 \times 2}(\mathbb{R})$

$$1 \leftrightarrow \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = I_2 = I$$

$$\begin{aligned} c_1 \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + c_2 \begin{pmatrix} a & b \\ c & d \end{pmatrix} &= x \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + y \begin{pmatrix} a & b \\ c & d \end{pmatrix}, \langle a, b, c, d \rangle \in \mathbb{R}^4 \\ &= xI + yJ, J = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathcal{M}_{2 \times 2}(\mathbb{R}), \langle x, y \rangle \in \mathbb{R}^2 \end{aligned}$$

$$J^2 = -I$$

$$J^2 = -I$$

$$\begin{pmatrix} a^2 + bc & ab + bd \\ ca + cd & cb + d^2 \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} a & b \\ c & d \end{pmatrix} = - \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\begin{cases} a^2 + bc = -1 & b = 0 \Rightarrow a^2 = -1 \Rightarrow a \in \mathbb{R} \Rightarrow b \neq 0 \\ ab + bd = 0 & (b = 0) \vee (a = -d) \stackrel{b \neq 0}{\Rightarrow} a = -d \\ ca + cd = 0 & \\ cb + d^2 = -1 & a^2 = d^2 \Rightarrow (a = d) \vee (a = -d) \end{cases} \Rightarrow \begin{cases} a = d \\ a = -d \end{cases} \Rightarrow a = d = 0 \Rightarrow bc = -1$$

$$J = \begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} a & b \\ \frac{-a^2 - 1}{b} & -a \end{pmatrix} = J(a, b), b \neq 0$$

$$J(a, b) = \begin{pmatrix} a & b \\ \frac{-a^2 - 1}{b} & -a \end{pmatrix}, b \neq 0$$

$$J(a = 1, b) = \begin{pmatrix} 1 & b \\ -2 & -1 \end{pmatrix} \Rightarrow J^2(a = 1, b) = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} = -I$$

$$xI + yJ(a = 1, b) = \begin{pmatrix} x + y & yb \\ y \cdot \frac{-2}{b} & x - y \end{pmatrix}$$

$$J(a = 0, b) = \begin{pmatrix} 0 & b \\ -1 & 0 \end{pmatrix}$$

$$J(a=0, b=1) = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$\begin{aligned} J(a=0, b=-1) &= \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} = - \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} = -J(a=0, b=1) \\ \Rightarrow J^2(a=0, b=-1) &= \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} = -I \end{aligned}$$

$$\begin{aligned} J = J(a=0, b=-1) &= \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \\ \Rightarrow \begin{cases} 1 \leftrightarrow I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\ i \leftrightarrow J = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \end{cases} \\ \Rightarrow x + yi \leftrightarrow xI + yJ \\ = x \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + y \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} &= \begin{pmatrix} x & -y \\ y & x \end{pmatrix} \end{aligned}$$

$$x + yi \leftrightarrow \begin{pmatrix} x & -y \\ y & x \end{pmatrix} = xI + yJ$$

realizing

$$\mathbb{C} \rightarrow \mathcal{M}_{2 \times 2}(\mathbb{R}) = \mathcal{M}_2(\mathbb{R})$$

37.3.3 (determinant of complex group representation) equivalent to (squared modulus of complex number)

$$\det(xI + yJ) = \det \begin{pmatrix} x & -y \\ y & x \end{pmatrix} = \begin{vmatrix} x & -y \\ y & x \end{vmatrix} = x^2 + y^2 = |x + yi|^2$$

37.3.3.1 Lagrange identity

https://en.wikipedia.org/wiki/Lagrange's_identity

generalization of Brahmagupta–Fibonacci identity

specialization of Binet–Cauchy identity

cf. Euler identity^[??]

