How to Reproduce this Book Exactly with LaTeX

A Self-contained Tutorial on Writing Mathematical Notes

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Contents

Chapter 1

The Basic Set-up and Structure of a LaTeX Book

Introduction The first chapter discusses how to properly configure LaTeX files and organize the content structure so that we can generate our first readable LaTeX book PDF.

1.1 Class, Commands, Options, and Packages

Class For each LaTeX document, we need to specify its *class*. Throughout this book, we will use the `scrbook` class provided by the **KOMA-Script**. To do so, we write `\documentclass{scrbook}` at the very beginning (*preamble*, everything before `\begin{document}`) of the main TeX file. Although not explored in this book, some other notable classes that may be of use include `beamer`, `moderncv`, and `article` (or `scrartcl`).

Commands and Options The `scrbook` class provides several *options* to customize the format of the book. We can either supply the arguments when declaring the class, or use the command `\KOMAoptions` in the preamble. A *command* works like a function in common programming languages and performs some specific action. Commands in LaTeX are denoted by the backslash `\` as the first character. In this book, we have used

```
\KOMAoptions{paper=a4, fontsize=12pt, chapterprefix=true, twoside=
   semi, DIV=classic, parskip=half}
```

The arguments are typed inside the curly brackets `{}` following the name of the command. Clearly, here the `paper` option requires the pages to be in A4 size while `fontsize` indicates that the font is 12 pt large. The remaining options will be explained as we go through the later chapters.

Packages To enable extra functionalities, we need to import *packages*. We can write along the lines of `\usepackage[<options>]{<package_name>}` in the preamble to do so. We will not list all the required packages now at once, but only when they are needed. The first package we usually need is the `fontenc` package with the `T1` option, flagged inside a pair of square brackets.

Exercise(s)

1.1) Try to import the `fontenc` package with the `T1` option as suggested above. There may not be any noticeable difference, but at least you should not be receiving errors.

1.2) Also, try to achieve the same class setting through the `\documentclass [<options>]{scrbook}` declaration instead of the `\KOMAoptions` command.

1.2 Structure Hierarchy

1.2.1 Chapters and (Sub-)Sections

Chapters, Sections In most of the books, the entire content is divided into *chapters*, which in turn usually consist of several *sections*. To mark the beginning of a chapter or section in LaTeX, we place the commands `\chapter{<chapter_name>}` or `\section{<section_name>}` within the `document` environment, which contains the main content and is marked by a pair of `\begin{document}` and `\end{document}` declarations. As mentioned in the beginning, the preamble has to be inserted before such a `document` group. So, to typeset the very first section at the start, we write

```
% <preamble before the main document>
\begin{document}
...
\chapter{The Basic Set-up and Structure of a \LaTeX{} Book}
...
\section{Class, Options, and Packages}
\paragraph{Class}
For each \LaTeX{} document, we need to specify its \textit{class}.
   Throughout this book, ...
...
\end{document}
```

The `%` symbol indicates a trailing *comment* (highlighted in green) whose purpose is to leave some note about the code. Comments are neither interpreted nor displayed. The LaTeX system records and updates the numbering for chapters/sections internally (??). The `\textit{<text>}` command presents the text in italic shape.

Subsections, Paragraphs Attentive readers may have already figured out that it is possible to stack an extra level (a *subsection*) in the content hierarchy. This is aptly done not long ago by the `\subsection{<section_name>}` command:

```
\section{Structure Hierarchy}

\subsection{Chapters and (Sub-)Sections}

\paragraph{Chapters, Sections}
As in any other book, the entire content is divided into \textit{
   chapters}, ...
```

He/she may also notice that we have used the `\paragraph` command a few times to attach an unnumbered heading for each *paragraph*. There are also starred versions like `\chapter*{<chapter_name>}`, `\section*{<section_name>}`, `\subsection*{<section_name>}`, and so on, which neither display nor increment the numbering/counters.

(labels?)

1.2.2 Generating Table of Contents

Table of Contents After establishing the structure of the book, it is convenient to generate a *table of contents (TOC)* as well. In the `scrbook` class, it is easily done by adding the command `\tableofcontents` within the main `document` environment. To control the depth of layers shown, we can call `\setcountertocdepth{<integer>}` in the preamble, where the `integer` usually ranges from -1 to 3 (0: chapters, 1: sections, 2: subsections).

Exercise(s)

1.3) Try to add some (numbered or unnumbered) chapters, sections, subsections, or even subsubsections (which are, not surprisingly, produced by `\subsubsection`) to see how they are displayed in the book. You may want to check out `\part`.

1.4) As a follow-up to the last exercise, turn on the table of contents and confirm how the new entries are linked to it. Also, try to adjust the value for `\setcountertocdepth` as proposed above to see the effect.

1.2.3 Organizing the TEX Files behind the Scenes

include As the size of the project scales up, it is often helpful to keep the files sorted in a clean order for maintenance. We can put the content of each chapter into separate TEX files, and then use the `\include{<tex_file_name>}` command to import them into the main script. For example, this chapter is stored as `ch1_basic_structure.tex` in my project space, and in the main TEX file, we shall write something like

```
% <preamble again>
\begin{document}
...
\include{ch1_basic_structure}
\include{ch2_text_format}
...
\end{document}
```

1.3 Testing the Book Layout by Lipsum

Dummy Text Sometimes we may need to insert some placeholder text into the document to test how well the book will look in a specific layout. In this case, we can borrow the standard dummy text *Lorem Ipsum* (or in short *Lipsum*) widely used by the community. Just import the `lipsum` generator package, and add `\lipsum[<paragraph_no.>]` to the desired locations. For example, the code segment

```
...
produces the following text exactly: \par
\lipsum[1-2]
```

produces the following text exactly:

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

The `\par` command signals the end of a paragraph and appends a vertical line spacing afterwards.

Chapter 2

Formatting of Text and Paragraphs

Introduction This chapter describes how to adjust the various aspects of text, such as fonts, size/shape/style, and positioning.

2.1 About Fonts

2.1.1 The Three Font Family Types

(Sans) Serif, Typewriter In any LaTeX document, the text can be typed in three different *font families*: *serif*, *sans serif*, and *typewriter*. In this book, headings (of chapters, sections, etc.) are in the sans serif family, while the remaining main text is in serif. Table 2.1 below demonstrates how to select a specific font family for a piece of text. For instance, both

```
...
produces the following output: \par
\textsf{\lipsum[3]} % or {\sffamily \lipsum[3]}, mind the curly
   brackets {} to limit the scope of the \sffamily command.
```

Font Family	Command	Switch	Output
Serif	`\textrm{Hello World!}`	`\rmfamily`	Hello World!
Sans Serif	`\textsf{Hello World!}`	`\sffamily`	Hello World!
Typewriter	`\texttt{Hello World!}`	`\ttfamily`	`Hello World!`

Table 2.1: The commands for switching between the three font families and how they appear in the PDF.

produces the following output:

Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis. Donec nonummy pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.

2.1.2 Changing the Actual Font for a Font Family

Font Libraries Each of the previous font families is internally assigned a specific *font*. To change the actual font, we can call the corresponding font package. The **LaTeX Font Catalogue** https://tug.org/FontCatalogue/ provides a comprehensive list of available fonts and the way to import them. This book has substituted the **Noto Sans** font for the sans serif family, via the preamble

```
\usepackage[T1]{fontenc}
\usepackage[sf]{noto}
```

Exercise(s)

2.1) Change the font family just for the dummy Lipsum paragraph above to typewriter.

2.2) Choose a font of your liking from the Font Catalogue to replace the original one in the book.

2.2 Text Attributes

2.2.1 Font Size

Size Commands In Section 1.1, we talked about setting the base global font size by `\KOMAoptions`. However, to control the *local font size* for some places, we can use the *size commands*, listed in Table 2.2 below. For example, writing

```
... produces \par
{\small Though she be but little} {\LARGE she is fierce} \\ % scope
\scriptsize % switch
taken from Shakespeare's A Midsummer Night's Dream
\normalsize % back to default ...
```

produces

Though she be but little she is fierce
taken from Shakespeare's A Midsummer Night's Dream

The `\\` sign breaks the current line and starts a new line right below. And again, the curly brackets `{}` limit the effect of command(s) within their scope.

Table 2.2: The various commands for text size.[1]

Command	Output
`\tiny`	Who am I?
`\scriptsize`	Who am I?
`\footnotesize`	Who am I?
`\small`	Who am I?
`\normalsize`	Who am I?
`\large`	Who am I?
`\Large`	Who am I?
`\LARGE`	Who am I?
`\huge`	Who am I?
`\Huge`	Who am I?

selectfont It is also possible to fix a numerical value for the font size using `\fontsize{<font_size>}{<line_spacing>}` and `\selectfont`. As an illustration, the code

```
... leads to \par
{\fontsize{15pt}{21pt}\selectfont May those who accept their fate be
   granted happiness. May those who defy their fate be granted glory.
    \\
-- Princess Tutu \par} % the \par is needed for renewing the
   parameters
```

leads to

[1] `\huge` and `\Huge` have the same size when the font size is 12 pt (but different for 10 or 11 pt).

Font Style	Command	Switch	Output
Bold	`\textbf{"10 Downing"}`	`\bfseries`	**"10 Downing"**
Medium	`\textmd{"10 Downing"}`	`\mdseries`	"10 Downing"
Italic	`\textit{"10 Downing"}`	`\itshape`	*"10 Downing"*
Slanted	`\textsl{"10 Downing"}`	`\slshape`	*"10 Downing"*
Small Caps	`\textsc{"10 Downing"}`	`\scshape`	"10 DOWNING"
Upright	`\textup{"10 Downing"}`	`\upshape`	"10 Downing"

Table 2.3: The commands for different font styles. The medium/upright style is effectively the default normal.

May those who accept their fate be granted happiness. May those who defy their fate be granted glory.

– Princess Tutu

2.2.2 Font Shapes

Italic, Bold, and More Similar to font families, there are different *font shapes/styles* such as the commonly seen italic or bold. Table 2.3 above shows the relevant commands to invoke them. Adding to the previous example, we can write

```
... which produces \par
\textit{\small Though she be but little} {\LARGE \bfseries \scshape
   she is fierce} \\ % scope
\scriptsize % switch
taken from \slshape \underline{Shakespeare's A Midsummer Night's
   Dream}
\normalsize \upshape \par % back to default
...
```

which produces

Though she be but little SHE IS FIERCE

taken from *Shakespeare's A Midsummer Night's Dream*

We also have `\underline` and `\emph`. You may want to try them out.

2.2.3 Text Color

xcolor While there are built-in colors in the LaTeX system, we can load a variety of additional colors from the `xcolor` package, often with the `svgnames` and `dvipsnames` flags as

```
\usepackage[svgnames, dvipsnames]{xcolor}
```

The reference color list can be found in https://www.overleaf.com/learn/latex/Using_colors_in_LaTeX. To set the color for a piece of text, we can enclose it with the `\textcolor{<color_name>}{<text>}` command. It is also possible to change the color within a group by `\color{<color_name>}`. For instance,

```
... outputs \par
\textcolor{Red}{Roses are red,} \\
\textcolor{Blue}{violets are blue,} \\
{\color{Purple} Sugar is sweet and so are you.} % again, remember to
   limit the scope by the curly brackets!
```

outputs

Roses are red,
violets are blue,
Sugar is sweet and so are you.

Self-defined colors It is also possible to design a custom color by the command `\definecolor{<color_name>}{<color_model>}{<values>}`. There are 4 possible color models: `rgb`, `RGB`, `cmyk`, and `gray`. For example,

```
...
\definecolor{mint}{rgb}{0.24, 0.71, 0.54} % in the preamble
...
\textcolor{mint}{Mint Tears}
```

gives Mint Tears. Color codes can be checked via https://latexcolor.com/.

In addition, we can mix colors by the expression <color_1>!<mix_ratio>!<color_2>. For instance,

```
\textcolor{Blue!40!Green}{Copper (II)} \textcolor{Orange!50}{Sulphate
   }
```

is displayed as Copper (II) Sulphate.

2.3 Paragraphs and Positioning

2.3.1 Paragraphs and Line Breaks

New Lines As explained before, the `\\` symbol issues a *line break*, and the `\par` command ends a paragraph and starts a new one.
Both of them initiate a *new line*, but with (without) an extra *line skip/line spacing* for `\par` (`\\`). There is also `\newline` which is seldom used.

A blank line in a TeX file has the same effect as `\par`. They, in fact, end the so-called *horizontal mode* and distribute the text into lines held in the current vertical list (see TeX StackExchange 82664).

The effects of `\\`, `\par`, and blank lines can be observed right in this subsection, which is typed as

```
\paragraph{New Lines}
As explained before, ... ends a paragraph and starts a new one. \\
Both of them initiate a \textit{new line}, ... which is seldom used.
                % here is a blank line with this comment only
```

```
A blank line in a \TeX{} file ... held in the current vertical list (
    see ...). \par
The effects of \texttt{\textbackslash\textbackslash}, \texttt{\
    textbackslash par}, and blank lines can be observed right in this
    subsection, which is typed as
... % this code block
```

2.3.2 Justification and Indents

raggedleft/right, centering The `\raggedright` and `\raggedleft` commands produce *left/right-justified* text respectively. As you may have figured out, this paragraph is "*ragged* right" (although not very obvious, notice →) so that the text sticks to the left boundary, but the right side is now uneven.

Meanwhile, this lipsum text is "ragged left": Quisque ullamcorper placerat ipsum. Cras nibh. Morbi vel justo vitae lacus tincidunt ultrices. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. In hac habitasse platea dictumst. Integer tempus convallis augue. Etiam facilisis. Nunc elementum fermentum wisi. Aenean placerat. Ut imperdiet, enim sed gravida sollicitudin, felis odio placerat quam, ac pulvinar elit purus eget enim. Nunc vitae tortor. Proin tempus nibh sit amet nisl. Vivamus quis tortor vitae risus porta vehicula.

The default setting is *fully-justified* so that the text extends to both edges like this one. `\raggedleft` and `\raggedright` act like a switch, changing all paragraphs beyond, and we may want to put them within a group enclosed by curly brackets.

We also have `\centering` which is quite self-explanatory and is demonstrated here. For these three commands to work properly, we require `\par` to finish, similar to before. The code to generate the above paragraphs is

```
\paragraph{Raggedleft/right, Centering}
```

```
{\raggedright The \texttt{\textbackslash raggedright} and \texttt{\
   textbackslash raggedleft} commands produce ... but the right side
   is now uneven. \par}
{\raggedleft Meanwhile, this lipsum text is "ragged left": \lipsum
   [4]\par}
The default setting is \textit{fully-justified} ... we may want to
   put them within a group enclosed by curly brackets. \par
{\centering We also have \texttt{\textbackslash centering} ... The
   code to generate the above paragraphs is \par} ...
```

flushleft/right, center (Environments) The alternative to the above is to put the text into a `flushleft`/`flushright`/`center` environment. An *environment* contains content that is to be processed and displayed according to the specific design indicated by the environment itself. Environments always start with the `\begin{<env_name>}` and end with the `\end{<env_name>}` statements. For example, the previous part can also be reproduced by

```
...
\begin{flushright}
Meanwhile, this lipsum text is "ragged left": \lipsum[4]
\end{flushright}
...
\begin{center}
We also have \texttt{\textbackslash centering} ... The code to
   generate the above paragraphs is
\end{center}
```

`flushleft` (`flushright`) corresponds to (`\raggedright`) `\raggedleft`. If you test this new code, notice the increased separation[2] around the environments.

Indents, parskip Attentive readers may have figured out that there is no *indent* for paragraphs in the book, and they are only separated by a slight vertical spacing.

[2]This is dictated by `\topsep`, see the next subsection.

This is controlled by the `parskip=half` value inside `\KOMAoptions` in the preamble, which means that paragraphs are identified with a vertical spacing of half a line. The two other options `parskip=no` and `parskip=full` use indents (without vertical spacing) and one full line instead.

Also, we can control indents manually by adding `\indent`[3] or `\noindent` to the start of paragraphs.

microtype Finally, for a better typesetting behavior (e.g. hyphenation), it is recommended to always import the `microtype` package, which provides helpful patches on this.

> **Exercise(s)**
>
> **2.3)** Try experimenting with different `parskip` options (there are additional modifiers like `half-`, `half+`, `half*`, similar for `full`) for the KOMA-script class, as well as the on-and-off of indents.

2.3.3 Lengths and Sizes

Length Units Before learning how to adjust the size of objects and spacing, we need to be able to express and measure lengths in LaTeX. There are various *length units* for this, summarized in Table 2.4 below.

Length Values, setlength Subsequently, the *lengths* of different markers are stored as parameters, listed in Table 2.5. By using `\setlength{<length_param>}{<length_value>}`, we can modify them and adjust distances on the page.

[3] It will not work if `parskip` is `half` or `full`.

Unit	Description
pt	The usual "point" unit adopted in other documenting software.
mm/cm/in	A millimeter/A centimeter/An inch.
ex	The height of a lowercase "x" character in the current font. (usually used for vertical distance)
em	The width of an uppercase "M" in the current font. (usually used for horizontal distance)
mu	1/18 of an em with respect to the math symbols. (usually used in math mode)

Table 2.4: The various length units in LaTeX.

2.3.4 Horizontal and Vertical Spaces

hspace, vspace To control the position of different objects or blocks, the primary way is via the `\hspace{<length>}` and `\vspace{<length>}` commands. As their names hint, they add a horizontal/vertical space of fixed lengths. For example, the code

```
\hspace{3ex} Hello \hspace{5ex} World \vspace{1.5em} !!! \\
Ouch...
```

gives

   Hello   World !!!

Ouch...

The first two `hspace` commands should work as you have expected, but notice that on the other hand, `vspace` in the middle of a line will only take effect after it, and so the exclamation marks above are not moved down (but "Ouch..." is). Finally, they accept negative lengths, and you may want to play with that.

Parameter	Description
\baselineskip	Vertical distance between adjacent lines within a paragraph.
\columnsep	Distance between columns.
\columnwidth	The width of a column.
\fboxsep and \fboxrule	The padding and line width around boxes.
\linewidth	The width of a line.
\paperheight and \paperwidth	The height and width of the page.
\parindent	The length of the indent before a paragraph.
\parskip	The vertical spacing between paragraphs.
\textheight and \textwidth	The height and width of the text area in a page.
\topmargin	The length of the top margin.
\topsep and \itemsep	The vertical space added above and below an environment, as well as around the items within it.

Table 2.5: Commonly involved length parameters in LaTeX.

It is also to achieve the same effect after a line break by writing something along the lines of \\[<length>], e.g.

```
Don't come any closer!!!\\[-1em]
Nope *Taking out the axe*
```

Don't come any closer!!!
Nope *Taking out the axe*

hspace*, vspace* There also exist starred versions of \hspace*{<length>} and \vspace*{<length>}. The difference is that the original ones will be "gobbled up" (see TeX StackExchange 89082) and disappear at line breaks, but the new ones will not. To see this clearly, let's try

```
x\hspace{3ex}y\\
\hspace{4ex}y?\\
\hspace*{4ex}y!
```

which gives

x   y
y?
    y!

hfill, vfill, fill, stretch In the case where a fixed distance is only needed in a certain place, while other remaining empty spaces can extend automatically, we can make use of the `\hfill`, `\vfill` commands, or more generally `\fill`, plus `\stretch{<factor>}`. `\hfill` and `\vfill` will take up all the possible spaces after other `hspace` or `vspace` commands are calculated.

If there are multiple `\hfill` or `\vfill`, then the length will be partitioned equally. To assign different weightings to the partition, we can go back and write `\hspace{\stretch{<factor>}}` (similarly for `\vspace`). For example,

```
\hfill Hope \hspace{4cm} Faith \hspace*{\stretch{2}} \\
\hspace*{\stretch{2}} Love \hspace{4cm} Luck \hspace*{\fill} \par %
   the asterisks * are needed!
```

yields

Hope   Faith
Love   Luck

Notice how we have to use the starred forms to circumvent the gobbling. (Try not using them and see how it fails!)

smallskip, medskip, bigskip Finally, there are also shorthands for generating vertical line skips: `\smallskip`, `\medskip`, and `\bigskip`. Note that they are just `\vspace` with `\smallskipamount`, `\medskipamount`, and `\bigskipamount` under the hood.