$$\begin{aligned}
& \det [(aI + bJ)(cI + dJ)] \\
&= \det \left[\begin{pmatrix} a & -b \\ b & a \end{pmatrix} \begin{pmatrix} c & -d \\ d & c \end{pmatrix} \right] \\
&= \det \begin{pmatrix} ac - bd & -ad - bc \\ ad + bc & ac - bd \end{pmatrix} = |(ac - bd) + (ad + bc)i|^2 = (ac - bd)^2 + (ad + bc)^2 \\
&= \left[\det \begin{pmatrix} a & -b \\ b & a \end{pmatrix} \right] \left[\det \begin{pmatrix} c & -d \\ d & c \end{pmatrix} \right] = |a + bi|^2 |c + di|^2 = (a^2 + b^2)(c^2 + d^2) \\
&|a + bi|^2 |c + di|^2 = (a^2 + b^2)(c^2 + d^2) = (ac - bd)^2 + (ad + bc)^2
\end{aligned}$$

$$\begin{aligned}
& \det [(x_1 I + y_1 J)(x_2 I + y_2 J)] \\
&= \det \left[\begin{pmatrix} x_1 & -y_1 \\ y_1 & x_1 \end{pmatrix} \begin{pmatrix} x_2 & -y_2 \\ y_2 & x_2 \end{pmatrix} \right] \\
&= \det \begin{pmatrix} x_1 x_2 - y_1 y_2 & -x_1 y_2 - y_1 x_2 \\ x_1 y_2 + y_1 x_2 & x_1 x_2 - y_1 y_2 \end{pmatrix} = |(x_1 x_2 - y_1 y_2) + (x_1 y_2 + y_1 x_2)i|^2 = (x_1 x_2 - y_1 y_2)^2 + (x_1 y_2 + y_1 x_2)^2 \\
&= \left[\det \begin{pmatrix} x_1 & -y_1 \\ y_1 & x_1 \end{pmatrix} \right] \left[\det \begin{pmatrix} x_2 & -y_2 \\ y_2 & x_2 \end{pmatrix} \right] = |x_1 + y_1 i|^2 |x_2 + y_2 i|^2 = (x_1^2 + y_1^2)(x_2^2 + y_2^2) \\
&|x_1 + y_1 i|^2 |x_2 + y_2 i|^2 = (x_1^2 + y_1^2)(x_2^2 + y_2^2) = (x_1 x_2 - y_1 y_2)^2 + (x_1 y_2 + y_1 x_2)^2
\end{aligned}$$

37.3.4 Euler formula proved by complex group representation

$$\begin{aligned}
\begin{pmatrix} x' \\ y' \end{pmatrix} &= \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = R_\theta \begin{pmatrix} x \\ y \end{pmatrix} \\
&= \begin{pmatrix} \cos n \frac{\theta}{n} & -\sin n \frac{\theta}{n} \\ \sin n \frac{\theta}{n} & \cos n \frac{\theta}{n} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \cos \frac{\theta}{n} & -\sin \frac{\theta}{n} \\ \sin \frac{\theta}{n} & \cos \frac{\theta}{n} \end{pmatrix}^n \begin{pmatrix} x \\ y \end{pmatrix} = R_{\frac{\theta}{n}}^n \begin{pmatrix} x \\ y \end{pmatrix}
\end{aligned}$$

$$\begin{aligned}
\lim_{n \rightarrow \infty} R_{\frac{\theta}{n}} &= \lim_{n \rightarrow \infty} \begin{pmatrix} \cos \frac{\theta}{n} & -\sin \frac{\theta}{n} \\ \sin \frac{\theta}{n} & \cos \frac{\theta}{n} \end{pmatrix} = \begin{pmatrix} 1 & -\frac{\theta}{n} \\ \frac{\theta}{n} & 1 \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{\theta}{n} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{\theta}{n} \begin{pmatrix} \cos \frac{\pi}{2} & -\sin \frac{\pi}{2} \\ \sin \frac{\pi}{2} & \cos \frac{\pi}{2} \end{pmatrix} \\
&= I + \frac{\theta}{n} R_{\frac{\pi}{2}}
\end{aligned}$$

$$\begin{aligned}
\begin{pmatrix} x' \\ y' \end{pmatrix} &= \lim_{n \rightarrow \infty} \begin{pmatrix} x' \\ y' \end{pmatrix} = \lim_{n \rightarrow \infty} R_{\frac{\theta}{n}}^n \begin{pmatrix} x \\ y \end{pmatrix} = \left[\lim_{n \rightarrow \infty} R_{\frac{\theta}{n}}^n \right] \left[\lim_{n \rightarrow \infty} \begin{pmatrix} x \\ y \end{pmatrix} \right] = \left[\lim_{n \rightarrow \infty} R_{\frac{\theta}{n}}^n \right] \begin{pmatrix} x \\ y \end{pmatrix} \\
&= \lim_{n \rightarrow \infty} \left[\lim_{n \rightarrow \infty} R_{\frac{\theta}{n}} \right]^n \begin{pmatrix} x \\ y \end{pmatrix} = \lim_{n \rightarrow \infty} \left[I + \frac{\theta}{n} R_{\frac{\pi}{2}} \right]^n \begin{pmatrix} x \\ y \end{pmatrix} \\
&= \lim_{n \rightarrow \infty} \left[I + \frac{\theta}{n} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \right]^n \begin{pmatrix} x \\ y \end{pmatrix} = \lim_{n \rightarrow \infty} \left[I + \frac{\theta J}{n} \right]^n \begin{pmatrix} x \\ y \end{pmatrix}, J = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \\
&= e^{J\theta} \begin{pmatrix} x \\ y \end{pmatrix}
\end{aligned}$$

$$\begin{aligned} \begin{cases} \begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \\ \begin{pmatrix} x' \\ y' \end{pmatrix} = e^{J\theta} \begin{pmatrix} x \\ y \end{pmatrix} \end{cases} \\ \Rightarrow e^{J\theta} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \stackrel{x+y \leftrightarrow \begin{pmatrix} x & -y \\ y & x \end{pmatrix} = xI + yJ}{\Rightarrow} e^{i\theta} = \cos \theta + i \sin \theta \end{aligned}$$

□

37.4 quaternion group representation

https://groupprops.subwiki.org/wiki/Linear_representation_theory_of_quaternion_group#Two-dimensional_irreducible_representation_over_a_splitting_field

$$\begin{aligned} q = a + bi + cj + dk &= a + ib + jc + kd, \quad \begin{cases} q \in \mathbb{H} \\ a, b, c, d \in \mathbb{R} \end{cases} \Leftrightarrow \langle a, b, c, d \rangle \in \mathbb{R}^4 \\ w = t + xi + yj + zk &= t + ix + jy + kz, \quad \begin{cases} w \in \mathbb{H} \\ t, x, y, z \in \mathbb{R} \end{cases} \Leftrightarrow \langle t, x, y, z \rangle \in \mathbb{R}^4 \\ a1 + bi + cj + dk &= t1 + xi + yj + zk = x_0 1 + e_i x_i \end{aligned}$$

37.4.1 $\mathbb{H} \rightarrow \mathcal{M}_{2 \times 2}(\mathbb{C})$

$$1 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = 1_2 = 1$$

$$\begin{aligned} e = \begin{pmatrix} a & b \\ c & d \end{pmatrix} &= \begin{pmatrix} a & b \\ \frac{-a^2 - 1}{b} & -a \end{pmatrix} \\ &= \begin{cases} \begin{pmatrix} a & b \\ \frac{-a^2 - 1}{b} & -a \end{pmatrix} = \begin{pmatrix} 0 & b \\ \frac{-1}{b} & 0 \end{pmatrix} = \begin{pmatrix} 0 & \beta \\ -\beta & 0 \end{pmatrix} \Rightarrow e_2 = J = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} = j & a = 0 \\ \begin{pmatrix} a & b \\ \frac{-a^2 - 1}{b} & -a \end{pmatrix} = \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix} & a \neq 0 \end{cases} \end{aligned}$$

$$\begin{pmatrix} \alpha^2 + \beta^2 & 0 \\ 0 & \beta^2 + \alpha^2 \end{pmatrix} = \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix} \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix} = e^2 = -1 = - \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$$

\Downarrow

$$\alpha^2 + \beta^2 = -1 \Leftrightarrow \beta^2 + \alpha^2 = -1$$

$$\alpha^2 + \beta^2 = -1 \Rightarrow \langle \alpha, \beta \rangle \notin \mathbb{R}^2 \Rightarrow \langle \alpha, \beta \rangle \in \mathbb{R}^2 \Rightarrow \alpha^2 + \beta^2 \geq 0$$

quaternion group has no irreducible two-dimensional representation over the reals ¹

$$\langle \alpha, \beta \rangle \in \mathbb{C}^2 - \mathbb{R}^2$$

$$\alpha^2 + \beta^2 = -1 = \beta^2 + \alpha^2$$

$$\begin{pmatrix} \beta & \alpha \\ \alpha & -\beta \end{pmatrix} \begin{pmatrix} \beta & \alpha \\ \alpha & -\beta \end{pmatrix} = \begin{pmatrix} \beta^2 + \alpha^2 & 0 \\ 0 & \alpha^2 + \beta^2 \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} = - \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = -1$$