2.3.5 Boxes and Rules

mbox, fbox By calling `\mbox{<text>}`, a piece of text may be placed and contained inside a *horizontal box*. This also means that the text will not be disrupted by automatic line breaks or stretched (see TEX StackExchange 475056), and can spill out of the main area into the margin. There is also `\fbox{<text>}` as a wrapped version of `\mbox` with a frame around it, and we will use it for a visualized comparison: The code

```
Preparation is the key to success, but a good plan today is better
   than a perfect plan tomorrow.
\fbox{Preparation is the key to success, but a good plan today is
   better than a perfect plan tomorrow.}
```

produces: Preparation is the key to success, but a good plan today is better than a perfect plan tomorrow. Preparation is the key to success, but a good plan today is better than a pe
From this, we can clearly see how the horizontal box extends all the way outside.

makebox, framebox An improved version for the box commands above consists of `\makebox[<width>][<alignment>]{<text>}` and also similarly `\framebox[<width>][<alignment>]{<text>}`, where we can specify the width of the box and how the text inside is justified (`l, c, r, s`: left, center, right, spread) inside the box. For example,

```
\framebox[100pt][c]{I fit inside!} and \\
\framebox[130pt][l]{Unfortunately, this one is too small for me...}
```

generates I fit inside! and
Unfortunately, this one is too small for me...
These box commands can be manipulated to control the distribution of text.

parbox Meanwhile, *vertical boxes* where the text inside can break just like normally can be constructed by the `\parbox[<alignment>]{<width>}{<text>}` command. The effect is not hard to inspect from the input

```
that produces \parbox[b]{100pt}{Empty your mind, be formless,
   shapeless, like water.} ...
```

Empty your mind, be formless, shape-
that produces less, like water. This time, the alignment option (`t, c, b`: top, center, bottom) decides how the `\parbox` will be positioned relative to the current line. To add a frame around it, simply enclose it with an extra `\fbox`.

raisebox Sometimes we may want to raise or lower a text while pretending it still occupies some space with a fixed extent. Then the `\raisebox{<vertical_distance>}[<extend_above>][<extend_below>]{<text>}` command will do the job. This is demonstrated by including a `\fbox` to visualize the effect:

```
\fbox{\raisebox{15pt}[10pt][10pt]{I am a rising star!}} and this is
   my stage!
```

I am a rising star!
and this is my stage!

This command can be very useful in achieving several invisible spacing tricks.

Rules Another useful ingredient is the possibility to draw *rules* as lines. The basic command is `\rule{<horizontal_extent>}{vertical_extent}`. For example, `\rule{5ex}{1ex}` generates this: ▬. We also have more primitive versions of `\hrule` and `\vrule`. The code below will yield

```
\vrule \hspace{6pt} If you remove me, the vertical rule to the left
   will disappear! \hrule
```

| If you remove me, the vertical rule to the left will disappear!

Exercise(s)

2.4) Use the `\setlength` command to change different lengths and test what the result would look like, e.g. `\setlength{\parindent}{5cm}`.

2.5) Copy your favorite quote or paragraph to the document, and use the commands/techniques introduced in these two sections to make it beautiful and stylish.

2.4 Verbatim Mode

verb To type short inline code pieces, we can use the *verbatim* mode through the `\verb|<content>|` command. This preserves the input exactly as it is typed, without invoking any would-be LaTeX command or special character. For example, entering `\verb|func|` will output `func` here. However, a major pitfall is that `\verb` can fail when it is used inside the argument of a command.[4] Since we may use the `\include` command to import each chapter separately as suggested by Section 1.2.3, this will be problematic. An alternative is to use `\texttt{<content>}`, with `\textbackslash` as the replacement for `\`, and writing `\_` for `_`, `\{` and `\}` for `{` and `}`.

lstlisting When we need to display larger blocks of code, we can use the `listings` package and its `lstlisting` environment. Actually, it has already

[4]Interested readers can search fragile commands.

been used (shown as yellow areas) in this book many times. A self-explanatory example[5] is

```
\begin{lstlisting} % can pass the overriding option [style=<style_
   name>]
\textit{I guess this counts as a recursion...}
\end{lstlisting}
```

To design the appearance of the code blocks, we can define our own `lstlisting` style. The one adopted in the book is given by

```
\lstdefinestyle{lstTeXstyle}{ % give a name for the lstlisting style
    language=[latex]TeX,
    basicstyle=\footnotesize\ttfamily, % the font style
    backgroundcolor=\color{Goldenrod!20},
    keywordstyle=\color{blue!80}\bfseries, % for highlighting
        functions
    commentstyle=\color{Green},
    breaklines=true,
    numbers=none, % none, left, or right
    showstringspaces=false,
    belowskip=0pt}
\lstset{style=lstTeXstyle} % set the style
```

Most of the options above are not hard to understand, but you may want to fiddle with the last four of them.

Like `\verb`, this package also comes up with `\lstinline` for writing inline code.

Exercise(s)

2.6) Take any of the code blocks in this book and reproduce it using the `lstlisting` environment.

[5]It is a bit involved to make this one work, the option `escapeinside` (as well as its variants) is intentionally left out below, but you should look it up.

Chapter 3

The Fundamentals of Writing Mathematics in LaTeX

Introduction This chapter covers the basic methods regarding how to typeset and align different mathematical expressions and formulae in LaTeX.

3.1 The Two Math Modes

3.1.1 Inline Math Mode and Basic Math Syntax

Inline Math by $$ To be able to write mathematical expressions in LaTeX, we need to first enter the so-called *math mode*. There are two types of math mode in LaTeX, and the simpler one will be the *inline* math mode. As its name suggests, it renders the mathematical expressions as a usual part of a paragraph. We can enter the inline mode by enclosing an expression with the dollar signs like `$<expression>$`. For example, typing `$3x+4y-z = 5$` here readily outputs $3x + 4y - z = 5$.

Basic Operators The plus, minus, divide, and equal signs $+$, $-$, $/$, $=$ are just the usual ones and can be typed directly in math mode. Meanwhile, the multiplication sign ($\times$) has to be typed explicitly as `\times`, and we may also use the dot sign ($\cdot$) through `\cdot` instead. Round and square brackets in math mode are also simply given by `()`, `[]`.

Superscripts and Subscripts Superscripts (e.g. raising to a power) and subscripts can be added via `^{<superscript>}` and `_{<subscript>}`. For example, `C^{2n}_n` is output as C^{2n}_n.

Fractions, smash Fractions can be typeset easily as `\frac{<numerator>}{<denominator>}`, e.g. `\frac{2x^2}{3x+1}` produces $\frac{2x^2}{3x+1}$. However, notice that this `\frac` in the inline mode is shrunk. One workaround is to simply use the slash / instead, but we can also replace `\frac` by `\dfrac`, which gives $\dfrac{2x^2}{3x+1}$. Unfortunately, this leads to another issue where the full-size fraction interferes with the line spacing (the lines directly above and below the `\dfrac` are slightly pushed away if you look closely). A quick fix is to enclose it with the `\smash{}` command to tell LaTeX to ignore its extent.

Common Mathematical Functions, Symbols The commands for some notable, frequently used mathematical functions and symbols are summarized in Table 3.1 below.

Function/Symbol(s)	Command(s)	Description
sin, cos, tan, csc, sec, cot	`\sin()`, `\cos()`, `\tan()`, `\csc()`, `\sec()`, `\cot()`	Trigonometric Functions.
exp, log, ln	`\exp()`, `\log()`, `\ln()`	Exponential and (Natural) Logarithm.
$\sqrt{x}$, $\sqrt[3]{x}$	`\sqrt{x}`, `\sqrt[3]{x}`	Square (Cubic) Root of x.
i, e, π	`i`, `e`, `\pi`	Important constants: The imaginary number, e, and pi.
α, β, γ, ...	`\alpha`, `\beta`, `\gamma`	Greek letters. (see the full list at http://www.phys.uri.edu/~nigh/TeX/sym1.html)
$\pm$, ∞	`\pm`, `\infty`	The plus/minus sign and infinity symbol.
$\sum_i^n$, $\int_a^b$	`\sum_{i}^{n}`, `\int_{a}^{b}`	Summation and integral signs with lower and upper limits.

Table 3.1: Commonly used mathematical commands in LaTeX.

Exercise(s)

3.1) Try to reproduce the following mathematical expressions.

a) $ax^2 + by^2 + c(z-4)^2 = R^2$;

b) $g(x) = \frac{1}{e^{-qx}+1}$;

c) $A_{ij}^2 = A_{ik}A_{kj}$;

d) $\int_0^\infty \frac{\sin(\pi x)}{x} dx = ?$;[1]

e) $\beta \pm \ln\left(\sqrt{\frac{\alpha}{10}}\right)i$.

3.1.2 Display Math Mode

equation The second type of math mode is the *display* math mode, which involves putting the expressions inside an environment on their own. The most frequently used one is the `equation` group, which processes a single line of equation or formula. For instance,

```
\begin{equation}
f(t) = 1 - e^{-at}
\end{equation}
```

results in

$$f(t) = 1 - e^{-at} \tag{3.1}$$

Notice that the `equation` is automatically numbered.

align More often than not, we want to show the detailed steps involved in a calculation. The `align` environment enables us to write them in multiple lines, in addition to providing the `&` character as the anchor for aligning these lines. The `\\` symbol is again used as a line break just like in any ordinary text. As an example,

```
\begin{align}
\frac{d}{dx}(2x+3)^5 ={}& [5(2x+3)^4][\frac{d}{dx}(2x+3)] & & \text{(
   Chain Rule)} \\
={}& [5(2x+3)^4](2) = 10(2x+3)^4
\end{align}
```

will give

$$\begin{align}
\frac{d}{dx}(2x+3)^5 ={}& [5(2x+3)^4][\frac{d}{dx}(2x+3)] & & \text{(Chain Rule)} \tag{3.2} \\
={}& [5(2x+3)^4](2) = 10(2x+3)^4 \tag{3.3}
\end{align}$$

[1] To the curious readers, the result is equal to $\pi/2$.

There are some points worth mentioning. First, the `align` environment will create a line number for each individual line by default. Second, the two lines above are aligned via the first `&` character in them, as expected. Third, by adding some extra `&`, we can append any note to the right. In fact, odd-numbered `&` control the exact alignment positions and even-numbered `&` dictate the partition of pieces. Finally, the `{}` after $=$ are needed for appropriate spacing (try removing them!).

split Sometimes, an entire expression is too long to be captured in a single line and may require us to break it into multiple lines, while still treating it as a whole entity. The `split` sub-environment then comes in handy. It works like `align` but can be embedded in another larger `align` group. For example,

```
\begin{align}
(2x+3)^5 ={}& \sum_{k=0}^{5} C^{5}_k (2x)^k(3)^{5-k}\\
\begin{split}
={}& 32x^5 + 240x^4 + 720x^3 \\
& + 1080x^2 + 810x + 243
\end{split}
\end{align}
```

produces

$$\begin{align}
(2x+3)^5 ={}& \sum_{k=0}^{5} C^{5}_k (2x)^k(3)^{5-k} \tag{3.4}\\
\begin{split}
={}& 32x^5 + 240x^4 + 720x^3 \\
& + 1080x^2 + 810x + 243
\end{split} \tag{3.5}
\end{align}$$

As you can see, `split` only occupies a single equation number (in the middle) and the `&` inside it can "communicate" with those outside `split`.

aligned On the contrary, we have the related `aligned`, and the readers can try (strongly recommended as an exercise)

```
\begin{align}
(2x+3)^5 ={}& \sum_{k=0}^{5} C^{5}_k (2x)^k(3)^{5-k}\\
={}&
\begin{aligned}
& 32x^5 + 240x^4 + 720x^3 \\
& + 1080x^2 + 810x + 243
\end{aligned}
\end{align}
```

to see the difference (particularly the `&`). There is also `multline`, however, most of the usages are already covered by `split` and `aligned`, so we will not discuss it.

Starred Equations Sometimes, the equations may not be worthy of assigning an equation number. By using the starred versions of these environments (`equation*`, `align*`, etc.), the equation numbers will be suppressed. For example,

```
\begin{equation*}
1 + 1 = 2
\end{equation*}
```

yields

$$1 + 1 = 2$$

A quick alternative is to use the `\[<math>\]` shorthand.

nonumber We can also use `\nonumber` to manually prevent numbering for any line. For instance,

```
\begin{align}
\int xe^{-x} dx &= -\int x d(e^{-x}) \nonumber \\
&= -[xe^{-x}] + \int e^{-x} dx & & (\text{Integration by Parts}) \
   nonumber \\
&= -xe^{-x} - e^{-x} + C
\end{align}
```

will give

$$\begin{aligned}\int xe^{-x}dx &= -\int xd(e^{-x}) \\ &= -[xe^{-x}] + \int e^{-x}dx && \text{(Integration by Parts)} \\ &= -xe^{-x} - e^{-x} + C && (3.6)\end{aligned}$$

Equation Numbers Referencing From time to time, we may need to refer to previous equations during the derivation of a new one. This is straightforward if the equations are numbered, where we can explicitly attach a *label* to the specific lines by `\label{<name>}`. Subsequently, we can call the equation numbers by `\ref{<name>}`. To demonstrate, we may update the integration by parts example in the above paragraph:

```
...
&= -xe^{-x} - e^{-x} + C \label{eqn:IBP1}
```

then `(\ref{eqn:IBP1})` will properly return (3.6).

It is also possible to achieve letter numbering in the `subequations` mode, e.g.

```
\begin{subequations}
\begin{align}
\cos (2x) &= \cos^2 x - \sin^2 x \\
\sin (2x) &= 2 \sin x \cos x
\end{align}
\end{subequations}
```

will generate

$$\cos(2x) = \cos^2 x - \sin^2 x \qquad (3.7a)$$

$$\sin(2x) = 2\sin x \cos x \qquad (3.7b)$$

allowdisplaybreaks When we are using the `align` environment (or other similar ones), the blocks may become too lengthy to be included in a single page. By appending the switch `\allowdisplaybreaks` (in the preamble), the LaTeX system will then be allowed to break them across multiple pages. This may or may not be desirable and will depend on the situation. As a side note, if an inline expression in a paragraph is too long and hangs outside the main text area, we may add the command `\allowbreak` so that a line break may be inserted there.

Exercise(s)

3.2) Try to reproduce the paragraphs below with the numbered equations. Notice that the enlarged brackets can be obtained by `\left(<math>\right)`.
Solving

$$x^2 \frac{d^2y}{dx^2} - 3x\frac{dy}{dx} + 3y = 0 \tag{3.8}$$

Let $z = \ln x$, then

$$\begin{aligned}
\frac{dy}{dx} &= \frac{dy}{dz}\frac{dz}{dx} = \frac{1}{x}\frac{dy}{dz} && (3.9)\\
\frac{d^2y}{dx^2} &= \frac{d}{dx}\left(\frac{dy}{dx}\right) = \frac{d}{dx}\left(\frac{1}{x}\frac{dy}{dz}\right) && \text{(continuing from (3.9))}\\
&= \frac{1}{x}\frac{d}{dx}\left(\frac{dy}{dz}\right) - \frac{1}{x^2}\frac{dy}{dz}\\
&= \frac{1}{x}\frac{dz}{dx}\frac{d}{dz}\left(\frac{dy}{dz}\right) - \frac{1}{x^2}\frac{dy}{dz}\\
&= \frac{1}{x^2}\frac{d^2y}{dz^2} - \frac{1}{x^2}\frac{dy}{dz} && (3.10)
\end{aligned}$$

Substituting (3.9) and (3.10) into (3.8), we have ...

(displaystyle?)

3.2 Advanced Mathematical Expressions and Notations

amsmath, amssymb, mathtools Before getting into the main section, it is necessary to load the prerequisite `amsmath`, `amssymb`, and `mathtools` packages for the symbols, as well as enhancing the mathematical typesetting.

3.2.1 Calculus

Differentiation and Integral Symbols Table 3.2 below is a list of notable symbols used to denote derivatives and integrals for calculus, aside from Table 3.1.

Function/Symbol(s)	Command(s)	Description
∂, ∂_x	`\partial`, `\partial_x`	Partial derivatives (with respect to x).
∇, Δ	`\nabla`, `\Delta`	The del and Laplacian operators.
$\lim_{x\to 0}$, $\liminf$, $\limsup$	`\lim_{x\to 0}`, `\liminf`, `\limsup`	Limit (inferior and superior).
$\iint_S$, $\iiint$, $\oint$	`\iint_S`, `\iiint`, `\oint`	Double, triple[2], and contour integrals.

Table 3.2: Commonly used differentiation and integral symbols.

[2]If the limits of the multiple integral have to be spelled out explicitly, then just resort to using the original `\int_{}^{}` for multiple times.

3.2.2 Logic and Description

Logic and Set Symbols Meanwhile, Table 3.3 below contains a number of commonly used logical operators and set symbols.

Function/Symbol(s)	Command(s)	Description
$<, >, \leq, \geq, \ll, \gg$	`<`, `>`, `\leq`, `\geq`, `\ll`, `\gg`	(Much) Smaller and greater than (or equal to).
$\neq$	`\neq`	Not equal to.
$\equiv, \coloneqq$	`\equiv`, `\coloneq`	Equivalence, Definition of a quantity.
$\approx, \sim$	`\approx`, `\sim`	Approximately equal to, similar to.
$\min, \max$	`\min`, `\max`	Minimum and Maximum.
$\forall, \exists, \nexists$	`\forall`, `\exists`, `\nexists`	For all, (not) exists.
$\in, \notin$	`\in`, `\notin`	In/not in a set.
$\subset, \subseteq$	`\subset`, `\subseteq`	Being a subset of (or equal to) another set.
$\cup^{n}_{i=1}, \cap^{n}_{i=1}$	`\cup^{n}_{i=1}`, `\cap^{n}_{i=1}`	Union and Intersection.
$\emptyset$	`\emptyset`	The empty set.
$\perp$	`\perp`	Perpendicular/orthogonal to.
$\binom{n}{k}$	`\binom{n}{k}`	The binomial coefficient.
$\ldots, \cdots, \ddots, \vdots$	`\ldots`, `\cdots`, `\ddots`, `\vdots`	Various ellipses.

Table 3.3: Some important logical and set symbols.

Arrows and Braces The subsequent Table 3.4 shows different methods of making *arrows* and *braces*, possibly with text above/below them.

Function/Symbol(s)	Command(s)	Description
$\leftarrow, \rightarrow, \leftrightarrow$	`\leftarrow`, `\rightarrow`, `\leftrightarrow`	Single arrows.
$\Leftarrow, \Rightarrow$ ($\implies$), $\Leftrightarrow$	`\Leftarrow`, `\Rightarrow` (`\implies`), `\Leftrightarrow`	Double arrows.
$\xleftarrow[l]{u}, \xrightarrow[l]{u}, \xleftrightarrow[l]{u}$	`\xleftarrow[l]{u}`, `\xrightarrow[l]{u}`, `\xleftrightarrow[l]{u}`	Single arrows with labels.
$\xLeftarrow[l]{u}, \xRightarrow[l]{u}, \xLeftrightarrow[l]{u}$	`\xLeftarrow[l]{u}`, `\xRightarrow[l]{u}`, `\xLeftrightarrow[l]{u}`	Double arrows with labels.
$\overleftarrow{xyz}, \overrightarrow{xyz}$	`\overleftarrow{xyz}`, `\overrightarrow{xyz}`	Over-arrows.
$\overline{xyz}, \underline{xyz}$	`\overline{xyz}`, `\underline{xyz}`	Overline and Underline.
$\overbrace{xyz}^{abc}, \underbrace{xyz}_{abc}$	`\overbrace{xyz}^{abc}`, `\underbrace{xyz}_{abc}`	Overbrace and underbrace with labels.

Table 3.4: Arrows and braces in LaTeX.