$$1 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, e_1 = \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix}, e_2 = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

$$1 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, i = \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix}, j = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

$$ij = \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} = \begin{pmatrix} \beta & -\alpha \\ -\alpha & -\beta \end{pmatrix} = k$$

$$1 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, e_1 = \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix}, e_2 = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, e_3 = \begin{pmatrix} \beta & -\alpha \\ -\alpha & -\beta \end{pmatrix}$$

$$1 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, i = \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix}, j = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, k = \begin{pmatrix} \beta & -\alpha \\ -\alpha & -\beta \end{pmatrix}$$

$$jk = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \beta & -\alpha \\ -\alpha & -\beta \end{pmatrix} = \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix} = i$$

¹ https://groupprops.subwiki.org/wiki/Linear_representation_theory_of_quaternion_group#Four-dimensional_irreducible_representation_over_a_non-splitting_field

$\alpha^2 + \beta^2 = -1$	$\begin{cases} \alpha = \sqrt{-1} \\ \beta = 0 \end{cases}$	$\begin{cases} \alpha = \sqrt{-2} \\ \beta = 1 \end{cases}$	$\beta = \alpha^2, n \in \{1, 2, 4, 5\}$
1	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$
-1	$\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$	$\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$	$\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$
i	$\begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix}$	$\begin{pmatrix} \sqrt{-1} & 0 \\ 0 & -\sqrt{-1} \end{pmatrix}$	$\begin{pmatrix} \sqrt{-2} & 1 \\ 1 & -\sqrt{-2} \end{pmatrix}$
-i	$\begin{pmatrix} -\alpha & -\beta \\ -\beta & \alpha \end{pmatrix}$	$\begin{pmatrix} -\sqrt{-1} & 0 \\ 0 & \sqrt{-1} \end{pmatrix}$	$\begin{pmatrix} -\sqrt{-2} & -1 \\ -1 & \sqrt{-2} \end{pmatrix}$
j	$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$
-j	$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$
k	$\begin{pmatrix} \beta & -\alpha \\ -\alpha & -\beta \end{pmatrix}$	$\begin{pmatrix} 0 & -\sqrt{-1} \\ -\sqrt{-1} & 0 \end{pmatrix}$	$\begin{pmatrix} 1 & -\sqrt{-2} \\ -\sqrt{-2} & -1 \end{pmatrix}$
-k	$\begin{pmatrix} -\beta & \alpha \\ \alpha & \beta \end{pmatrix}$	$\begin{pmatrix} 0 & \sqrt{-1} \\ \sqrt{-1} & 0 \end{pmatrix}$	$\begin{pmatrix} -1 & \sqrt{-2} \\ \sqrt{-2} & 1 \end{pmatrix}$

$$-1 = \alpha^2 + \beta^2$$

$$\beta = \alpha^2 = \alpha^2 + \alpha^4$$

$$\alpha^4 + \alpha^2 + 1 = 0, \alpha^4 + \alpha^2 + 1 = (\alpha^2 + \alpha + 1)(\alpha^2 - \alpha + 1)$$

$$(\alpha^2 - 1)(\alpha^4 + \alpha^2 + 1) = 0$$

$$\alpha^6 - 1 = 0$$

$$\alpha^6 = 1 = e^{2\pi k \sqrt{-1}}, k \in \mathbb{Z}$$

$$\alpha = e^{2\pi \frac{n}{6} \sqrt{-1}}, n \in \{0, 1, 2, 3, 4, 5\} - \{0, 3\}$$

$$= e^{\pi \frac{n}{3} \sqrt{-1}}, n \in \{1, 2, 4, 5\}$$

$$\begin{array}{ll}
 \alpha^2 + \beta^2 = -1 & \left\{ \begin{array}{l} \alpha = i \\ \beta = 0 \end{array} \right. \quad \left\{ \begin{array}{l} \alpha = \sqrt{2}i \\ \beta = 1 \end{array} \right. \\
 & \omega = e^{i\pi\frac{n}{3}}, n \in \{1, 2, 4, 5\}
 \end{array}$$

1	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$
-1	$\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$	$\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$	$\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$	$\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$
i	$\begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix}$	$\begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix}$	$\begin{pmatrix} \sqrt{2}i & 1 \\ 1 & -\sqrt{2}i \end{pmatrix}$	$\begin{pmatrix} \omega & \omega^2 \\ \omega^2 & -\omega \end{pmatrix}$
-i	$\begin{pmatrix} -\alpha & -\beta \\ -\beta & \alpha \end{pmatrix}$	$\begin{pmatrix} -i & 0 \\ 0 & i \end{pmatrix}$	$\begin{pmatrix} -\sqrt{2}i & -1 \\ -1 & \sqrt{2}i \end{pmatrix}$	$\begin{pmatrix} -\omega & -\omega^2 \\ -\omega^2 & \omega \end{pmatrix}$
j	$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$
-j	$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$
k	$\begin{pmatrix} \beta & -\alpha \\ -\alpha & -\beta \end{pmatrix}$	$\begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix}$	$\begin{pmatrix} 1 & -\sqrt{2}i \\ -\sqrt{2}i & -1 \end{pmatrix}$	$\begin{pmatrix} \omega^2 & -\omega \\ -\omega & -\omega^2 \end{pmatrix}$
-k	$\begin{pmatrix} -\beta & \alpha \\ \alpha & \beta \end{pmatrix}$	$\begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix}$	$\begin{pmatrix} -1 & \sqrt{2}i \\ \sqrt{2}i & 1 \end{pmatrix}$	$\begin{pmatrix} -\omega^2 & \omega \\ \omega & \omega^2 \end{pmatrix}$

realizing

$$\mathbb{H} \rightarrow \mathcal{M}_{2 \times 2}(\mathbb{C}) = \mathcal{M}_2(\mathbb{C})$$

37.4.1.1 Euler identity

cf. Lagrange identity^[??]

$$\begin{aligned}
 & \det(a + bi + cj + dk) \\
 &= \det \left[a \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + b \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix} + c \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} + d \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \right] \\
 &= \det \begin{pmatrix} a + bi & -c - di \\ c - di & a - bi \end{pmatrix} = \begin{vmatrix} a + bi & -c - di \\ c - di & a - bi \end{vmatrix} \\
 &= (a^2 + b^2) + (c^2 + d^2) = a^2 + b^2 + c^2 + d^2
 \end{aligned}$$

$$\det(a + bi + cj + dk) = \det \begin{pmatrix} a + bi & -c - di \\ c - di & a - bi \end{pmatrix} = a^2 + b^2 + c^2 + d^2$$