Delimiters Simple *delimiters* can be typed directly in math mode (except the curly brackets {} that require `\{\}`), like

```
\begin{align*}
&\frac{1}{N}(1+\frac{n}{N}) & & [\ln|x|]_a^b & & \{x|f(x) \neq 0\}
\end{align*}
```

outputs

$$\frac{1}{N}(1+\frac{n}{N}) \qquad [\ln|x|]_a^b \qquad \{x|f(x)\neq 0\}$$

However, if the content inside the delimiters is too tall, then we can append `\left` and `\right` before the delimiters on both sides to match the height. Note that they must be balanced. For example,

```
\begin{equation*}
\left[p + a\left(\frac{n}{V}\right)^2\right](V-nb) = nRT
\end{equation*}
```

is rendered as

$$\left[p + a\left(\frac{n}{V}\right)^2\right](V-nb) = nRT$$

Exercise(s)

3.3) Try to type the following statements.

a) $\oint Mdx + Ndy = \iint(\frac{\partial N}{\partial x} - \frac{\partial M}{\partial y})dxdy$;

b) $\mu \ll \nu \Leftrightarrow \mu(A) = 0, \forall A|\nu(A) = 0$;

c) $A \subseteq B \cup (A \cap B^c)$.

3.2.3 Vectors and Matrices

Denoting Vectors The most essential object in linear algebra is undoubtedly *vectors*, and we need a standard way to denote and distinguish them. One possible solution is to use an overhead arrow: the command `\vec{v}` will output $\vec{v}$. For longer variables, we can instead use `\overrightarrow` introduced in the last subsection. Another approach is to use boldface, which can be applied to general mathematical symbols if we load the `bm` package: `\bm{v}` will then produce $\boldsymbol{v}$.

Unit Vectors For unit vectors, we often use the hat symbol to denote them, e.g. `\hat{v}` gives $\hat{v}$. Particularly, for the three-dimensional standard unit vectors $\hat{\imath}$, $\hat{\jmath}$, $\hat{k}$, we can type `\hat{\imath}`, `\hat{\jmath}`, and `\hat{k}`, where we use the versions `\imath`: $\imath$, `\jmath`: $\jmath$ without the usual dot at the top for placing the hat.

Matrices and Determinants: bmatrix, vmatrix Another class of objects closely related to vectors is *matrices*. To typeset a matrix in LaTeX, we use the `bmatrix` environment provided by the `amsmath` package. For example,

```
\begin{align*}
\begin{bmatrix}
1 & 2 & 3 \\
-4 & \sqrt{5} & c
\end{bmatrix}
\end{align*}
```

outputs

$$\begin{bmatrix} 1 & 2 & 3 \\ -4 & \sqrt{5} & c \end{bmatrix}$$

where & separates the entries into columns and `\\` marks the end of a row. By replacing `bmatrix` by `matrix`, `pmatrix`, or `Bmatrix`, the delimiters become none, round, and curly brackets correspondingly. Particularly, we have the `vmatrix` (vertical lines) group to represent determinants. For instance, writing

```
\begin{equation*}
\det(A) =
\begin{vmatrix}
a & b \\
c & d
\end{vmatrix} = ad-bc
\end{equation*}
```

leads to

$$\det(A) = \begin{vmatrix} a & b \\ c & d \end{vmatrix} = ad - bc$$

On top of that, we can manipulate the ellipses symbols to denote a matrix of an arbitrary shape. The following

```
\begin{equation*}
A_{m \times n} =
\begin{bmatrix}
a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\
a_{21} & a_{22} & a_{23} &        & a_{2n} \\
a_{31} & a_{32} & a_{33} &        & a_{3n} \\
\vdots &        &        & \ddots & \vdots \\
a_{m1} & a_{m2} & a_{m3} & \cdots & a_{mn}
\end{bmatrix}
\end{equation*}
```

produces

$$A_{m \times n} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & & a_{2n} \\ a_{31} & a_{32} & a_{33} & & a_{3n} \\ \vdots & & & \ddots & \vdots \\ a_{m1} & a_{m2} & a_{m3} & \cdots & a_{mn} \end{bmatrix}$$

A column vector can then be represented by a matrix consisting of a single column.

array For an advanced control of matrices, we can use the `array` environment instead. Let's first see how the code will look in the scenario of Gaussian Elimination, and then break down the details. Given

```
\begin{align*}
\left[\begin{array}{@{}wc{10pt}wc{10pt}wc{10pt}|r}
1 & 2 & 1 & -1 \\
2 & 5 & 3 & 2 \\
0 & 1 & 1 & 0
```

```
\end{array}\right]
& \to
\left[\begin{array}{@{}wc{10pt}wc{10pt}wc{10pt}|r}
1 & 2 & 1 & 1 \\
0 & 1 & 1 & 4 \\
0 & 1 & 1 & 0
\end{array}\right]
& & R_2 - 2R_1 \to R_2
\end{align*}
```

the output will be

$$\left[\begin{array}{@{}ccc|r}
1 & 2 & 1 & -1 \\
2 & 5 & 3 & 2 \\
0 & 1 & 1 & 0
\end{array}\right] \to \left[\begin{array}{@{}ccc|r}
1 & 2 & 1 & 1 \\
0 & 1 & 1 & 4 \\
0 & 1 & 1 & 0
\end{array}\right] \qquad R_2 - 2R_1 \to R_2$$

The `array` group places each entry just like the `matrix` one. However, notice the input string `{@{}wc{10pt}wc{10pt}wc{10pt}|r}` before the main content. `@{}` replaces the default left padding with an empty space. `wc` indicates the entries along that column to take a fixed width (`w`) of 10 pt and are centered (`c`). This is repeated for the first three columns to the left. A bar `|` then generates a vertical separating line at the desired location. (For a horizontal line, put `\hline` between the rows inside.) Finally, `r` makes the entries right-aligned (similarly there is `l`) in the last column with a flexible width, and we surround the `array` environment with tall delimiters (see last subsection) manually.

3.2.4 Other Formatting Trivia

abs, norm from physics The `physics` package provides many symbols well-known in the area of physics. Particularly, it defines `\abs{<expression>}` and `\norm{<expression>}` commands for absolute value and norm (length/magnitude), which are quite convenient even for other usages. For example,

```
$\norm{\bm{x}}_1 = \sum_{i=1}^n\abs{x_i}$
```

gives $\|\boldsymbol{x}\|_1 = \sum_{i=1}^{n} |x_i|$.

mathbb, mathcal Two other types of symbols that may be of interest come from `\mathbb{<character>}` and `\mathcal{<character>}` for sets and classes. For example, the set of all real numbers is commonly denoted by $\mathbb{R}$ (`\mathbb{R}`), while the class of continuously differentiable functions is denoted by $\mathcal{C}^1$ (`\mathcal{C}^1`).

siunitx For other science applications, the physical quantities involved are often accompanied by units. The `siunitx` package helps facilitate the typesetting of units and expressing the exponents. For example, `\si{\N} = \si{\kg \per \m \per \square \s}` is interpreted as $\mathrm{N} = \mathrm{kg\,m^{-1}\,s^{-2}}$, while `\SI{4.184e3}{\J \per \kg \per \K}` generates $4.184 \times 10^3\,\mathrm{J\,kg^{-1}\,K^{-1}}$.

System of Equations To typeset a system of equations, we can use either `aligned` with a large curly bracket to the left, or the `cases` environment. There will be slight differences between these two methods. For instance,

```
\begin{equation*}
\left\{\begin{aligned}
3x + 4y + 5z &= 6 \\
x - 2y + 3z &= -4 \\
x^2 + y^2 &= 1
\end{aligned}\right.
\end{equation*}
```

will produce (notice that we need `\right.` at the end to make a placeholder delimiter to the right for balance)

$$\left\{\begin{aligned}
3x + 4y + 5z &= 6 \\
x - 2y + 3z &= -4 \\
x^2 + y^2 &= 1
\end{aligned}\right.$$

Alternatively, we can write

```
\begin{equation*}
\begin{cases}
3x + 4y + 5z &= 6 \\
x - 2y + 3z &= -4 \\
x^2 + y^2 &= 1
\end{cases}
\end{equation*}
```

to achieve

$$\begin{cases} 3x + 4y + 5z &= 6 \\ x - 2y + 3z &= -4 \\ x^2 + y^2 &= 1 \end{cases}$$

As its name suggests, `cases` is actually designed to represent the values of a variable in different cases, e.g. we may write

```
\begin{equation*}
\begin{aligned}
y(x) =
\begin{cases}
1 & x \in \mathbb{Q} \\
0 & x \notin \mathbb{Q}
\end{cases}
\end{aligned}
\end{equation*}
```

to get

$$y(x) = \begin{cases} 1 & x \in \mathbb{Q} \\ 0 & x \notin \mathbb{Q} \end{cases}$$

Spacing in Math Mode In math mode, we often employ pre-defined commands instead of `\hspace` or `\vspace` to adjust the spacing. They are shown in Table 3.5 below.

Command	Description	Effect
`\quad`	Space of 1 em in the current math font size (= 18 mu)	$a \quad b$
`\qquad`	Double of `\quad` (= 36 mu)	$a \qquad b$
`\,`	3/18 of `\quad`/3 mu	$a \, b$
`\:`	4/18 of `\quad`/4 mu	$a \: b$
`\;`	5/18 of `\quad`/5 mu	$a \; b$
`\!`	−3/18 of `\quad`/−3 mu	$a \! b$
`\(space)`	Space as in normal text	$a \ b$

Table 3.5: Spacing commands in math mode.

Sizes We can control the font size in either math mode with the usual size commands in Table 2.2. For the inline mode, we can write something like

```
{\Large $N(0,1) \sim e^{-x^2/2}$}
```

to get $N(0,1) \sim e^{-x^2/2}$. On the other hand, for the display mode, we may put the size command before the math environment, e.g.

```
\footnotesize
\begin{align*}
\mathcal{L}[y^{(n)}](s) &= s^n Y(s) - s^{n-1}y(0) - s^{n-2}y'(0) - \
   cdots - y^{(n-1)}(0) \\
&= s^n Y(s) - \sum_{k=0}^{n-1} s^{(n-1)-k}y^{(k)}(0)
\end{align*}
\normalsize % back to default font size
```

will yield

$$
\begin{aligned}
\mathcal{L}[y^{(n)}](s) &= s^n Y(s) - s^{n-1}y(0) - s^{n-2}y'(0) - \cdots - y^{(n-1)}(0) \\
&= s^n Y(s) - \sum_{k=0}^{n-1} s^{(n-1)-k}y^{(k)}(0)
\end{aligned}
$$

mathcolor To apply colors in math mode, we can replace the `\textcolor` command with `\mathcolor`. For example,

```
\begin{align*}
\mathcolor{Blue}{\frac{\partial \vec{u}}{\partial t}} + \mathcolor{
   Green}{\vec{u}\cdot\nabla\vec{u}} = \mathcolor{Red}{\vec{F}}
\end{align*}
```

is displayed as

$$\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\nabla\vec{u} = \vec{F}$$

Exercise(s)

3.4) Reproduce the following output.

$$\begin{cases} x + 2y = 3 \\ x - 3y = -2 \\ -x + y = 1 \end{cases} \qquad \Leftrightarrow \qquad \begin{bmatrix} 1 & 2 \\ 1 & -3 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 3 \\ -2 \\ 1 \end{bmatrix} \tag{3.11}$$

Chapter 4

Various Special Structures in LaTeX

Introduction This chapter presents different special environments in LaTeX apart from the display math mode and verbatim form previously, such as lists, figures, tables, and minipages.

4.1 Lists

4.1.1 Unordered Lists

itemize The ability to organize things into a *list* is essential in any documenting system. In LaTeX, we can achieve this by using the `itemize` environment with the `\item` command. For example, if we write

```
\begin{itemize}
\item Canada
\item Japan \begin{itemize}
    \item Tokyo
    \item Kyoto
    \end{itemize}
\item Korea \begin{itemize}
```

```
    \item Seoul
    \item Pusan
    \end{itemize}
\end{itemize}
```

then it will show up as

- Canada
- Japan
  - Tokyo
  - Kyoto
- Korea
  - Seoul
  - Pusan

Notice that the list can be nested and the items are *unordered/bulleted*.

4.1.2 Ordered Lists

enumerate Similarly, we can have an *ordered/numbered* list by using the `enumerate` environment. For example, by typing

```
\begin{enumerate}
    \item A robot may not injure a human being ... % (continue)
    \item A robot must obey the orders given it by human ...
    \item A robot must protect its own existence ...
\end{enumerate}
```

we acquire the following outcome:

1. A robot may not injure a human being or, through inaction, allow a human being to come to harm.

2. A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.

3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.

It is also possible to have nested `enumerate` groups.

enumitem The `enumitem` package enhances the typesetting of lists. One of the prime utilities is to change the starting labels or bullets for every item by providing the `label` option. For example,

```
\begin{enumerate}[label=\alph*)]
    \item Apple
    \item Banana
    \item Grape
\end{enumerate}
```

generates

a) Apple

b) Banana

c) Grape

There are other possible choices for `label`, e.g. `\arabic*`, `\roman*`, `\Roman*`, `\Alph*`. Another usage of the `enumitem` package is to make a continued list. For example, by ticking the `resume*` option:

```
\begin{enumerate}[resume*]
    \item Watermelon
    \item Orange
\end{enumerate}
```

we have

d) Watermelon

e) Orange

4.2 Figures and Tables

4.2.1 Figures

figure, includegraphics To import figures into the document, we need to load the `graphics` package and then use the `\includegraphics{<file_name>}` command. Given that the image is placed under the project directory, we hereby go through an example which is displayed as Figure 4.1 on the next page. The code to produce that figure is

```
\begin{figure}[ht!]
\centering
\includegraphics[width=0.4\linewidth]{graphics/Ada_Lovelace_portrait.
    jpg} % replace the path with your own file
\caption{The portrait of Ada Lovelace.}
\label{fig:ada}
\end{figure}
```

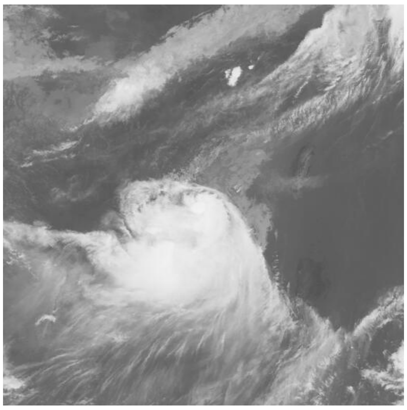
First, we need to enclose the `\includegraphics` command within a `figure` environment. The `ht!` option indicates that priority is given to put the figure structure exactly in the place where the code is inserted (`h`: here), or at the top of a page (`t`). The `width` option enforces the width of the image to the input value (and similarly there are `height` and `scale`). The `caption` command unsurprisingly generates the caption, while the `label` command works as it is in math mode and allows us to reference it by writing `\ref{fig:ada}`.

subcaption We can construct a set of subfigures within an overarching figure by utilizing the `subcaption` package and `subfigure` groups. To illustrate, the following code is deployed to generate Figure 4.2:

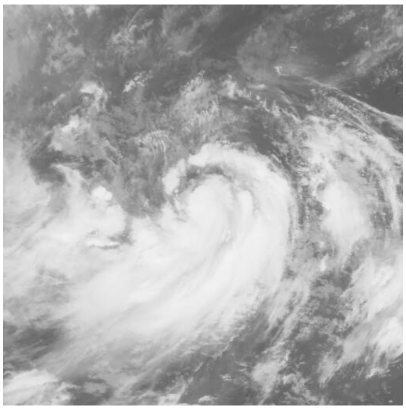
Figure 4.1: The portrait of Ada Lovelace.

```
\begin{figure}[ht!]
\centering
\begin{subfigure}[b]{0.45\textwidth}
\centering
\includegraphics[width=0.8\linewidth]{graphics/MTS108082203.200812.
   jpg}
\caption{Typhoon Nuri (2008).}
\end{subfigure}
\begin{subfigure}[b]{0.45\textwidth}
\centering
\includegraphics[width=0.8\linewidth]{graphics/MTS212072303.201208.
   jpg}
\caption{Typhoon Vicente (2012).}
\end{subfigure}
\caption{The infrared satellite images of various Tropical Cyclones
   affecting Hong Kong.}
\label{fig:TC1}
\end{figure}
```

The `b` option sets the vertical alignment of `subfigure` at the bottom.



(a) Typhoon Nuri (2008).



(b) Typhoon Vicente (2012).

Figure 4.2: The infrared satellite images of various Tropical Cyclones affecting Hong Kong. (Source: Digital Typhoon)

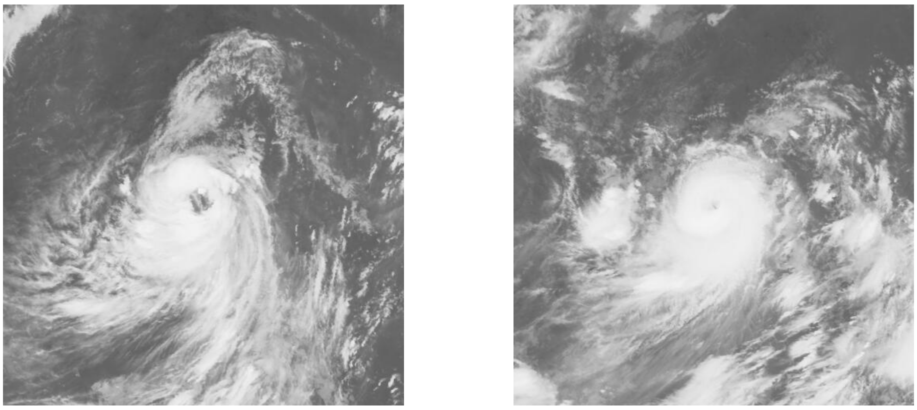
ContinuedFloat To make a longer figure of subfigures that spans multiple pages, we can simply arrange them into separate `figure` environments and call the `\ContinuedFloat` command in all the subsequent `figure` groups. Continuing from the last example, we may have

```
\begin{figure}[hb!]
\ContinuedFloat % here!
\caption{(Cont.) The infrared satellite images of various Tropical
   Cyclones affecting Hong Kong.}
\centering
\begin{subfigure}[b]{0.45\textwidth}
...
\caption{Typhoon Haima (2016).}
\end{subfigure}
...
\begin{subfigure}[b]{0.45\textwidth}
...
\caption{Typhoon Saola (2023).}
```

```
\end{subfigure}
\end{figure}
```

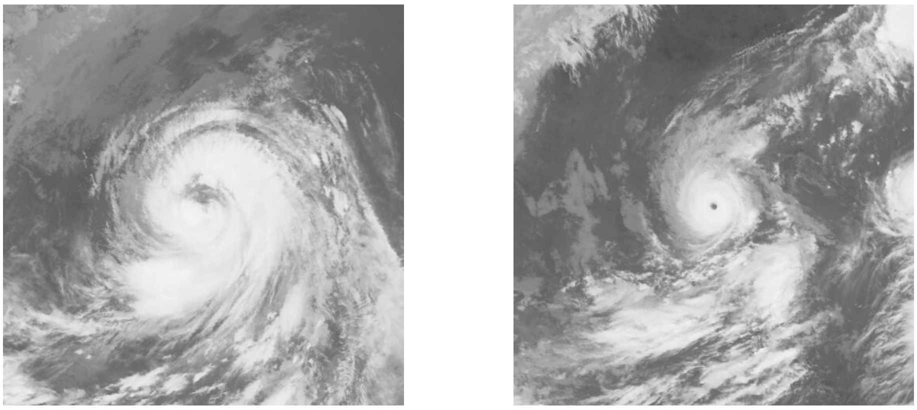
producing

Figure 4.2: (Cont.) The infrared satellite images of various Tropical Cyclones affecting Hong Kong.



(c) Typhoon Haima (2016).

(d) Typhoon Hato (2017).



(e) Typhoon Mangkhut (2018).

(f) Typhoon Saola (2023).