$$\begin{aligned}
& \det [(q_{10} + q_{11}\mathbf{i} + q_{12}\mathbf{j} + q_{13}\mathbf{k})(q_{20} + q_{21}\mathbf{i} + q_{22}\mathbf{j} + q_{23}\mathbf{k})] = \det [(a + b\mathbf{i} + c\mathbf{j} + d\mathbf{k})(\alpha + \beta\mathbf{i} + \gamma\mathbf{j} + \delta\mathbf{k})] \\
&= \det \left\{ \left[q_{10} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + q_{11} \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix} + q_{12} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} + q_{13} \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \right] \right. \\
&\quad \left. \left[q_{20} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + q_{21} \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix} + q_{22} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} + q_{23} \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \right] \right\} \\
&= \det \left\{ \left[a \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + b \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix} + c \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} + d \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \right] \right. \\
&\quad \left. \left[\alpha \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \beta \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix} + \gamma \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} + \delta \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \right] \right\} \\
&= \det \left\{ \begin{pmatrix} a + bi & -c - di \\ c - di & a - bi \end{pmatrix} \begin{pmatrix} \alpha + \beta i & -\gamma - \delta i \\ \gamma - \delta i & \alpha - \beta i \end{pmatrix} \right\} \\
&= \det \begin{pmatrix} a + bi & -c - di \\ c - di & a - bi \end{pmatrix} \det \begin{pmatrix} \alpha + \beta i & -\gamma - \delta i \\ \gamma - \delta i & \alpha - \beta i \end{pmatrix} = (a^2 + b^2 + c^2 + d^2)(\alpha^2 + \beta^2 + \gamma^2 + \delta^2) \\
&= \det \left\{ \begin{pmatrix} [a + bi][\alpha + \beta i] - [c + di][\gamma - \delta i] & [a + bi][- \gamma - \delta i] - [c + di][\alpha - \beta i] \\ [c - di][\alpha + \beta i] + [a - bi][\gamma - \delta i] & [c - di][- \gamma - \delta i] + [a - bi][\alpha - \beta i] \end{pmatrix} \right\} \\
&= \det \left\{ \begin{pmatrix} ((a\alpha - b\beta - c\gamma - d\delta) + i(a\beta + b\alpha + c\delta - d\gamma)) & -(a\gamma - b\delta + c\alpha + d\beta) - i(a\delta + b\gamma - c\beta + d\alpha) \\ (a\gamma - b\delta + c\alpha + d\beta) - i(a\delta + b\gamma - c\beta + d\alpha) & (a\alpha - b\beta - c\gamma - d\delta) - i(a\beta + b\alpha + c\delta - d\gamma) \end{pmatrix} \right\} \\
&= \det \{(a\alpha - b\beta - c\gamma - d\delta) + (a\beta + b\alpha + c\delta - d\gamma)\mathbf{i} + (a\gamma - b\delta + c\alpha + d\beta)\mathbf{j} + (a\delta + b\gamma - c\beta + d\alpha)\mathbf{k}\} \\
&= (a\alpha - b\beta - c\gamma - d\delta)^2 + (a\beta + b\alpha + c\delta - d\gamma)^2 + (a\gamma - b\delta + c\alpha + d\beta)^2 + (a\delta + b\gamma - c\beta + d\alpha)^2 \\
&= (q_{10}q_{20} - q_{11}q_{21} - q_{12}q_{22} - q_{13}q_{23})^2 + (q_{10}q_{21} + q_{11}q_{20} + q_{12}q_{23} - q_{13}q_{22})^2 \\
&\quad + (q_{10}q_{22} - q_{11}q_{23} + q_{12}q_{20} + q_{13}q_{21})^2 + (q_{10}q_{23} + q_{11}q_{22} - q_{12}q_{21} + q_{13}q_{20})^2 \\
&\quad (a^2 + b^2 + c^2 + d^2)(\alpha^2 + \beta^2 + \gamma^2 + \delta^2) \\
&= (a\alpha - b\beta - c\gamma - d\delta)^2 + (a\beta + b\alpha + c\delta - d\gamma)^2 \\
&\quad + (a\gamma - b\delta + c\alpha + d\beta)^2 + (a\delta + b\gamma - c\beta + d\alpha)^2
\end{aligned}$$

Theorem 37.2. For any two integers greater than zero, their multiplication can be the summation of squared four integers greater than zero.

$$\forall \langle m_1, m_2 \rangle \in (\mathbb{N} \cup \{0\})^2, \exists \langle k_1, k_2, k_3, k_4 \rangle \in (\mathbb{N} \cup \{0\})^4 [m_1 m_2 = k_1^2 + k_2^2 + k_3^2 + k_4^2]$$

Proof:

$$\text{Let } \begin{cases} m_1 = a^2 + b^2 + c^2 + d^2 & \langle a, b, c, d \rangle \in (\mathbb{N} \cup \{0\})^4 \\ m_2 = \alpha^2 + \beta^2 + \gamma^2 + \delta^2 & \langle \alpha, \beta, \gamma, \delta \rangle \in (\mathbb{N} \cup \{0\})^4 \end{cases} \xrightarrow{\text{closure property}} \begin{pmatrix} m_1 \\ m_2 \end{pmatrix} = \begin{pmatrix} a^2 + b^2 + c^2 + d^2 \\ \alpha^2 + \beta^2 + \gamma^2 + \delta^2 \end{pmatrix} \in (\mathbb{N} \cup \{0\})^2,$$