4.2.2 Tables

table, tabularx Just like embedding figures, building a table requires us to place the content inside the corresponding `table` environment. While it is possible to use the native `tabular` class for the actual table itself, a more powerful version is provided by the `tabularx` package and its class that bears the same name. This is demonstrated via Table 4.1 thereafter, which is generated by

```
\begin{table}[ht!]
\centering
\begin{tabularx}{\textwidth}{|l|p{0.55\textwidth}|>{\raggedleft}X|>{\
   raggedleft\arraybackslash}X|}
\hline
Unit & Description & Attack & Defense \\
\hline
Infantry & The most basic unit and backbone of any army, all-around
   abilities with a cheap cost. & 20 & 25 \\
\hline
Cavalry & The shock unit in an army with very strong power. & 40 & 30
    \\
\hline
Artillery & The support unit that provides bombardment support from
   far away. & 30 & 5 \\
\hline
\end{tabularx}
\caption{The unit statistics table for a hypothetical game.}
\label{tab:armyunits}
\end{table}
```

The `ht!` option, `caption`, and `label` work exactly as the figure counterpart. For the `tabularx` group, the first argument indicates the width of the entire table, set to `\textwidth` here. The second argument `{|l|p{0.55\textwidth}|>{\raggedleft}X|>{\raggedleft\arraybackslash}X|}` indicates the justification of the columns: the first column is left-aligned (`l`, similarly we have `c` and `r`) and its size will fit the text; the second column (`p`) forces a width of 0.55

Unit	Description	Attack	Defense
Infantry	The most basic unit and backbone of any army, all-around abilities with a cheap cost.	20	25
Cavalry	The shock unit in an army with very strong power.	40	30
Artillery	The support unit that provides bombardment support from far away.	30	5

Table 4.1: The unit statistics table for a hypothetical game.

times `\textwidth`; the remaining width is distributed evenly to last two columns (`X`). The part of `>{\raggedleft}` is applied to the `X` columns, making them right-aligned.[1] Finally, `|` and `\hline` produce vertical/horiztonal separating lines; `&` slices between the columns and `\\` marks the end of a row.

Also, note that `\ContinuedFloat` can also be applied to `table`.

captionbeside It is also possible to arrange the table so that the caption appears to the side of it. This is done by stacking the `captionbeside` environment provided by KOMA-script. For example, the code

```
\begin{table}[ht]
\begin{captionbeside}{This caption appears to the left of the
   Fibonacci numbers table.}[l][\textwidth]{
\adjustbox{valign=t}{
    \begin{tabularx}{0.4\textwidth}{|X|X|}
    \hline
    $n$ & $F_n$ \\
    \hline
    $1$ & $1$ \\
    \hline
    $2$ & $1$ \\
```

[1] `\arraybackslash` is needed in the last column, see TEX StackExchange 372464.

```
    \hline
    $3$ & $2$ \\
    \hline
    $4$ & $3$ \\
    \hline
    $5$ & $5$ \\
    \hline
    $6$ & $8$ \\
    \hline
    \end{tabularx}}
}
\end{captionbeside}
\label{tab:fib}
\end{table}
```

produces Table 4.2 below.

Table 4.2: This caption appears to the left of the Fibonacci numbers table.

n	F_n
1	1
2	1
3	2
4	3
5	5
6	8

We fill the caption in the first argument, followed by the relative position of the caption (`l`: left) and the full width of the structure, finally with the actual `tabularx` object. We also have to additionally load the `adjustbox` package and use the corresponding command to tell the table to align itself at the top (`valign=t`). This also requires us to first set the `\KOMAoptions` to take `captions=besidetop` (likewise we have `captions=besidebottom` and more).

Shared Numbering between Figures and Tables Sometimes we may want to share the numbering between *floats* (including figures, tables, and so on). This is done by the following patch that can be inserted into the preamble:

```
\makeatletter
\let\c@table\c@figure
\let\ftype@table\ftype@figure
\makeatother
```

This involves the primitive TEX functions, so we will not discuss them there. For more information, read StackOverflow 3865036, and TEX StackExchange 8351 for what the `\makeatletter` and `\makeatother` commands do.

Exercise(s)

4.1) Try to import and load your favorite image into the document.

4.2) Recreate any one of the tables in Chapter 3.

4.3 Minipages and Multiple Columns

minipage Sometimes we may want to partition the content into smaller blocks that are embedded within the current page, and can be placed or ordered (e.g. parallel) in the way we want. The `minipage` environment basically acts like a more versatile version of a `parbox` environment and serves this purpose. For example, something like

```
yields \par
\begin{center}
\begin{minipage}[b]{0.48\textwidth}
\lipsum[6]
\end{minipage}
\hfill
\begin{minipage}[b]{0.48\textwidth}
\lipsum[7]
\end{minipage}
\end{center}
```

yields

Suspendisse vel felis. Ut lorem lorem, interdum eu, tincidunt sit amet, laoreet vitae, arcu. Aenean faucibus pede eu ante. Praesent enim elit, rutrum at, molestie non, nonummy vel, nisl. Ut lectus eros, malesuada sit amet, fermentum eu, sodales cursus, magna. Donec eu purus. Quisque vehicula, urna sed ultricies auctor, pede lorem egestas dui, et convallis elit erat sed nulla. Donec luctus. Curabitur et nunc. Aliquam dolor odio, commodo pretium, ultricies non, pharetra in, velit. Integer arcu est, nonummy in, fermentum faucibus, egestas vel, odio.

Sed commodo posuere pede. Mauris ut est. Ut quis purus. Sed ac odio. Sed vehicula hendrerit sem. Duis non odio. Morbi ut dui. Sed accumsan risus eget odio. In hac habitasse platea dictumst. Pellentesque non elit. Fusce sed justo eu urna porta tincidunt. Mauris felis odio, sollicitudin sed, volutpat a, ornare ac, erat. Morbi quis dolor. Donec pellentesque, erat ac sagittis semper, nunc dui lobortis purus, quis congue purus metus ultricies tellus. Proin et quam. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Praesent sapien turpis, fermentum vel, eleifend faucibus, vehicula eu, lacus.

The `[b]` option indicates the baseline is set at the bottom, and hence the two blocks will be bottom-aligned, provided that their width is fixed to 0.48 times `\textwidth` and thus they fit in the main text area.

parcolumns The `parcolumns` package can also achieve the above effect and is more specialized for typesetting different pieces in two or more parallel columns. It also supports page breaks. Using the same example, we can write

```
\begin{parcolumns}{2}
\colchunk[1]{\lipsum[6]}
\colchunk[2]{\lipsum[7]}
\colplacechunks
```

```
\colchunk[1]{\lipsum[8]}
\colchunk[2]{\lipsum[9]}
\end{parcolumns}
```

to get

Suspendisse vel felis. Ut lorem lorem, interdum eu, tincidunt sit amet, laoreet vitae, arcu. Aenean faucibus pede eu ante. Praesent enim elit, rutrum at, molestie non, nonummy vel, nisl. Ut lectus eros, malesuada sit amet, fermentum eu, sodales cursus, magna. Donec eu purus. Quisque vehicula, urna sed ultricies auctor, pede lorem egestas dui, et convallis elit erat sed nulla. Donec luctus. Curabitur et nunc. Aliquam dolor odio, commodo pretium, ultricies non, pharetra in, velit. Integer arcu est, nonummy in, fermentum faucibus, egestas vel, odio.

Sed commodo posuere pede. Mauris ut est. Ut quis purus. Sed ac odio. Sed vehicula hendrerit sem. Duis non odio. Morbi ut dui. Sed accumsan risus eget odio. In hac habitasse platea dictumst. Pellentesque non elit. Fusce sed justo eu urna porta tincidunt. Mauris felis odio, sollicitudin sed, volutpat a, ornare ac, erat. Morbi quis dolor. Donec pellentesque, erat ac sagittis semper, nunc dui lobortis purus, quis congue purus metus ultricies tellus. Proin et quam. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Praesent sapien turpis, fermentum vel, eleifend faucibus, vehicula eu, lacus.

Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Donec odio elit, dictum in, hendrerit sit amet, egestas sed, leo. Praesent feugiat sapien aliquet odio. Integer vitae justo. Aliquam vestibulum fringilla lorem. Sed neque lectus, consectetuer at, consectetuer sed, eleifend

Morbi luctus, wisi viverra faucibus pretium, nibh est placerat odio, nec commodo wisi enim eget quam. Quisque libero justo, consectetuer a, feugiat vitae, porttitor eu, libero. Suspendisse sed mauris vitae elit sollicitudin malesuada. Maecenas ultricies eros sit amet ante. Ut venenatis velit. Maecenas sed ac, lectus. Nulla facilisi. Pellentesque eget lectus. Proin eu metus. Sed porttitor. In hac habitasse platea dictumst. Suspendisse eu lectus. Ut mi mi, lacinia sit amet, placerat et, mollis vitae, dui. Sed ante tellus, tristique ut, iaculis eu, malesuada ac, dui. Mauris nibh leo, facilisis non, adipiscing quis, ultrices a, dui.

mi eget dui varius euismod. Phasellus aliquet volutpat odio. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Pellentesque sit amet pede ac sem eleifend consectetuer. Nullam elementum, urna vel imperdiet sodales, elit ipsum pharetra ligula, ac pretium ante justo a nulla. Curabitur tristique arcu eu metus. Vestibulum lectus. Proin mauris. Proin eu nunc eu urna hendrerit faucibus. Aliquam auctor, pede consequat laoreet varius, eros tellus scelerisque quam, pellentesque hendrerit ipsum dolor sed augue. Nulla nec lacus.

where the first argument of the environment clearly indicates the number of columns and the `\colplacechunks` command releases the loaded `\colchunk[<col_no.>]` and goes to the next paragraph.

multicol A task closely related to what `parcolumns` does above is to typeset a single, continuous stream of text along multiple columns, like in many academic papers. The `multicol` package is designed for this and will carry out the automatic splitting. For example, by encapsulating the text inside the `multicols` environment as

```
\begin{multicols}{2}
Zhuge Liang (born 181, Yangdu [now Yinan, Shandong province], China--
   died August 234, Wuzhangyuan [now in Shaanxi province], China) was
    a celebrated adviser to Liu Bei, founder of the Shu-Han dynasty
   (221--263/264).
...
```

```
A mechanical and mathematical genius, Zhuge is credited with
   inventing a bow for shooting several arrows at once and with
   perfecting the Eight Dispositions, a series of military tactics.
   In the Sanguozhi yanyi (Romance of the Three Kingdoms), the great
   14th-century historical novel, Zhuge is one of the main characters
   ; he is portrayed as being able to control the wind and foretell
   the future.
\end{multicols}
```

(again with the number of columns indicated in the first argument) we may acquire the following layout:

Zhuge Liang (born 181, Yangdu [now Yinan, Shandong province], China–died August 234, Wuzhangyuan [now in Shaanxi province], China) was a celebrated adviser to Liu Bei, founder of the Shu-Han dynasty (221–263/264).

Quick Facts:
Wade-Giles romanization: Chu-ko Liang
Courtesy name: Kongming
Born: 181, Yangdu [now Yinan, Shandong province], China
Died: August 234, Wuzhangyuan [now in Shaanxi province], China (aged 53)

Zhuge, to whom supernatural powers often are ascribed, has been a favoured character of many Chinese plays and stories. Legend states that Liu Bei, then a minor military figure, heard of Zhuge Liang's great wisdom and came three times to the wilderness retreat to which Zhuge had retired to seek him out as an adviser. It is known that Zhuge helped Liu organize a large army and found a dynasty. Liu was so impressed with Zhuge's wisdom that on his deathbed Liu urged his son to depend on Zhuge's advice and urged Zhuge to ascend the throne himself if the prince were unable to rule. Some historical accounts indicate that Zhuge died from illness while leading a military campaign in 234.

A mechanical and mathematical genius, Zhuge is credited with inventing a bow for shooting several arrows at once and with perfecting the Eight Dispositions, a series of military tactics. In the Sanguozhi yanyi (Romance of the Three Kingdoms), the great 14th-century historical novel, Zhuge is one of the main characters; he is portrayed as being able to control the wind and foretell the future. (Source: Encyclopaedia Britannica)

twocolumn We can also pass the `twocolumn=true` option to `\KOMAoptions` to demand the entire book to be formatted in two columns globally. However, note that it will greatly mess up the layout of this book. (The decision to adopt such a format should be made at an early time!)

Chapter 5

Self-defined Commands and Environments

Introduction This chapter concerns the possibility for users to define new commands and environments in LaTeX, by leveraging flow control just like any other programming language.

5.1 Self-defined Commands

newcommand* The main way to define our own commands (*macros*) is to invoke the `\newcommand*{<command_name>}[<no._arg>]{<code>}`[1] statement. The necessity arises mainly when we want to repeatedly apply the same action, in addition to ensuring code readability and maintenance. Now, let's see a simple example of highlighting keywords in a particular style:

```
\newcommand*{\mykeyword}[1]{\textcolor{Red}{\textbf{#1}}}
```

[1]There is an unstarred version, but just sticking to the starred version will be adequate.

This definition can be put either in the preamble (preferable) or any suitable location in the main document. Writing `\mykeyword{Attention!}` then gives **Attention!** The `#1` part indicates where the first argument will go during the code execution, and the logic is similar when there are multiple arguments. Remember that when calling any command, each argument requires exactly one pair of curly brackets to receive it.

Optional Arguments As in many programming languages, there can also be optional arguments that may come with a default value when defining a command. The syntax will become `\newcommand*{<command_name>}[<no._arg>][<default_value>]{<code>}`. For example, if we define

```
\newcommand*{\homoeqn}[2][0]{$f(#2x,#2y) = #2^{#1}f(x,y)$}
```

Then `\homoeqn{t}` gives $f(tx, ty) = t^0 f(x, y)$ while `\homoeqn[1]{s}` gives $f(sx, sy) = s^1 f(x, y)$. When interpreting indices in the code statement, optional arguments will take precedence over the compulsory arguments. In this case, `#1` represents the optional argument with the default value of 0, which has been overridden by the new option 1 within the square brackets during the second call.

renewcommand* If we want to edit a command that is already defined by us or another package, we will need to use the `\renewcommand*` statement to properly update and overwrite the original command. Its has the same format as `\newcommand*`. Using the same example, we can write

```
\renewcommand*{\mykeyword}[1]{\textcolor{Green}{\textit{\textbf
    {#1}}}}
```

Writing `\mykeyword{Okay!}` now then gives ***Okay!***

Exercise(s)

5.1) Create a command that takes two arguments and outputs a sentence in the form of: There are `<no._of_population>` (comma-separated) people in `<city>`. The `\num[group-separator={,}]` command by the `siunitx` package will be useful for processing the first argument. Try to execute it multiple times with different inputs.

5.2 Flow Control

5.2.1 If-then-else Statements

ifthen Commands/functions are rather boring if there is no constraint or checking imposed. As you probably know, *if-then-else* statements are one of the major flow control constructs in all programming languages, and LaTeX is no exception. With these, we can produce more complex outcomes with commands. While there are primitive TeX syntax such as `\if` and `\else` for that, it is easier and more natural (at least in my opinion) if we use the verbose `\ifthenelse` construct provided by the `ifthen` package. The format is

```
\ifthenelse{<boolean_test>}{<then clause>}{<else clause>}
```

The first argument contains a test that evaluates to some *boolean* value (true or false). If the test returns true, then the "then clause" in the second argument is executed. Otherwise, if it is false, then the "else clause" in the third argument is executed instead. The most basic test is to compare two quantities, and here is a very simple example: if we type

```
\ifthenelse{1 > 2}{Preposterous!}{Of course not...}
```

we should see "Of course not...".

pgfmath When designing a boolean test for the `\ifthenelse` statement above, we often need a way to compute the results of math expressions for comparison. The native TEX does offer some commands such as `\numexpr` or `\dimexpr` for that, but here we will utilize the `pgfmath` package to parse math expressions. The usage mainly takes the form of `\pgfmathparse{<expression>}`. For instance, `\pgfmathparse{2+2}\pgfmathresult` returns 4.0 where the `\pgfmathresults` command stores the last value processed and prints it out. Alternatively, we can save it to a macro by `\pgfmathsetmacro{<macro>}{<expression>}`. Using the same example, we can write something like

```
\pgfmathsetmacro{\myans}{2+2}
```

typing `\myans` then gives 4.0.

To learn more about how a `pgfmath` expression should be formatted, see https://tikz.dev/math-parsing.

lengthtest Subsequently, we can design a command that checks equality and looks like

```
\newcommand*{\myequal}[2]{\pgfmathsetmacro{\Lhs}{#1}\pgfmathsetmacro
   {\Rhs}{#2}% <- this % is needed to consume the spacing
\ifthenelse{\lengthtest{\Lhs pt = \Rhs pt}}{#1 is equal to #2}{#1 is
   not equal to #2.}}
```

Typing `\myequal{2*3}{6}` then outputs "2*3 is equal to 6" as expected. Notice that in the `ifthenelse` boolean test, we have not directly done the naive comparison as `\Lhs = \Rhs`. This is because the original method only handles integers, but the `pgfmath` calculation produces float numbers. To circumvent this, we must use the `\lengthtest` command, which is designed to compare decimal dimensions, and we will only need to add the same length unit to both sides. (TEX StackExchange 84625)

\AND, \OR, \NOT In an `ifthenelse` test, we may need to compose different booleans using logical operators. There are the self-explanatory `\AND`, `\OR`, and `\NOT` for that. As a demonstration,

```
\ifthenelse{\NOT \(1 = 2\) \AND \(0 = 0\)}{These make sense!}{What?}
```

gives "These make sense!". We enclose each smaller test with `\( \)`. Note that there is no precedence rule in `ifthen` and the evaluation goes from left to right straightly, except when using `\( \)`.

equal, isundefined There are two other boolean tests that can be helpful: `\equal{<string>}{<string>}` and `\isundefined{<command_name>}`, which check whether two strings are equal and if a command exists, respectively. A quick use is to determine if a string is empty by `\equal{<string>}{}`.

5.2.2 For Loops

pgffor Another essential type of flow control is *for loops*, which repeatedly execute a code block over some range of values. The `pgffor` offers this functionality with the `\foreach` construct. The format goes like

```
\foreach \<variable> in {<range>} {
    % do something
}
```

A toy example will be

```
\foreach \x in {5,...,1} {
    \\ \x!}
Time is up! \\
```

that outputs

5!

4!

3!
2!
1! Time is up!
The `{5, ..., 1}` part is a shorthand for `{5, 4, 3, 2, 1}` and it also works for ascending order or other patterns.[2]

We can also simultaneously loop over multiple variables by separating them with `/`, for example:

```
\foreach \y/\z in {1/2, 2/3, 3/5, 4/7} {
    \\ Prime $\y \rightarrow \z$}
```

produces
Prime $1 \rightarrow 2$
Prime $2 \rightarrow 3$
Prime $3 \rightarrow 5$
Prime $4 \rightarrow 7$

Nested Loops Moreover, we can produce nested loops as in other programming languages. For instance, the block

```
\foreach \ii in {0,...,2} {\\%
    \foreach \jj in {1,...,4} {%
    (\ii, \jj)%
    }
}
```

will generate the following pattern:
(0, 1)(0, 2)(0, 3)(0, 4)
(1, 1)(1, 2)(1, 3)(1, 4)
(2, 1)(2, 2)(2, 3)(2, 4)

[2]For a general discussion, see TEX StackExchange 142188.

count When iterating over a range of values, the corresponding index can be saved into a variable as `count`. For example, the previous example of printing out the first four primes can be replaced by the following equivalent snippet:

```
\foreach \z [count=\y] in {2, 3, 5, 7} {
    \\ Prime $\y \rightarrow \z$}
```

evaluate Also, in a `\foreach` loop, calculations can be applied over the iterated variable by the `evaluate` option. As an illustrative example, this loop

```
\foreach \x [evaluate=\x as \y using \x^2] in {1,...,10} {
    \\ $\x ^2 = \y$}
```

readily outputs
$1^2 = 1.0$
$2^2 = 4.0$
$3^2 = 9.0$
$4^2 = 16.0$
$5^2 = 25.0$
$6^2 = 36.0$
$7^2 = 49.0$
$8^2 = 64.0$
$9^2 = 81.0$
$10^2 = 100.0$

remember Another feature of a `\foreach` loop is the `remember` option, which stores the current variable and recalls it in the next iteration. Stealing the example from the **PGF** User Manual:

```
\foreach \x [remember=\x as \lastx (initially A)] in {B,...,H}{\lastx
   $\to$\x, }
```

produces A→B, B→C, C→D, D→E, E→F, F→G, G→H, in the expected order.

breakforeach An important component of any for loop is the ability to *break* it given some certain condition. This is done by the `\breakforeach` command. This will be used in combination with an `\ifthenelse` statement. For example, the code snippet

```
\foreach \x in {1,...,100} {%
\ifthenelse{\NOT \(\x = 13\)}{\x, }{13 is an unlucky number! Stop! \
    breakforeach}
}
```

outputs 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, Wait, 13 is an unlucky number! Stop!

Exercise(s)

5.2) Define a command that converts Celsius temperature to Fahrenheit and prints a warning if the Fahrenheit temperature is higher than 100 degrees.

5.3) By manipulating all the tools introduced in this chapter, efficiently imitate the following outputs. The `int` and `Mod` operators for `pgfmath` will be useful.

1 is not divisible by 3. 1 is not divisible by 5.
2 is not divisible by 3. 2 is not divisible by 5.
3 is divisible by 3. 3 is not divisible by 5.
4 is not divisible by 3. 4 is not divisible by 5.
5 is not divisible by 3. 5 is divisible by 5.
6 is divisible by 3. 6 is not divisible by 5.
7 is not divisible by 3. 7 is not divisible by 5.
8 is not divisible by 3. 8 is not divisible by 5.
9 is divisible by 3. 9 is not divisible by 5.
10 is not divisible by 3. 10 is divisible by 5.
11 is not divisible by 3. 11 is not divisible by 5.
12 is divisible by 3. 12 is not divisible by 5.

13 is not divisible by 3. 13 is not divisible by 5.
14 is not divisible by 3. 14 is not divisible by 5.
15 is divisible by both 3 and 5.
16 is not divisible by 3. 16 is not divisible by 5.
17 is not divisible by 3. 17 is not divisible by 5.
18 is divisible by 3. 18 is not divisible by 5.
19 is not divisible by 3. 19 is not divisible by 5.
20 is not divisible by 3. 20 is divisible by 5.

5.3 Self-defined Environments

newenvironment* Similarly, we can also define our own environments by the `\newenvironment*{env_name}{begin}{end}` method. `begin`/`end` stores the code to be run before the start/after the end of the new environment. For example, by defining

```
\newenvironment*{mylargeblueeqn}{\color{Blue}\LARGE\begin{equation
  }}{\end{equation}}
```

[3] Then writing

```
\begin{mylargeblueeqn}
1+1 = 2
\end{mylargeblueeqn}
```

displays the expected blue, magnified equation:

$$1+1=2 \tag{5.1}$$

[3] Note that replacing `equation` with `align` instead will throw an error, read TEX StackExchange 236664.

renewenvironment* There is also the concurrent `\renewenvironment*` for renewing the definition of an environment. However, we seldom need to (re)define an environment on our own: In a math document, the interface provided by the `tcolorbox` package (see Chapter ??) will fulfill most of the usages. So we will keep this section short.

Chapter 6

More on Book Layout Design

Introduction This chapter will go into the details about designing and refining the layout of a LaTeX book, including how to edit the page style with running headers/footers, chapter/section headings, a good-looking title page, and more.

6.1 Page Configuration

6.1.1 Some Universal Settings for the Pages

twoside In a printed book, there will be a distinction between odd (right) and even (left) pages, i.e. *two-sided*, whereas an electronic PDF document is usually *one-sided* and has no such issue. To choose one of these configurations in a `scrbook`, we can change the `twoside` parameter in `\KOMAoptions` to `false`, `semi`, or `true`. Unsurprisingly, `false` indicates one-sided and `true` means two-sided. Being two-sided means that there will be a difference between the inner/outer margins, with the outer margin (left/right on even/odd pages) occupying two times the space as the inner one. The running headers on odd and even pages will also show the current section/chapter differently.

In this book, the `twoside` option is set to `semi` by adding `\KOMAoptions{twoside=semi}`. This retains equal margins as if the document is one-sided, but the headers will switch alternately just like two-sided.

DIV The extent of the type area in pages is controlled by the `DIV` factor passed to `\KOMAoptions`. The higher the value of `DIV`, the larger the fraction of the main text area and the smaller the margins. The reference value of `DIV` usually ranges from 9 to 12. However, we can delegate the calculation of an optimal `DIV` by setting `DIV` to either `calc` or `classic`. If a new font is loaded, it is also desirable to recalculate an appropriate type area by calling `\KOMAoptions{DIV=last}` that reuses the same setting.

linespread Finally, to control the *line spread* in the main text, just add `\linespread{<value>}`. Here it is set to 1.25.

6.1.2 Page Style

Headers and Footers A very important part of a page is its *header* and *footer*. Editing the content within a header/footer requires us to load the `scrlayer-scrpage` package. The default page style for the main content in the book is invoked by `\pagestyle{scrheadings}`. We can refer the inner/center/outer header/footer via `ihead`, `chead`, `ohead`, `ifoot`, `cfoot`, and `ofoot` correspondingly. For example, the default page number is put at the outer footer, and this book has moved it to the center footer by declaring:

```
\pagestyle{scrheadings}
\ofoot*{}
\cfoot*{\pagemark}
```

where the variable `\pagemark` stores the page number in `scrbook`.

There is also a finer division between even/odd pages for headers/footers: `lehead`, `cehead`, `rehead`, `lohead`, `cohead`, `rohead`, where `l`, `c`, `r` stand for left/center/right, and `e`, `o` represent even and odd respectively. If we want to swap the chapter and section in the even/odd-paged headers, we can write something like

```
\lehead*[]{\rightmark}
\rohead*[]{\leftmark}
```

The optional argument will be applied to the chapter page (more accurately, the *plain* page style), and is left empty as in the default setting. The `\leftmark` and `\rightmark` hold the original left/right headers, the depth of which is controlled by

```
\automark[section]{chapter} % [right]{left}
```

setkomafont Now we will further customize the font style and color of our header by the command `\setkomafont{<element>}{<commands>}`. As its name suggests, it applies commands to set up a certain element in a page. For headers, the corresponding alias is `pagehead`, and in this book, we have

```
\setkomafont{pagehead}{\color{RoyalBlue}\slshape\bfseries}
```

Many other elements can be changed as well, including `chapter`, `section`, `footnote`, `caption`, `pagefoot`, and so on.

headsepline The separating line under the header is added via passing the switch `headsepline=on` to `\KOMAoptions`. We similarly have `footsepline`.

chaptermarkformat Sometimes we may want to change the chapter label in the header too. This is done by applying `\renewcommand*` to `\chaptermarkformat`. In this book, we have

```
\renewcommand*{\chaptermarkformat}{\chapapp~\thechapter\autodot~--~}
   % ~ occupies a space, -- is a dash
```

`\chapapp` stores the word "Chapter", `\thechapter` contains the current chapter counter, and `\autodot` is empty, reserved for an extra dot after any chapter/section numbering. As you may have guessed, there is also `\sectionmarkformat`.

Exercise(s)

6.1) Edit the page style to make your own header and footer.

6.2 Appearance of Chapters and Sections

chapterprefix, chapterformat We can single out the chapter number as a prefix in the chapter title by setting `chapterprefix=true` in `\KOMAoptions`. Furthermore, we can customize it by `\addtokomafont` which behaves similarly as `\setkomafont`:

```
\addtokomafont{chapterprefix}{\itshape\color{white}}
```

In addition, we can again call `\renewcommand*` to manipulate `\chapterformat`. In this book, the following code is adopted:

```
\renewcommand*{\chapterformat}{\raggedleft\colorbox{RoyalBlue}{\
    parbox[b][2.8em]{2.8em}{\vfill\centering{\large\chapapp}\\[-0.4em
    ]\thechapter\vfill}}}
```

sectionformat In the same way, we have `\sectionformat` that can be edited for section headings. The code to produce the white section number in a black box is

```
\renewcommand*{\sectionformat}{\colorbox{black}{\textcolor{white}{\
    thesection}}\enskip}
```

where `\enskip` denotes a space as wide as half an em.

sectionlinesformat Meanwhile, the black line under the section headings is governed by `\sectionlinesformat`. It has to accept 4 arguments, where only the third (section number) and the last (section name) will be relevant here:

```
\renewcommand*{\sectionlinesformat}[4]{\makebox[0pt][l]{\rule[-\
   fboxsep]{\textwidth}{1pt}}#3\parbox[b]{0.85\textwidth}{\linespread
   {1}\selectfont#4}}
```

The `makebox` command creates an artificial empty box that does not occupy any width (0 pt) and contains the desired separating line (`\rule` with a length of `\textwidth`). It is vertically offset downwards by `\fboxsep` to compensate for the padding around the black numbering box (`#3`) that follows, defined via `\sectionformat` above. The section name (`#4`) is subsequently wrapped by a `\parbox` that is bottom-aligned and can account for any title longer than one line.

chapterheadendvskip While there is also the `\chapterlinesformat` command for making a line below the chapter title, we can achieve more by tackling `\chapterheadendvskip` instead. It controls the stuff (usually some vertical skip) that occurs after a chapter heading. For aesthetics, we will load the `pgfornament` package that supplies many beautiful visual patterns. Then, we can write

```
\renewcommand*{\chapterheadendvskip}{\pgfornament[width=\textwidth
   ]{88}\par} % the 88th ornament
```

to achieve the layout present in the book.

chapterheadstartvskip There exists the `\chapterheadstartvskip` counterpart for anything before the chapter title as well. The default vertical space above the chapter heading may be too much, and we can shorten it via

```
\renewcommand*{\chapterheadstartvskip}{\addvspace{2em}}
```

`\addvspace` is a variant of `\vspace`, which is a kind of rubber length: it adds just enough vertical space so that the total space is as large as the input length if the existing space is shorter than that, and does nothing when it is already long enough.

sfdefaults As you may notice, the chapter/section headings are written in sans-serif. To change this, we can set `sfdefaults` to `no` in `\KOMAoptions`. We can also mark up text with `\textmaybesf{<text>}` that is toggled by `sfdefaults` too.

6.3 Title Page and Front/Back Matter

Title Page The easiest way to generate a *title page* is to simply use the `\maketitle` command. Just enter the book (sub)title, author name, and the like in the preamble using the corresponding commands, for example:

```
\title{How to Reproduce this Book Exactly with \LaTeX}
\subtitle{A Self-contained Tutorial on Writing Mathematical Notes}
\author{C.~L.~Loi}
```

and maybe `\date` and `\publishers`, etc. Then calling `\maketitle` will automatically build a title page for you. In addition, the `titlepage` switch in `\KOMAoptions` can decide if it is embedded in-page. However, it is more flexible to design our own title page using the `titlepage` environment. In this book, we have adopted:

```
\begin{titlepage}
\parbox{0.7\textwidth}{\Huge\raggedright\textbf{\textmaybesf{How to
   Reproduce this Book Exactly with \LaTeX}}}\par
\vspace{2mm}
\parbox[b]{0.9\textwidth}{\large\raggedright\textit{A Self-contained
   Tutorial on Writing Mathematical Notes}}
\hfill\textcolor{RoyalBlue}{\rule{3mm}{3mm}}\par
```

```
\vspace{4mm}\hrule\par
{\Large\raggedleft\textmaybesf{v1.0.0}\hfill C.~L.~Loi\par}
\vfill
{\large\raggedleft A student from \\
CUHK-EESC/NTU-AS\par}
\end{titlepage}
```

Front/Main/Back Matter Usually in a book, there will be *front matter* (title page, preface, table of contents) and *back matter* (bibliography, index). To mark them, just write `\frontmatter` and `\backmatter` in front of the corresponding parts. We also have `\mainmatter` for transitioning to the main content. So it should look like

```
\frontmatter
\include{ch0}

\mainmatter
\include{ch1_basic_structure}
...
```

`\frontmatter` will use Roman page numbering, and `\mainmatter` will switch it back to the normal Arabic numbering. We can also manually do this by

```
\pagenumbering{roman}
...
\cleardoubleoddpage
\pagenumbering{arabic}
```

The `\cleardoubleoddpage` command is needed to properly flush the page.

lowertitleback, uppertitleback Sometimes we may want to put a copyright statement or other information at the back of the title page. If we choose to create the title page by the `\maketitle` method, then we can simply supply the `\lowertitleback` or `\uppertitleback` command, e.g. for this book:

```
\lowertitleback{"How to Reproduce this Book Exactly with \LaTeX"\\
Copyright, C.~L.~Loi, 2025. All rights reserved.}
```

However, if the title page is designed manually, then we may instead write, after it:

```
\thispagestyle{empty}
\vspace*{\fill}
"How to Reproduce this Book ... All rights reserved.
```

`\thispagestyle{empty}` selects the `empty` page style for just this one page.

Exercise(s)

6.2) Design your own title page.

6.4 Footnotes and Markings

(Line numbers?)

6.4.1 Footnotes

Footnotes The basic way to add a footnote like this[1] is to use the `\footnote{<text>}` command, as

```
The basic way to add a footnote like this\footnote{This is a simple
   footnote that is directly inserted after the desired location.} is
    ...
```

Another way is to use the `\footnotemark` `\footnotetext` pair like this[2]

[1] This is a simple footnote that is directly inserted after the desired location.

```
Another way is to use the \texttt{\textbackslash footnotemark} \
    texttt{\textbackslash footnotetext} pair like this\footnotemark{}
...
where we can put the text anywhere after the mark.\footnotetext{This
    footnote by \texttt{\textbackslash footnotetext} will
    automatically be traced to the latest texttt{\textbackslash
    footnotemark}.}
```

where we can put the text anywhere after the mark.

Multiple Footnote Marks If there are more than one `\footnotemark` before a `\footnotetext`, the index of the `\footnotetext` will be set according to the newest `\footnotemark`. This can be problematic if the previous `\footnotetext` are delayed. Here we demonstrate the fix[3] for such a scenario[4].

Separating Line for Footnotes To customize the appearance of the separating line above the footnotes, we can call `\renewcommand*{\footnoterule}{<code>}`. However, a short-cut is to do `\setfootnoterule<length>`, where it is set to 0.8 times `\textwidth` in this book.

Referencing Footnote A footnote can be labeled and referenced as well. Just put `\label{<label_name>}` inside the footnote and use `\ref` as for other elements.

[2] This footnote by `\footnotetext` will automatically be traced to the latest `\footnotemark`.

[3] We manually decrease the footnote counter by 1 here with `\footnotetext[\numexpr\value{footnote}-1]`.

[4] Try removing the patch above, and the numbering will clash.

6.4.2 Hyperlinks and Bookmarks

Hyperlinks To enable inserting hyperlinks (e.g. websites, or referencing in the book) in the document, we need to import the `hyperref` package. Then we can simply use the `\href{<link>}{<text>}` command, for example

```
\href{https://www.google.com/}{Google}
```

yields the link to Google. Internal referencing links will be automatically formed.

Highlighting Options for hyperref The default highlighting effects for hyperlinks by `hyperref` can be controlled by `\hypersetup`. In this book, we have used

```
\hypersetup{
    colorlinks,
    linkcolor = black,
    urlcolor = blue!90!Green,
    pdfauthor = Benjamin Loi,
    pdftitle = How to Reproduce this Book Exactly with LATEX,
    pdfsubject = v1.0.0,
    pdfkeywords = {Mathematics, LATEX}
}
```

The `colorlinks` keyword replaces the default colored boxes by colored text, while `linkcolor` and `urlcolor` indicate the color for internal and external links respectively. The subsequent options are a by-product to set up the metadata for the PDF file.

PDF Bookmarks To further facilitate the PDF file, we can load the `bookmark` package with the following options:

```
\usepackage[open,openlevel=1,atend,numbered]{bookmark}
```

The `open` and `openlevel` options tell to which depth the bookmarks are expanded when the PDF file is open, while the `numbered` option reinstates the chapter/section numbering at the start of each bookmark.

Chapter
7

Framed Theorems and Exercises

Introduction This chapter touches on how to make beautiful, colored frames around theorems, examples, and so on. The typesetting and management of exercises and answers will also be discussed.

7.1 Colored Boxes for Theorems and Proofs

Colored Boxes by (new)tcolorbox We will start by generating a simple colored box first, which is most easily done by importing the `tcolorbox` package. Then we can define the design of the box by the `\newtcolorbox` command. An illustrative template is

```
\newtcolorbox{mybox}[1][]{
  colback=Green!20,
  colframe=Gray,
  coltitle=Yellow,
  title=This is my box,
  boxrule=1pt,
  leftrule=1ex,
  boxsep=1ex,
  left=1ex,
```

```
  right=1ex,
  sharp corners,
  breakable,
  before skip=\topsep,
  after skip=\topsep, #1}
```

that creates a box environment named `mybox`. Then typing

```
\begin{mybox}
The content goes here.
\end{mybox}
```

produces the following box:

> This is my box
>
> The content goes here.

`colback`, `colframe`, and `coltitle` denote the color of the background, frame, and title correspondingly. `boxrule` (`leftrule`) is the width of bounding lines (on the left), and `boxsep` indicates the overall padding around the title and content. `left`/`right` further refines the padding to the left/right. The meanings of the `sharp corners` and `breakable` keywords are not hard to guess: the box will have sharp corners instead of rounded ones, and it can break across pages. Finally, `before skip` and `after skip` indicate the vertical spacing to other objects before and after the entire box. The `[1][]` part is added so that the box can receive an optional argument, which can override the given setting of the box via putting `#1` at the end of the `\newtcolorbox` option list.

Colored Numbered Theorems/Examples by newtcbtheorem The readers are probably concerned more about how to construct a colored, numbered box for theorems, examples, definitions, and the like. This requires us to pass

```
\tcbuselibrary{theorems}
```

and then we can use the \newtcbtheorem[<init>]{<name>}{<display_name>}{<options>}{<prefix>} construct. The init part sets up the way of numbering, while the options part is just like the previous input lists for \newtcolorbox. For example, we can define

```
\newtcbtheorem[number within=chapter]{thm}{Theorem}{
  colback=Green!20,
  colframe=Green!50,
  fonttitle=\bfseries,
  boxrule=1pt,
  boxsep=1ex,
  left=1ex,
  right=1ex,
  pad after break=1.5ex,
  sharp corners,
  breakable,
  before skip=\topsep,
  after skip=\topsep}{thm}
```

where we have added some new parameters: fonttitle here indicates the title to be in boldface, and pad after break adds some padding after the box breaks across the page. The number within=chapter option tells the numbering to be based on chapters, and it can be changed to, e.g. section. Subsequently, writing

```
\begin{thm}{Mean Value Theorem}{mvt}
If ...
\begin{equation}
f'(c) = \frac{f(b)-f(a)}{b-a}
\end{equation}
\end{thm}
```

produces

Theorem 7.1: Mean Value Theorem

If $f(x)$ is continuous on $[a, b]$ and differentiable on (a, b), then there exists $c \in (a, b)$ such that

$$f'(c) = \frac{f(b) - f(a)}{b - a} \tag{7.1}$$

We can refer to this theorem as Theorem 7.1 by `\ref{thm:mvt}` (`prefix:alias`). It is also possible to supply additional options to override the base setting of the colored box.