$$\begin{aligned}
m_1 m_2 &= (a^2 + b^2 + c^2 + d^2)(\alpha^2 + \beta^2 + \gamma^2 + \delta^2) \\
&\stackrel{\text{Euler identity}}{=} (a\alpha - b\beta - c\gamma - d\delta)^2 + (a\beta + b\alpha + c\delta - d\gamma)^2 \\
&\quad + (a\gamma - b\delta + c\alpha + d\beta)^2 + (a\delta + b\gamma - c\beta + d\alpha)^2 \\
&= |a\alpha - b\beta - c\gamma - d\delta|^2 \\
&\quad + |a\beta + b\alpha + c\delta - d\gamma|^2 \\
&\quad + |a\gamma - b\delta + c\alpha + d\beta|^2 \\
&\quad + |a\delta + b\gamma - c\beta + d\alpha|^2 \\
&= k_1^2 + k_2^2 + k_3^2 + k_4^2, \begin{pmatrix} k_1 \\ k_2 \\ k_3 \\ k_4 \end{pmatrix} = \begin{pmatrix} |a\alpha - b\beta - c\gamma - d\delta| \\ |a\beta + b\alpha + c\delta - d\gamma| \\ |a\gamma - b\delta + c\alpha + d\beta| \\ |a\delta + b\gamma - c\beta + d\alpha| \end{pmatrix} \in (\mathbb{N} \cup \{0\})^4 \\
&\Leftrightarrow \begin{cases} \langle a, b, c, d \rangle \in (\mathbb{N} \cup \{0\})^4 \\ \langle \alpha, \beta, \gamma, \delta \rangle \in (\mathbb{N} \cup \{0\})^4 \end{cases} \\
&\stackrel{\text{closure property}}{\Rightarrow} \begin{pmatrix} |a\alpha - b\beta - c\gamma - d\delta| \\ |a\beta + b\alpha + c\delta - d\gamma| \\ |a\gamma - b\delta + c\alpha + d\beta| \\ |a\delta + b\gamma - c\beta + d\alpha| \end{pmatrix} \in (\mathbb{N} \cup \{0\})^4
\end{aligned}$$

□

37.4.2 $\mathbb{H} \rightarrow \mathcal{M}_{4 \times 4}(\mathbb{R})$

https://groupprops.subwiki.org/wiki/Linear_representation_theory_of_quaternion_group#Four-dimensional_irreducible_representation_over_a_non-splitting_field

$$\mathbb{H} \rightarrow \mathcal{M}_2(\mathbb{C}) \xrightarrow{\mathbb{C} \rightarrow \mathcal{M}_2(\mathbb{R})} \mathcal{M}_{4 \times 4}(\mathbb{R}) = \mathcal{M}_4(\mathbb{R})$$

$$\mathbb{C} \rightarrow \mathcal{M}_2(\mathbb{R}) \Leftarrow \begin{cases} 1 \rightarrow \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\ i \rightarrow \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \end{cases}$$

$$\begin{aligned}
1 &\rightarrow \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \rightarrow \begin{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} & \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \\ \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} & \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \\
-1 &\rightarrow \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} \rightarrow \begin{pmatrix} \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} & \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \\ \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} & \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} \end{pmatrix} \rightarrow \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}
\end{aligned}$$

$$i \rightarrow \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix} \rightarrow \begin{pmatrix} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} & \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \\ \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} & \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \end{pmatrix} \rightarrow \begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix}$$

$$-i \rightarrow \begin{pmatrix} -i & 0 \\ 0 & i \end{pmatrix} \rightarrow \begin{pmatrix} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} & \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \\ \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} & \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \end{pmatrix} \rightarrow \begin{pmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

$$j \rightarrow \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \rightarrow \left(\begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{pmatrix}, \begin{pmatrix} -1 & 0 \\ 0 & -1 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \right) \rightarrow \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

$$-j \rightarrow \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \rightarrow \begin{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} & \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\ \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} & \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \end{pmatrix} \rightarrow \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$

$$k \rightarrow \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \rightarrow \begin{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} & \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \\ \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} & \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \end{pmatrix} \rightarrow \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix}$$

$$-k \rightarrow \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix} \rightarrow \begin{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} & \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \\ \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} & \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \end{pmatrix} \rightarrow \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$$