Shared Numbering for Definitions and the Others Another feature that may be useful is to enable shared numbering for definitions, lemmas, corollaries, properties, and so on. To do so, we can invoke the `\newtcbtheorem` command again and pass the keyword `use counter from=` for the `init` option:

```
\tcbset{common/.style={
  colback=Green!20,
  colframe=Green!50,
  fonttitle=\bfseries,
  coltitle=black,
  theorem style=plain,
  ...}
}
\newtcbtheorem[use counter from=thm]{defn}{Definition}{common}{defn}
```

Here we use `\tcbset` to save the style for repeated use. Then

```
\begin{defn}{Taylor Expansion}{taylor}
For a function $f(x)$ infinitely differentiable at point $x = a$, we
   have its Taylor series as
\begin{equation}
f(x) = f(a) + \frac{f'(a)}{1!}(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \
   frac{f'''(a)}{3!}(x-a)^3 + \cdots
\end{equation}
\end{defn}
```

is rendered as

Definition 7.2 (Taylor Expansion): For a function $f(x)$ infinitely differentiable at point $x = a$, we have its Taylor series as

$$f(x) = f(a) + \frac{f'(a)}{1!}(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \frac{f'''(a)}{3!}(x-a)^3 + \cdots \tag{7.2}$$

Notice that we have set `theorem style=plain` (there are more possible values, like `break`), see if you can figure out where the difference is.

Proofs with tcolorboxenvironment For proofs or worked steps, their setting will often be slightly different. We can load the `amsthm` package, which comes along with the `proof` environment, and apply `\tcolorboxenvironment` on it. The template will be

```
\tcolorboxenvironment{proof}{
  blank,
  breakable,
  borderline west={0.5ex}{2pt}{black},
  left=2ex,
  before skip=\topsep,
  after skip=\topsep}
```

The `borderline west` option draws a long, thin black line to the left. Then, writing

```
\begin{proof}
Consider $\vec{w} = \vec{u} + t\vec{v}$, ...
\begin{align*}
\Delta = b^2 - 4ac &\leq 0 \\
(2(\vec{u} \cdot \vec{v}))^2 - 4\norm{\vec{u}}^2\norm{\vec{v}}^2 &\
   leq 0 \\
(\vec{u} \cdot \vec{v})^2 - \norm{\vec{u}}^2\norm{\vec{v}}^2 &\leq 0
   \\
(\vec{u} \cdot \vec{v})^2 &\leq \norm{\vec{u}}^2\norm{\vec{v}}^2 \\
```

```
|\vec{u} \cdot \vec{v}| &\leq \norm{\vec{u}}\norm{\vec{v}} \qedhere %
    putting \qedhere to eliminate the spurious gap
\end{align*}
\end{proof}
```

results in

Proof. Consider $\vec{w} = \vec{u} + t\vec{v}$, where t is any scalar, then $\|\vec{w}\|^2 = \vec{w} \cdot \vec{w} \geq 0$ by positivity. Also, $\vec{w} \cdot \vec{w}$ can be written as a quadratic polynomial in t:

$$\vec{w} \cdot \vec{w} = (\vec{u} + t\vec{v}) \cdot (\vec{u} + t\vec{v}) = \|\vec{u}\|^2 + 2t(\vec{u} \cdot \vec{v}) + t^2\|\vec{v}\|^2$$

Since this quantity is always greater than or equal to zero, i.e. the quadratic polynomial has no root or a repeated root, it means that the discriminant must be negative or zero. So,

$$\begin{aligned}
\Delta = b^2 - 4ac &\leq 0 \\
(2(\vec{u} \cdot \vec{v}))^2 - 4\|\vec{u}\|^2\|\vec{v}\|^2 &\leq 0 \\
(\vec{u} \cdot \vec{v})^2 - \|\vec{u}\|^2\|\vec{v}\|^2 &\leq 0 \\
(\vec{u} \cdot \vec{v})^2 &\leq \|\vec{u}\|^2\|\vec{v}\|^2 \\
|\vec{u} \cdot \vec{v}| &\leq \|\vec{u}\|\|\vec{v}\| \qquad \square
\end{aligned}$$

Moreover, we can copy it with "Proof" replaced by "Solution" as

```
\newenvironment{solution}{\begin{proof}[Solution]}{\end{proof}}
```

Exercise(s)

7.1) Design your own color box to display any example problem, followed by a worked solution.

7.2 Typesetting Exercises and Answers

Exercises The essence of any math book is its exercises. To deliver exercises and their solutions, we can import the `exercise` package with the following options (to be explained soon):

```
\usepackage[lastexercise,answerdelayed]{exercise}
```

Then we can typeset any exercise within the `Exercise` environment, which we have been doing for so long. As an example, the last exercise was created by

```
\begin{exercisebox}
\begin{Exercise}
\phantomsection
\label{exer:colorbox}
Design your own color box to display any example problem, followed by
    a worked solution.
\end{Exercise}
\end{exercisebox}
```

where `exercisebox` here is a self-defined[1] colored box environment generated by `newtcolorbox` as introduced in the last section. We can refer to this exercise as Exercise 7.1 via its label `\ref{exer:colorbox}`. As an extra note, to ensure the internal referencing link to the exercise is correct, we need a patch by inserting `\phantomsection` at its start before `label`.

Answers To typeset the answer for an exercise, we can use the `Answer` environment supplied with the corresponding label of that exercise. Here we will take Exercise 5.3 as a demonstration, where we can write

```
\begin{Exercise}
\phantomsection
\label{exer:modulo}
... % the exercise
\end{Exercise}
\begin{Answer}[ref=exer:modulo]
... % the answer goes here
\end{Answer}
```

[1] The actual implementation can be checked from my raw source code.

Alternatively, one can omit the `ref` part if the `lastexercise` option has been ticked when importing the package. It assumes that the answer is for the latest exercise, and hence we can type it immediately after that exercise.

The `answerdelayed` option saves all the answers until the end, and we can output all of them for once by `\shipoutAnswer`. You should be able to see the answers for Exercise 5.3 and others at the end of the book. The detailed code for the answer section of this book is

```
\cleardoubleoddpage
\chapter*{Answers to Exercises}
\addcontentsline{toc}{chapter}{Answers to Exercises} % add the answer
    section to the table of content
\ohead{Answer to Exercises}
\shipoutAnswer
```

Headers for Answers The default headers for answers may be too plain. To customize them, we can use the solution proposed in TeX StackExchange 369265 which involves declaring a boolean variable `firstansweroftheсhapter` by `\newboolean` in the `ifthen` package. A minimal version is

```
\newboolean{firstansweroftheсhapter}
\renewcommand{\AnswerHeader}{\ifthenelse{\boolean{
   firstansweroftheсhapter}}
    {\textbf{Answers for Chapter \thechapter}\par\vspace{1ex}%
     \theExercise)}
    {\theExercise)}
}
```

Then we can update the `\AnswerHeader` command with an if-then-else statement. We can call `\setboolean{firstansweroftheсhapter}{true}` whenever we are at the first answer in a chapter, then `\AnswerHeader` will first print the heading "Answers for Chapter `\thechapter`" where `\thechapter` is the chapter counter, and proceed to print the exercise number stored by `\theExercise` with a round bracket to the right. Afterwards, reset `\setboolean{first` `answerofthechapter}{false}` and the `\AnswerHeader` will just consist of the exercise number.

Chapter 8

Plotting with Tikz (Part I)

Introduction This chapter introduces the usage of the **TikZ** engine to draw various mathematical plots and diagrams in LaTeX.

8.1 Basic Drawing Syntax

8.1.1 Coordinates and Nodes

Cartesian Coordinates To create a **TikZ** plot, we first have to import the `pgfplots` package and initialize a `tikzpicture` environment. We will start by specifying *coordinates* and labeling that point on the plot as a *node*. A simple example is given in Figure 8.1 below, and the corresponding code is

```
\begin{tikzpicture}
\draw[help lines] (0,0) grid (4,3);
\coordinate (A) at (2,1);
\coordinate (B) at (3,3);
\node at (A) {\Large $(2,1)$};
\node at (B) {\footnotesize Another point}; % equivalently, directly
   use \node at (3,3) {\footnotesize Another point};
```

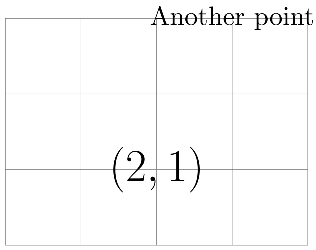


Figure 8.1: Simple Cartesian coordinates as nodes in TikZ.

```
\end{tikzpicture}
```

The `\draw[help lines]` sketches helper grids for refining the positioning. The `\coordinate (<name>) at (<coordinates>)` syntax marks the coordinates of a point internally for later use. Here we use the simplest Cartesian xy-coordinates. The `\node at (<coordinates>) {<text>}` then puts a node, possibly with some text, at the corresponding position.

Polar Coordinates Another common type of coordinates is the polar coordinates, whose expression is `(angle:radius)` where `angle` is relative to the positive x-axis. This is illustrated in the following Figure 8.2:

```
\begin{tikzpicture}
\draw[help lines] (0,0) grid (4,3);
\coordinate (O) at (0,0);
\coordinate[label=above:$A$] (A) at (30:4);
\node at (O) [below left] {$O$}; % below left can be replaced by
   anchor=north east
\node at (A) [circle,fill,inner sep=2pt] {};
\end{tikzpicture}
```

Point A is then positioned at $(4\cos 30°, 4\sin 30°) = (2\sqrt{3}, 2)$.

There are also some other new things. We can place the node text O below and to the left of the origin coordinates by adding `[below left]` (as you may have guessed, there are also `right`, `above`, and their combinations) before it. However,

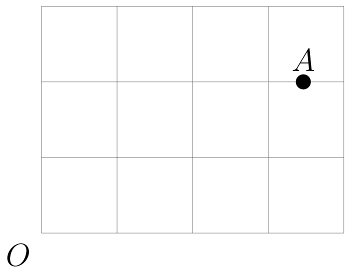


Figure 8.2: Defining a point in TikZ using polar form instead.

notice that it will also displace the node. Another labeling method is to provide the `[label=<position>:<text>]` option when calling `\coordinate`, which has been applied to point A. Then, we can make a dot to denote the point by using `\node` with the set of options `[circle,fill,inner sep=2pt]` so it fills a small circle with size 2 pt.

8.1.2 Drawing Paths

Straight Lines Given some coordinates, a natural next step is to connect them with curves. We will deal with the simplest case of straight lines first. The basic *path* syntax is `(coordinates) -- (coordinates)`, and can be stacked as we like. This is demonstrated in Figure 8.3 on the next page.

```
\begin{tikzpicture}
\draw[help lines] (-3,-3) grid (3,3);
\coordinate[label=$A$] (A) at (2,1);
\coordinate[label=$B$] (B) at (-2,0);
\coordinate[label=below:$C$] (C) at (1,-1);
\draw[blue,dashed] (-1,-3) -- node[midway,sloped]{Cut} (3,3);
\path[red,draw] (A) -- (B) -- (C) -- cycle;
\end{tikzpicture}
```

We have two possible methods to draw a line. The first one is to just use the `\draw` command, whereas the second one is more verbose and uses the `\path`

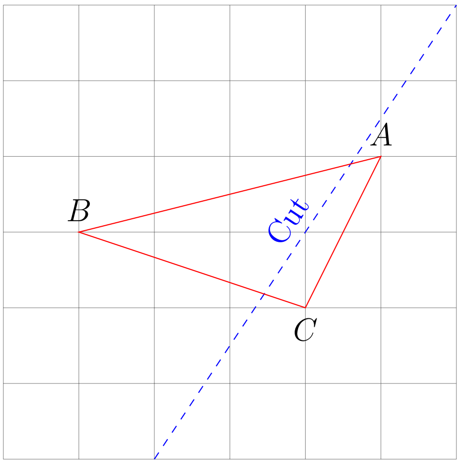


Figure 8.3: Drawing a line and a closed path as a triangle.

command combined with the `draw` option. For the triangle, the `cycle` alias tells the path to travel back to the initial point. Other takeaways are that we can supply color (`red`, `blue`) and line style (`dashed`, `dotted`) when drawing the path, and we can put a label over the line by adding the `node` syntax after the `--` part with the options `midway` (or `pos=0.5`, to put it in the middle) and `sloped` (sloped with respect to the line).

Relative Coordinates Sometimes it is more convenient to specify coordinates relative to the previous one when constructing a path. This is done by adding the incremental `++` after `--`. Figure 8.4 below is an illustrative example.

```
\begin{tikzpicture}
\draw[help lines] (-3,-3) grid (3,3);
\coordinate[label=below right:$O$] (O) at (0,0);
\draw[Green, line width=1.5] (O) -- (2,1) coordinate[at end](A) --++
   (-1.5,1) coordinate[at end](B) --++ (-3,-3) coordinate[at end](C)
   --++ (-30:2) coordinate[at end](D) -- cycle;
\node[right] at (A) {$A$}; \node[above] at (B) {$B$}; \node[left] at
   (C) {$C$};\node[below] at (D) {$D$};
\end{tikzpicture}
```

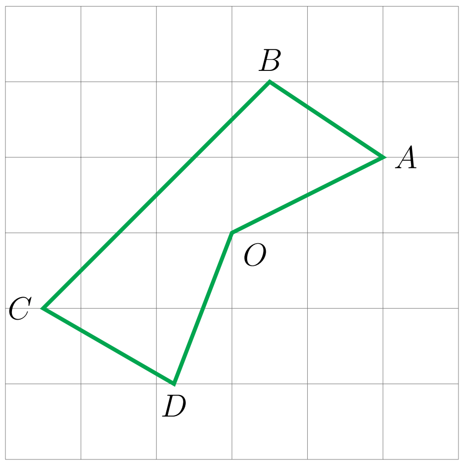


Figure 8.4: Connecting a path with relative coordinates.

where we have used incremental coordinates: Cartesian for the second and third segments, and polar for the fourth segment. We may append the `coordinate[at end]` constructs (can be omitted) at each step to remember their coordinates for subsequent labeling. In addition, we can supply the `line width` parameter (may be substituted by short keywords like `thin`, `thick`, etc.), which is self-explanatory.

Fill Apart from drawing lines, we may also want to fill the area bounded by them. This is done by either the `fill` (or `filldraw`) command or appending the `fill=<color>` option to the `draw` command. This is demonstrated by Figure 8.5 on the next page.

```
\begin{tikzpicture}
\draw[help lines] (-4,-4) grid (4,4);
\coordinate[label={[xshift=7]$A$}] (A) at (3,-1);
\coordinate[label=$B$] (B) at (2,2);
\coordinate[label={[yshift=-3]below:$C$}] (C) at (-1,-4);
\coordinate[label={[xshift=-7]$D$}] (D) at (-3,-1);
\coordinate[label=$E$] (E) at (-2,3);
```

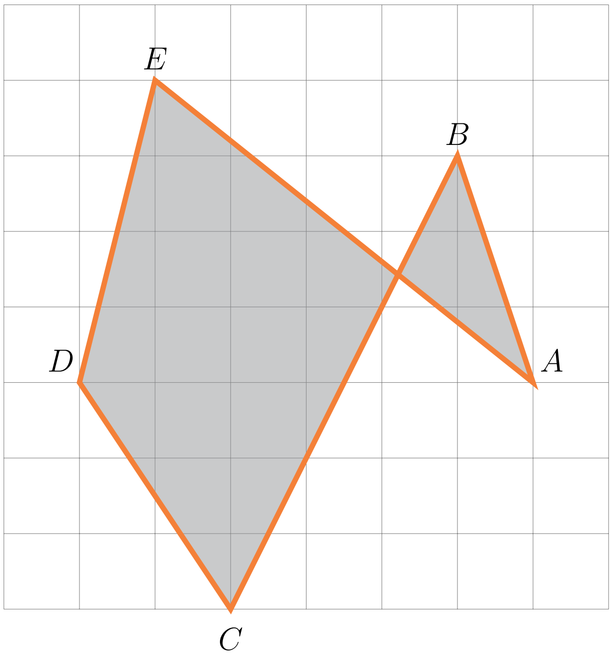


Figure 8.5: Filling the area enclosed by a path with color.

```
\draw[Orange, line width=2, fill=Gray, fill opacity=0.5] (A) \foreach
    \P in {B,...,E} { -- (\P)} -- cycle; % equivalent to \draw (A) --
    (B) -- (C) -- (D) -- (E) -- cycle;
\end{tikzpicture}
```

We can specify the fill color opacity with the `fill opacity` option. Notice that we have utilized the PGF for-loop functionality to simplify chaining the path. Finally, we have added the `xshift` and `yshift` parameters to fine-tune the positioning of labels.

Exercise(s)

8.1) Try to draw and fill a star shape using TikZ. An example is given below as Figure 8.6.

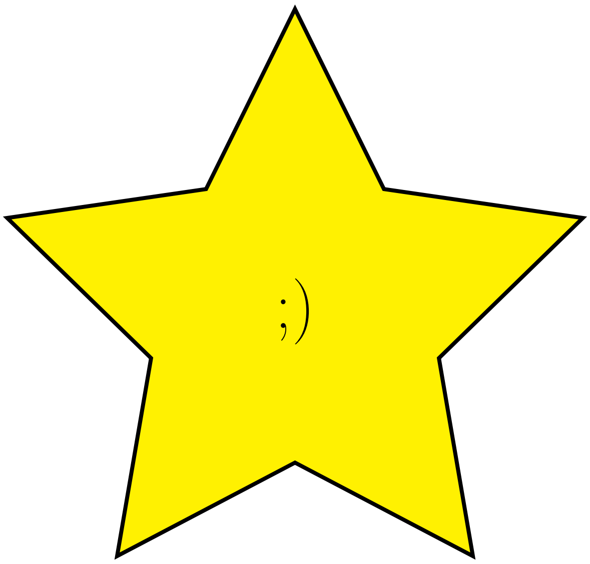


Figure 8.6: The example star for Exercise 8.1.

8.1.3 Shapes

Rectangles, Circles, Ellipses Often, we have to draw some simple shapes like rectangles, circles, and ellipses. In TikZ, it is easily done by writing exactly `rectangle`, `circle`, and `ellipse` with the appropriate dimensions after them. This is illustrated in Figure 8.7.

```
\begin{tikzpicture}
\draw[help lines] (-2,-3) grid (5,5);
\coordinate[label=$O$] (O) at (0,0);
\draw[Blue] (O) circle (1.5); % at origin with radius = 1.5
\coordinate (A) at (3,2);
\draw[Red] (A) ellipse (1 and 2); % with x/y-axis = 1 and 2
\draw[Green] (1.5,-1.5) rectangle (3.5,-2.5); % two opposite vertices
\end{tikzpicture}
```

There are also other shapes like `parabola`.

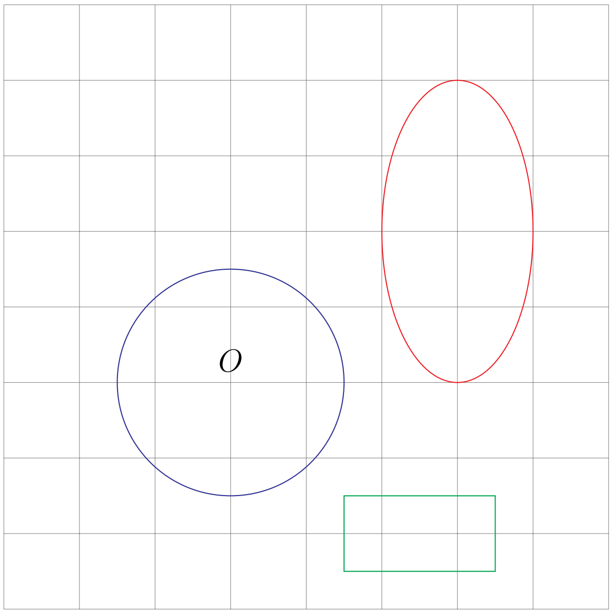


Figure 8.7: Drawing various simple shapes in Tikz.

Rotation Another useful functionality is to rotate lines and shapes. We can use either `rotate=<degree>` or the more advanced `rotate around=<degree>:<about_coordinates>` to achieve that (the former is a special case of the latter with the reference coordinates determined implicitly, usually the origin). Their difference is demonstrated in Figure 8.8.

```
\begin{tikzpicture}
\draw[help lines] (-3,-3) grid (5,5);
\coordinate[label=$O$] (O) at (0,0);
\coordinate[label=$A$] (A) at (3,0);
\draw[Gray] (A) ellipse (2 and 1);
\draw[Red, dashed, rotate=45] (A) ellipse (2 and 1);
\draw[Blue, dashed, rotate around={60:(O)}] ([rotate around={60:(O)}]
    A) ellipse (2 and 1); % an extra rotate around is needed in front
    of A
\draw[Blue, dashed, rotate=60] (1,0) -- (5,0);
\draw[Red, dashed, rotate around={45:(A)}] (1,0) -- (5,0);
\end{tikzpicture}
```

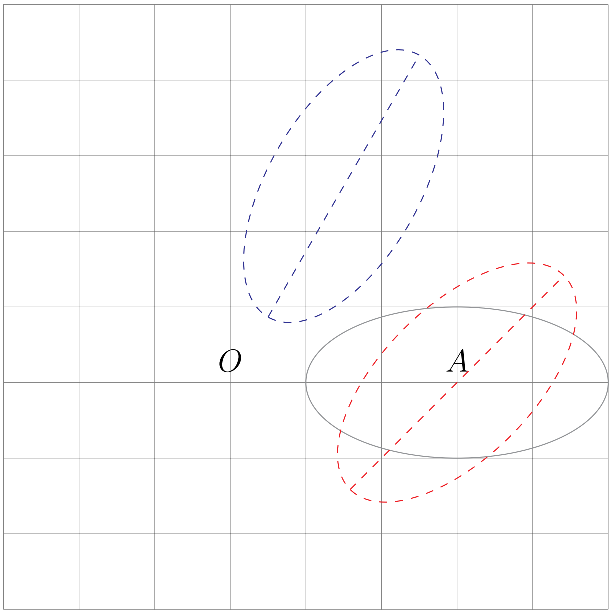


Figure 8.8: Two different kinds of coordinate rotation in Tikz.

Clipping Sometimes we may want to fill a limited area within a shape clipped by some other shape. This can be done by the `clip` construct. Here we draw a Venn diagram as an illustrative example in Figure 8.9.

```
\begin{tikzpicture}
\draw[Red] (0,0) circle (2) node{A};
\begin{scope}
\clip (0,0) circle (2);
\fill[Green!25] (2.5,0) circle (2);
\end{scope}
\draw[Blue] (2.5,0) circle (2) node{B};
\end{tikzpicture}
```

Be aware that clipping is cumulative, and we will have to limit its effect within a local `scope` so that the blue circle to the right can be drawn without being clipped wrongly.

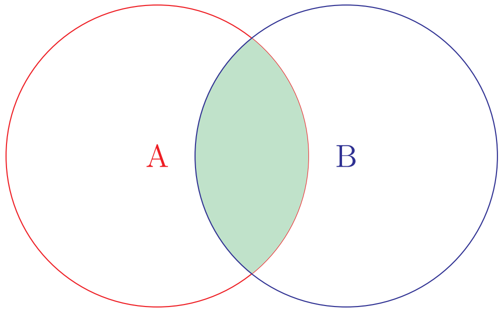


Figure 8.9: A Venn diagram created by clipping.

Perpendicular Lines A convenient feature in TikZ is to draw a line perpendicular to another line without the need to do the manual calculation by loading the extra TikZ library `calc` with

```
\usetikzlibrary{calc}
```

The intersection point for that perpendicular line will then be automatically computed by it along the lines of `$(A)!(B)!(C)$`. This is showcased in Figure 8.10 above.

```
\begin{tikzpicture}
\coordinate[label={below:$O$}] (O) at (0,0);
\node at (O) [circle,fill,inner sep=1pt] {};
\coordinate[label=$A$] (A) at (-1,2);
\coordinate[label=$B$] (B) at (4,1);
\coordinate[label=$C$] (C) at ($(A)!(O)!(B)$);
\draw (A) -- (B);
\draw[dashed] (O) -- (C);
\draw let \p1 = ($(C)-(O)$) in (O) circle ({veclen(\x1,\y1)});
\end{tikzpicture}
```

Alternatively, the special case of vertical/horizontal perpendicular lines can be done by the `|-` and `-|` syntax. We further use the `calc` library with its `let ...in` syntax (using `\p1` to denote the displacement vector resulting from the `$$` calculation and `\x1,\y1` for its x/y-component), and the `veclen` function to compute the length of it, a.k.a. the radius of the circle tangent to the line.

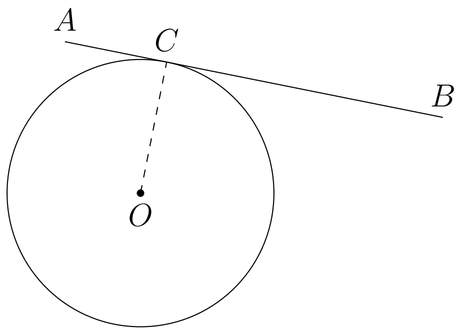


Figure 8.10: Demonstration of drawing perpendicular lines, in addition to calculating the distance between two coordinates.

Angles For geometry purposes, we often need to label angles, like in a triangle or polygon. The `angles` TikZ library is exactly made for this. Similar to above, we import it via writing

```
\usetikzlibrary{angles, quotes}
```

and then we can draw angles as some `pic` (refer to ?? later) with the construct in the form of `{angle = A--B--C}`, demonstrated in the following code for Figure 8.11 below:

```
\begin{tikzpicture}
\coordinate[label={left:$A$}] (A) at (-1,0);
\coordinate[label={below right:$B$}] (B) at (3,0);
\coordinate[label=$C$] (C) at (3,3);
\draw (A) -- (B) -- (C) -- cycle;
\pic [draw,angle radius=10] {right angle = A--B--C};
\pic [draw,"$\theta$",angle radius=15,angle eccentricity=1.5] {angle
   = B--A--C};
\end{tikzpicture}
```

The `angle radius` option controls the extent of the angle marking, and `angle eccentricity` determines the distance of the angle and its label (θ in this example).

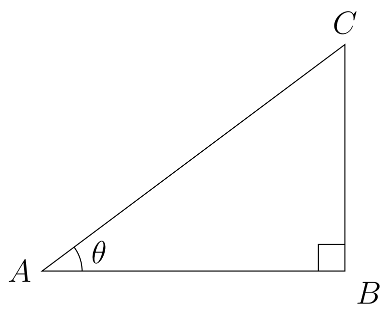


Figure 8.11: Drawing a right-angled triangle with the angles labeled.

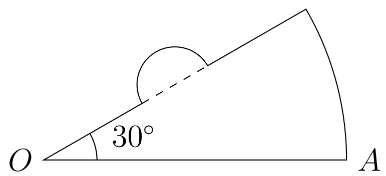


Figure 8.12: Drawing multiple arcs in one diagram involving relative coordinates.

Arcs While drawing circles is not a rare task, sometimes we will need to draw just an arc. It is not hard to do so in TikZ with the `arc` shape, the syntax of which is

```
\draw (x,y) arc (start_angle:stop_angle:radius);
```

The arc will start from point `(x,y)` as a part of the arc with an initial angle, stopping angle, and radius as indicated by the inputs. An example is shown in Figure 8.12 above.

```
\begin{tikzpicture}
\coordinate[label={left:$O$}] (O) at (0,0);
\coordinate[label={right:$A$}] (A) at (4,0);
\draw (O) -- (A) arc (0:30:4) --++ (-150:1.5) arc (30:210:0.5)
   coordinate[at end] (B) -- cycle;
\draw[dashed] (B) --++ (30:1);
\pic[draw,"$30^\circ$",angle radius=20,angle eccentricity=1.75] {
   angle = A--O--B};
\end{tikzpicture}
```

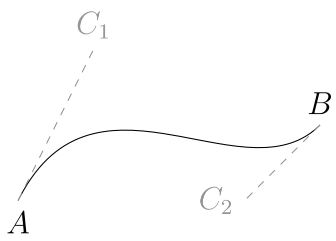


Figure 8.13: The anatomy of a Bézier control curve.

8.2 Advanced Controls on Paths

8.2.1 Curves

Bézier Control Curves Up until now, we have been drawing only straight lines or segments. A reasonable expectation is to go one step further and construct curved paths. In TikZ, it is implemented as *Bézier control curves* that take one or two control points, with either one of the following syntaxes:

```
\draw <starting_coords> .. controls <control_coords> .. <end_coords>;
\draw <starting_coords> .. controls <control_coords_1> and <control_
   coords_2> .. <end_coords>;
```

A schematic diagram is given as Figure 8.13 above, and the code to produce that example is

```
\begin{tikzpicture}
\coordinate[label={below:$A$}] (A) at (-1,0);
\coordinate[label=$B$] (B) at (3,1);
\coordinate[label={[Gray]$C_1$}] (C1) at (0,2);
\coordinate[label={[Gray]left:$C_2$}] (C2) at (2,0);
\draw (A) .. controls (C1) and (C2) .. (B);
\draw[dashed, Gray] (A) -- (C1);
\draw[dashed, Gray] (B) -- (C2);
\end{tikzpicture}
```

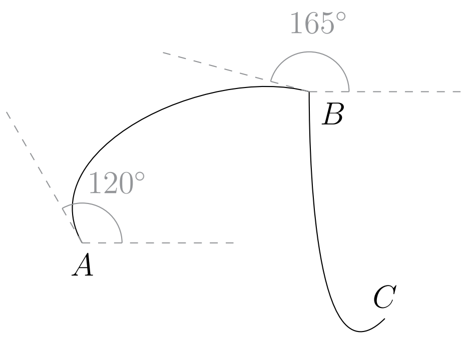


Figure 8.14: Another way to draw control curves specified by angles.

in and out An alternative way to draw a curve is to use the `to` operation plus the `in=<degree>, out=<degree>` construct. It is not difficult to guess that the `in` and `out` options represent the direction of the incoming/outgoing ray as degrees of angles (relative to the x-axis). This is demonstrated in Figure 8.14 above.

```
\begin{tikzpicture}
\coordinate[label={below:$A$}] (A) at (-1,-1);
\coordinate[label={below right:$B$}] (B) at (2,1);
\coordinate[label=$C$] (C) at (3,-2);
\draw (A) to[in=165, out=120] (B) to [in=225, out=-90] (C);
\draw[dashed, Gray] (A) --++ (120:2) coordinate[at end] (Aa);
\draw[dashed, Gray] (A) --++ (0:2) coordinate[at end] (X1);
\pic[draw,"$120^\circ$",Gray,angle radius=15,angle eccentricity=1.75]
    {angle = X1--A--Aa};
\draw[dashed, Gray] (B) --++ (165:2) coordinate[at end] (Ba);
\draw[dashed, Gray] (B) --++ (0:2) coordinate[at end] (X2);
\pic[draw,"$165^\circ$",Gray,angle radius=15,angle eccentricity=1.75]
    {angle = X2--B--Ba};
\end{tikzpicture}
```

Intersection It is handy if we can mark the intersection point(s) of two different curves. This can be delegated to the TikZ library `intersections`. To use it, we

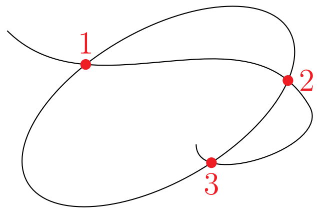


Figure 8.15: Labeling intersection points between an ellipse and an arbitrary curve.

need to give a name to those curves with the `name path` option, and then we can invoke the `name intersections` option that refers to the intersection points as `(intersection-<number>)`. For instance, Figure 8.15 can be produced by

```
\begin{tikzpicture}
\draw[name path=myellipse, rotate=30] (0,0) ellipse (2 and 1);
\draw[name path=mycurve] (-2,1) to[in=120, out=-45] (2,0) to[in=-90,
   out=-60] (0.5,-0.5);
\fill[Red, name intersections={of=myellipse and mycurve}]
    (intersection-1) circle (2pt) node[above]{1}
    (intersection-2) circle (2pt) node[right]{2}
    (intersection-3) circle (2pt) node[below]{3};
\end{tikzpicture}
```

Exercise(s)

8.2) Try to reproduce the (essence of) geometry in Figure 8.16. The `shorten >=<length>` (the space is needed!) option may be useful.

8.2.2 Decorations

Decorations/Morphing An interesting effect that can be applied to curves is decorations (or morphing, generating variations along them. This is done by loading the TikZ library `decorations.pathmorphing`. The simplest usage is via `decorate, decoration=<shape>` that applies the morphing to the entire path, illustrated by Figure 8.17 on the next page.

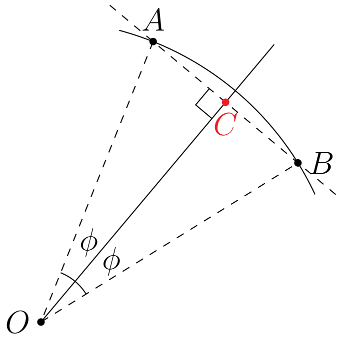


Figure 8.16: The "Bow" diagram for Exercise 8.2.

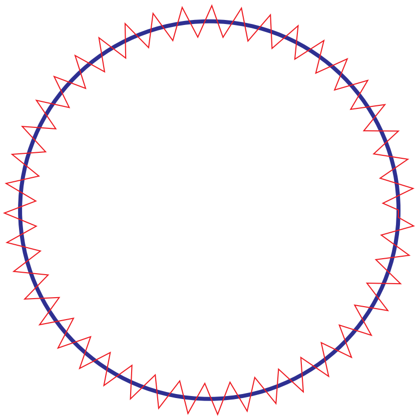


Figure 8.17: A circle decorated by the zigzag effect.

```
\begin{tikzpicture}
\coordinate (O) at (0,0);
\draw[Blue,line width=1.5] (O) circle (2.5);
\draw[Red,decorate,decoration={zigzag,segment length=2ex,amplitude
   =0.5em}] (O) circle (2.5);
\end{tikzpicture}
```

Notice that we have also passed some other options to adjust the shape of the zigzagging line.

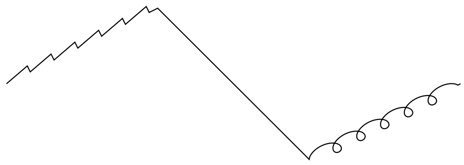


Figure 8.18: Different decorations on individual segments.

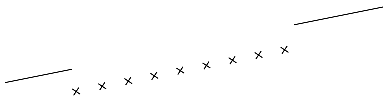


Figure 8.19: Fine-tuning a decoration of crosses.

Decorating Subpaths The previous syntax will decorate the entire path. If we want to apply the effect only on some parts of it, then we can put the `decorate` statement to enclose each of them correspondingly. Figure 8.18 is shown above as an example.

```
\begin{tikzpicture}
\draw decorate[decoration=saw] {(0,0) -- (2,1)} -- (4,-1) decorate[
   decoration={coil,aspect=1.5}] {-- (6,0)};
\end{tikzpicture}
```

Positioning and Extent of Decorations Furthermore, we can fine-tune the positioning, as well as the starting/ending points of a decoration. This is achieved by supplying the `raise` (displacement across the path), `pre length` (starts after), and `post length` (ends before) options, demonstrated by Figure 8.19.

```
\begin{tikzpicture}
\draw[decoration={pre length=9mm,post length=12mm,raise=-3mm,crosses
   }] decorate{(0,0) -- (5,1)}; % requires the extra library
   decorations.shapes too for the cross symbols
\end{tikzpicture}
```

There are many more possible choices for decorations; Unfortunately, we don't have the scope to include all of them.

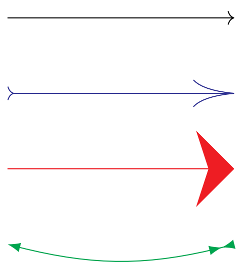


Figure 8.20: Different types of arrow tips and related options.

8.2.3 Arrows

Arrow Tips To draw arrows, we need to load the `arrows.meta` TikZ library. Then we can specify the type of arrow tip during a `\draw` command. The syntax is easier to understand by directly looking at the examples in Figure 8.20.

```
\begin{tikzpicture}
\draw[->] (0,0) --++ (3,0);
\draw[Blue, >-{>[length=3ex, width=2ex]}] (0,-1) --++ (3,0);
\draw[Red, -{Stealth[scale=3, angle'=90]}] (0,-2) --++ (3,0);
\draw[Green, {Latex}-{Latex[]Latex[reversed]}] (0,-3) to[out=-15,in
   =-165]++ (3,0);
\end{tikzpicture}
```

The two most frequently used named arrow tips are `Stealth` and `Latex`. Aside from `length`, `width`, `scale`, and `angle'` (remember the `'`!), there are many more keys like `inset`, `slant`, `left`, and `right`, etc.

It is also possible to set the global arrow style using `\tikzset`, like `\tikzset{>={Stealth}}`, which changes the type for all arrow tips to `Stealth`. Or, we can do it for an individual path by moving `>={<arrow_type>}` inside the corresponding `\draw` option.

Arrow in the Middle More often than not, we would like to put the arrow in the middle of a line. We can utilize the `decorations.markings` TikZ library

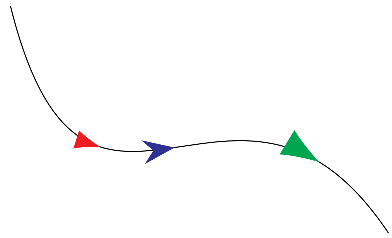


Figure 8.21: Marking multiple arrow tips along a curve.

for that. An example is given by Figure 8.21 above.

```
\begin{tikzpicture}
\draw[postaction={decorate}, decoration={markings,
      mark=at position 0.35 with {\arrow{Latex[Red,scale=2]}},
      mark=at position 0.5 with {\arrow{Stealth[Blue,scale=2.5]}},
      mark=at position 0.8 with {\arrow{Latex[Green,scale=3]}}}]
      (0,1) .. controls (1,-3) and (3,1) .. (5,-2);
\end{tikzpicture}
```

We need to first supply the `markings` keyword to the decoration option, then we can add the arrow `mark`s as `\arrow{<arrow_type>}` at the corresponding relative positions along the curve. A new thing is that the `decorate` keyword is now placed in the `postaction` option, which indicates that the decorations are laid on the original curve that is kept.

Exercise(s)

8.3) Draw the pendulum diagram in Figure 8.22.

8.4) Try to reproduce the closed integration path in Figure 8.23.

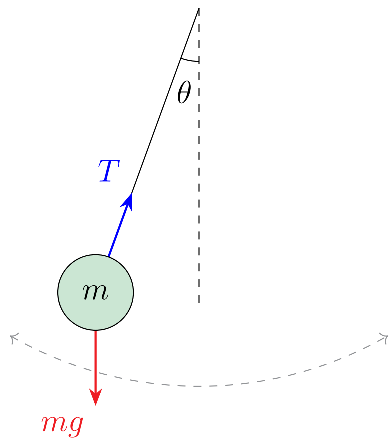


Figure 8.22: The pendulum schematic for Exercise 8.3.

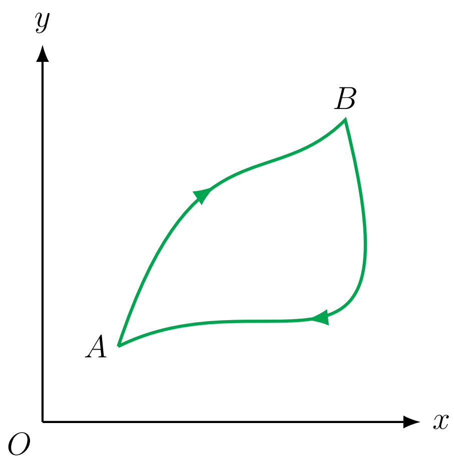


Figure 8.23: The integration path for Exercise 8.4.

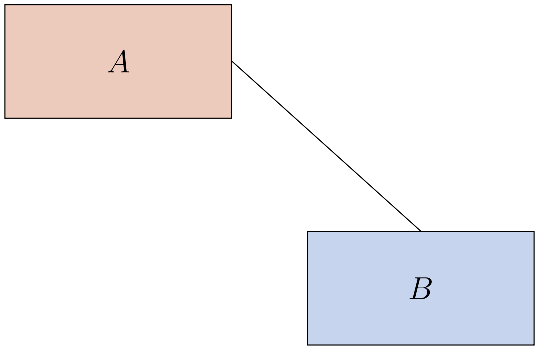


Figure 8.24: Two styled rectangle nodes.