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$$ij \rightarrow \begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix} \leftarrow k$$

$$ji \rightarrow \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \leftarrow -k$$

$$i^2 = ii \rightarrow \begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix} \begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \leftarrow -1$$

$$\begin{array}{ll}
 \left\{ \begin{array}{l} \alpha = i \\ \beta = 0 \end{array} \right. & \left\{ \begin{array}{l} 1 \rightarrow \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\ i \rightarrow \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \end{array} \right. \\
 1 & \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \\
 -1 & \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \\
 i & \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix} \\
 -i & \begin{pmatrix} -i & 0 \\ 0 & i \end{pmatrix} \\
 j & \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \\
 -j & \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \\
 k & \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \\
 -k & \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix}
 \end{array}
 \quad
 \begin{array}{ll}
 \left\{ \begin{array}{l} \alpha = \sqrt{2}i \\ \beta = 1 \end{array} \right. & \left\{ \begin{array}{l} 1 \rightarrow \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\ i \rightarrow \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \end{array} \right. \\
 1 & \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \\
 -1 & \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \\
 i & \begin{pmatrix} \sqrt{2}i & 1 \\ 1 & -\sqrt{2}i \end{pmatrix} \\
 -i & \begin{pmatrix} -\sqrt{2}i & -1 \\ -1 & \sqrt{2}i \end{pmatrix} \\
 j & \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \\
 -j & \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \\
 k & \begin{pmatrix} 1 & -\sqrt{2}i \\ -\sqrt{2}i & -1 \end{pmatrix} \\
 -k & \begin{pmatrix} -1 & \sqrt{2}i \\ \sqrt{2}i & 1 \end{pmatrix}
 \end{array}$$

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$$ij \rightarrow \begin{pmatrix} 0 & -\sqrt{2} & 1 & 0 \\ \sqrt{2} & 0 & 0 & 1 \\ 1 & 0 & 0 & \sqrt{2} \\ 0 & 1 & -\sqrt{2} & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & \sqrt{2} \\ 0 & 1 & -\sqrt{2} & 0 \\ 0 & \sqrt{2} & -1 & 0 \\ -\sqrt{2} & 0 & 0 & -1 \end{pmatrix} \leftarrow k$$

Chapter 38

tensor

38.1 Einstein summation convention

38.1.1 dummy index

38.1.2 free index

Chapter 39

dual space

dual space and linear functional

<https://ccjou.wordpress.com/2011/06/13/> /

39.1 linear equations

$$\begin{aligned} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n &= b_1 \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n &= b_2 \\ &\vdots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n &= b_m \end{aligned}$$

$$\begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{pmatrix}$$

$$Ax = b$$

$$(a_{i1} \quad a_{i2} \quad \cdots \quad a_{in}) \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} = (b_i) = b_i$$

$$(a_{i1} \quad \cdots \quad a_{ij} \quad \cdots \quad a_{in}) \begin{pmatrix} x_1 \\ \vdots \\ x_j \\ \vdots \\ x_n \end{pmatrix} = (b_i) = b_i$$

$$(\cdots \quad a_{ij} \quad \cdots) \begin{pmatrix} \vdots \\ x_j \\ \vdots \end{pmatrix} = b_i$$

$$a_i^\top x = a_i \cdot x = b_i$$

$$a_{ij}x_j = a_i^\top x = a_i \cdot x = b_i$$

$$a_i \cdot x = a_i^\top x = a_{ij}x_j = \dots + a_{ij}x_j + \dots$$

if finite,

$$a_i \cdot x = a_i^\top x = a_{ij}x_j = a_{i1}x_1 + \dots + a_{ij}x_j + \dots + a_{in}x_n$$

39.2 matrix multiplication

$$\begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{pmatrix} \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1p} \\ x_{21} & x_{22} & \cdots & x_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{np} \end{pmatrix} = \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1p} \\ b_{21} & b_{22} & \cdots & b_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ b_{m1} & b_{m2} & \cdots & b_{mp} \end{pmatrix}$$

$$AX = B$$

$$(a_{i1} \quad a_{i2} \quad \cdots \quad a_{in}) \begin{pmatrix} x_{1k} \\ x_{2k} \\ \vdots \\ x_{nk} \end{pmatrix} = (b_{ik}) = b_{ik}$$

$$(a_{i1} \quad \cdots \quad a_{ij} \quad \cdots \quad a_{in}) \begin{pmatrix} x_{1k} \\ \vdots \\ x_{jk} \\ \vdots \\ x_{nk} \end{pmatrix} = (b_{ik}) = b_{ik}$$

$$(\cdots \quad a_{ij} \quad \cdots) \begin{pmatrix} \vdots \\ x_{jk} \\ \vdots \end{pmatrix} = b_{ik}$$

$$a_i^\top x_k = a_i \cdot x_k = b_{ik}$$