8.3 Styles and Pics

Styles and Nodes It is convenient if we can repeatedly apply some style to similar objects in TikZ. This can be done by providing the name and attributes of that style at the beginning of the `tikzpicture`. Figure 8.24 here demonstrates the usage.

```
\begin{tikzpicture}[myrectangle/.style={rectangle, minimum width=3cm,
    minimum height=1.5cm, draw=black, fill=Mahogany!20}]
\node[myrectangle] (myA) at (0,0) {$A$}; % using style defined above
\node[rectangle, minimum width=3cm, minimum height=1.5cm, draw=black,
fill=RoyalBlue!20] (myB) at (4,-3) {$B$}; % equivalent syntax except
   the fill color
\draw (myA.east) -- (myB.north);
\end{tikzpicture}
```

Here we have created two nodes that are in the shape of a rectangle. The `minimum width` and `minimum height` keys work exactly as their name suggest and maintain the extent of the rectangles beyond the node text. We additionally draw a line between the two nodes with the anchors (at where the two ends of the line are fixed) stated (optional) as directions.

Pics - Small Pictures Similarly, it will be handy if we can insert and reuse the same piece of drawing that is needed many times. This is known as a `pic` (small picture) in TikZ, and we have been using this feature for labeling angles. To define a `pic`, we do it like it is a style by `<pic_name>/.pic={<drawing_code>}`. Then we can append the `pic` after a path. This is illustrated by the damper defined for the mechanical system (Reference: TEX StackExchange 476076) in the subsequent Figure 8.25.

```
\begin{tikzpicture}
    [dampic/.pic={
    \fill[pgftransparent!0] (-0.1,-0.3) rectangle (0.3,0.3);
    \draw (-0.3,0.3) -| (0.3,-0.3) -- (-0.3,-0.3);
    \draw[line width=1mm] (-0.1,-0.3) -- (-0.1,0.3);},
    spring/.style={decorate,decoration={zigzag,pre length=0.4cm,post
       length=0.4cm,segment length=2mm,amplitude=3mm}},
    mass/.style={rectangle,minimum height=1.6cm, minimum width=2.4cm,
        draw=black, fill=brown!50},
    ground/.style={fill,pattern=north east lines,draw=none}]
\node[mass] (mass1) at (0,0) {$m$};
\node[mass] (mass2) at (4,0) {$m$};
\draw ($(mass1.east)+(0,0.5cm)$) -- ($(mass2.west)+(0,0.5cm)$) pic[
   midway,sloped]{dampic};
\draw[spring] ($(mass1.east)-(0,0.5cm)$) -- ($(mass2.west)-(0,0.5cm)
   $);
\node[ground,minimum width=3mm,minimum height=2.5cm] (g1) at (-3,0)
   {};
\draw (g1.north east) -- (g1.south east);
\draw ($(mass1.west)+(0,0.5cm)$) -- ($(g1.east)+(0,0.5cm)$) pic[
   midway,sloped]{dampic};
\draw[spring] ($(mass1.west)-(0,0.5cm)$) -- ($(g1.east)-(0,0.5cm)$);
\end{tikzpicture}
```

There are some other points worth mentioning. The special `pgftransparent!0` color code is an alias equivalent to the white color, and covers the original path under it. We also need to load the `patterns` TikZ library to produce the hatching lines (`pattern=north east lines`) for the ground style. Also, we have used

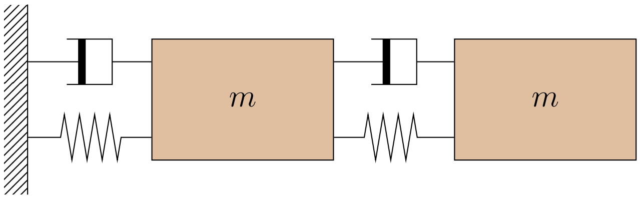


Figure 8.25: A schematic for a mechanical mass-spring-damper system.

the `$$` syntax to carry out coordinate calculations in deriving the starting/ending points of the connecting lines.

every node/path An even more convenient shortcut is to assign the same style for every node/path (of the same kind) at once. This is unsurprisingly done by providing the `every node`/`every path` name, and is readily showcased in Figure 8.26 below.

```
\begin{tikzpicture}[every node/.style={circle,black,solid,draw=black,
   fill=Red!20,minimum size=30pt},
every rectangle node/.style={black,solid,draw=black,fill=Blue!20,
   minimum height=15pt, minimum width=30pt},
every path/.style={Green,dashed}]
\node (A) at (0,0) {$A$};
\node (B) at (2,-1) {$B$};
\node[rectangle] (C) at (-0.5,-2) {$C$};
\node (D) at (3,-3) {$D$};
\draw (A) -- (B) -- (C) -- (D);
```

Notice that `every path` affects node texts and lines as well, and we have to override them in `every node` for it to work as intended.

show path construction We can further break down a path into the corresponding components (lines, curves, etc.) and execute certain code for each of them every time they occur. This is accomplished by the `show path construction`

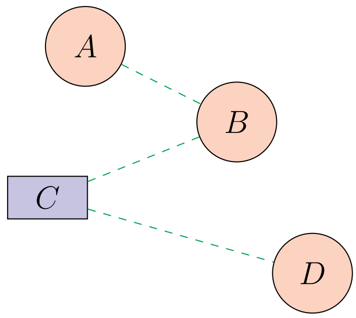


Figure 8.26: Reusing styles for every node and path.

key for `decoration`, demonstrated by the contour integration plot in Figure 8.27 as follows.

```
\begin{tikzpicture}
\newcommand*{\gap}{0.3}
\newcommand*{\bigradius}{3}
\newcommand*{\littleradius}{0.7}

\draw[very thick,-Latex] (-1.15*\bigradius, 0) -- (1.15*\bigradius,
   0);
\draw[very thick, decorate, decoration={zigzag, segment length=0.5cm,
    amplitude=0.2cm}] (0, 0) -- (1.15*\bigradius, 0);
\draw[very thick,-Latex] (0, -1.15*\bigradius) -- (0, 1.15*\bigradius
   );
\draw[red, thick, postaction=decorate, decoration={show path
   construction, curveto code={
    \draw[decorate, decoration={markings, mark=at position 0.75 with
       {\arrow{Latex[Red,scale=1.25]}}}]
    (\tikzinputsegmentfirst) .. controls (\tikzinputsegmentsupporta)
       and (\tikzinputsegmentsupportb) .. (\tikzinputsegmentlast);},
    lineto code={
    \draw[decorate, decoration={markings, mark=at position 0.65 with
       {\arrow{Latex[Red,scale=1.25]}}}]
    (\tikzinputsegmentfirst) -- (\tikzinputsegmentlast);}
    }]
let
```

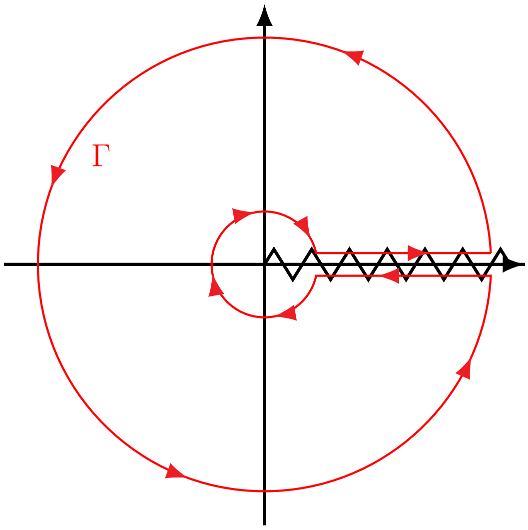
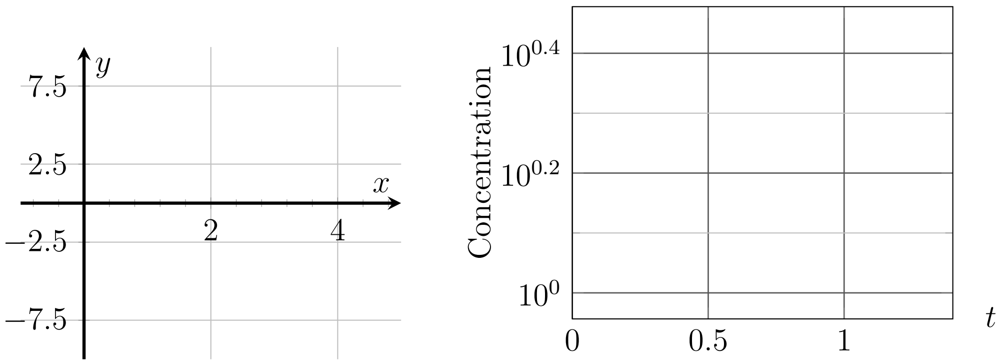


Figure 8.27: A standard complex contour integration path with a branch cut over the positive x-axis.

```
\n1 = {asin(\gap/2/\bigradius)},
\n2 = {asin(\gap/2/\littleradius)}
in (\n1:\bigradius) arc (\n1:360-\n1:\bigradius) node[pos=0.4,below
   right]{$\Gamma$} -- (-\n2:\littleradius) arc (-\n2:-360+\n2:\
   littleradius) -- (\n1:\bigradius);
\end{tikzpicture}
```

The code is a bit complex, and we will have it explained step by step. As their names suggest, the `curveto code`/`lineto code` part will be applied to every curve/line. The main purpose of involving `\tikzinputsegmentfirst`, `\tikzinputsegmentlast`, `\tikzinputsegmentsupporta`, in addition to `\tikzinputsegmentsupportb`, is to replicate the curve/line internally, which can be left untouched as a template. Then the `decorate` and `markings` parts are the same as previously to put an arrow mark along each replicated path segment. Finally, to draw the actual contour, we use `\newcommand` and the `let ...in` syntax to store lengths as variables and compute the coordinates for the turning points (copying TEX StackExchange 103176).



(a) A typical axis. (b) A semi-logarithmic axis.

Figure 8.28: Two example TikZ axes.

8.4 Plotting Functions

Axis Settings To plot a function or graph in TikZ, we have to configure an `axis` scope first. There are many options to customize an axis, some of which are showcased in the two examples in Figure 8.28 above.

```
\begin{tikzpicture}
\begin{axis}[xlabel=$x$, ylabel=$y$, xmin=-1, xmax=5, ymin=-10, ymax
   =10, ytick={-7.5,-2.5,2.5,7.5}, minor x tick num=4, grid=major,
   axis lines=center, axis line style={line width=1.2pt}, width=\
   textwidth]

\end{axis}
\end{tikzpicture}
\begin{axis}[ymode=log, xlabel=$t$, ylabel=Concentration, x label
   style={at={(axis description cs:1.1,0.2)}}, minor ytick={10^(0.1),
    10^(0.3)}, major grid style={line width=.5pt,draw=black!66}, grid
   =both, enlarge x limits={0.4,upper}, width=\textwidth]

\end{axis}
```

Most of the options are not hard to comprehend, maybe except `axis description cs:`, which refers to the position relative to the axis frame, and `enlarge limits`, which extends the axis limits by the amount indicated. The biggest difference between the two example axes is perhaps the appearance of the axis lines, produced by the option `axis lines=center` in the first one.

Plotting Simple Functions Of course, an axis is nothing if there are no data or functions plotted on it. To add points or graphs on it, we can use the `\addplot` command. For points, we may add a list of `coordinates` after that; while for functions, we can simply enter the expression in PGF format. We can control the `domain` of `x` and the number of points (`samples`) used in drawing. Both of these are demonstrated in Figure 8.29 on the next page.

```
\begin{tikzpicture}
\begin{axis}[xlabel=$T$, ylabel=$N$, title=Half-life Experiment, xmin
   =0, xmax=3, ymin=0, ymax=1, enlargelimits=0.1, legend pos=south
   west, width=0.9\textwidth, height=0.6\textwidth]
\addplot[Red, only marks]
coordinates {
(0,1) (0.2,0.86) (0.6,0.67) (0.9,0.53)
(1.4,0.37) (1.7,0.29) (2.5,0.17)};
\addplot[Blue, domain=0:4, samples=100]{(1/2)^(x)} node[pos=0.6,above
   ,sloped] {$N = (1/2)^T$};
\legend{Measurements, Theoretical}
\end{axis}
```

We have also adjusted the size of the figure and made a legend.

Exercise(s)

8.5) Try to reproduce the following plot in Figure 8.30. Notice that to draw with usual TikZ commands but now inside an axis, we can call the axis coordinate system with the syntax `axis cs:<coords>`.

Parametric Equations A natural generalization of `\addplot` is to draw parametric curves where the command now treats `x` as the parameter and accepts two

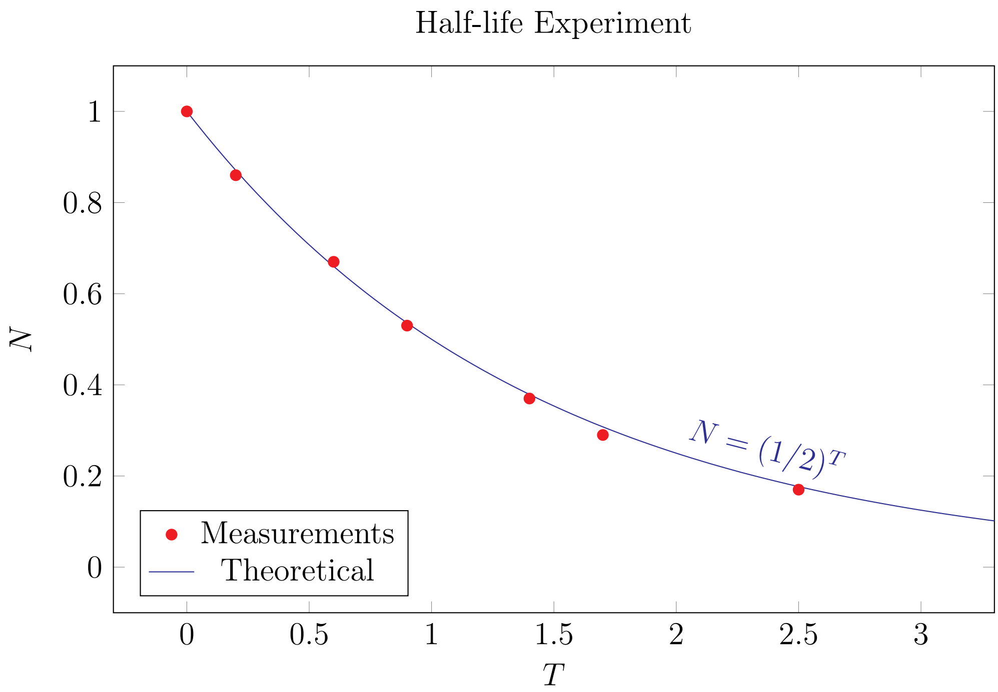


Figure 8.29: The half-life process as an example plot.

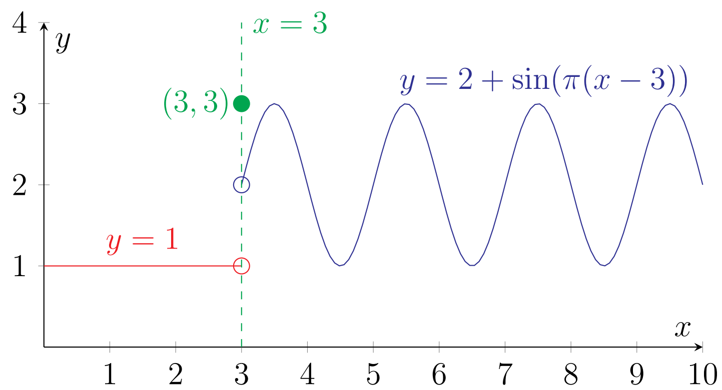


Figure 8.30: The plot for Exercise 8.5.

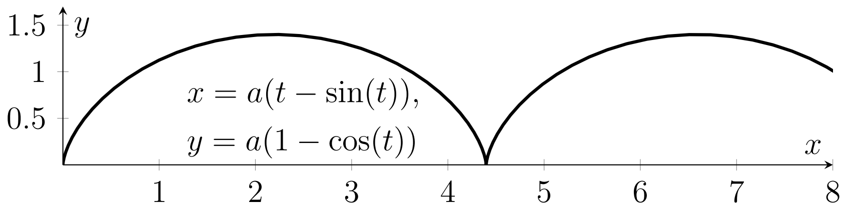


Figure 8.31: A parametric cycloid graph.

equations. We will borrow the famous cycloid to illustrate the usage in Figure 8.31.

```
\begin{tikzpicture}
\newcommand*{\ap}{0.7}
\begin{axis}[xlabel=$x$, ylabel=$y$, axis lines=center, xmin=0, xmax
    =8, ymin=0, ymax=1.7, width=0.8\textwidth, height=0.25\textwidth]
\addplot[very thick, domain=0:5*pi, samples=100] ({\ap*(x - sin(deg(x
    ))},{\ap*(1 - cos(deg(x)))});
\node[align=left] at (axis cs:2.5,0.5) {$x = a(t-\sin(t))$,\\ $y = a
    (1-\cos(t))$};
\end{axis}
\end{tikzpicture}
```

Vector Fields The final topic to introduce in this chapter is about drawing a vector field using the `\addplot3` function (used for 3D plotting, more in the next chapter) with the `quiver` option. This is illustrated in Figure 8.32 below, with the vector field defined by $(y/\sqrt{x^2+y^2}, -x/\sqrt{x^2+y^2})$.

```
\begin{tikzpicture}
\begin{axis}[xlabel=$x$, ylabel=$y$, xmin=-3, xmax=3, ymin=-3, ymax
    =3, view={0}{90}]
\addplot3[blue, domain=-2.5:2.5, quiver={u={y/(x^2+y^2)^0.5}, v={-x/(
    x^2+y^2)^0.5}, scale arrows=0.3}, -stealth, samples=20] {0};
\end{axis}
\end{tikzpicture}
```

The `u` and `v` keys represent the velocities along the x/y-axes, and we have set the

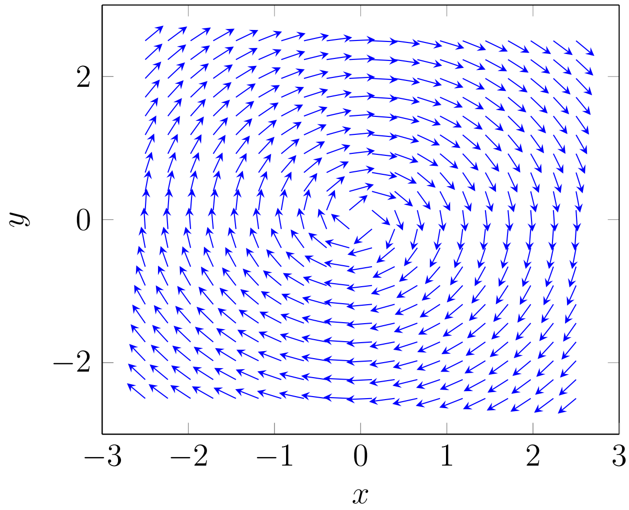


Figure 8.32: A clockwise rotational vector field.

scale, type, and density for the arrows. Finally, `view={0}{90}` is needed for the `axis` since we have invoked the 3D plotting method and need to reset the camera to look downward overhead.

Chapter 9

Plotting with Tikz (Part II)

Introduction This chapter continues to discuss the finer details and broad applications of TikZ plotting.

9.1 Advanced Axis Control

9.1.1 Axis Scales

Axis Units We can adjust the units of the coordinate axes in a TikZ plot by specifying them at the beginning. This is readily demonstrated in the small example of Figure 9.1 below.

```
\begin{tikzpicture}[x=1.2cm, y=0.9cm]
\draw[help lines, step = {(1,1)}] (0,0) grid (4,5);
\node at (0,0) [below left] {$0$};
\foreach \ii in {1,...,4} {\node at (\ii,0) [below]{$\ii$};}
\foreach \jj in {1,...,5} {\node at (0,\jj) [left]{$\jj$};}
\draw[decorate, decoration=brace, very thick, Green] (3,5) -- (4,5)
   node [midway, above] {$1.2$ cm};
```

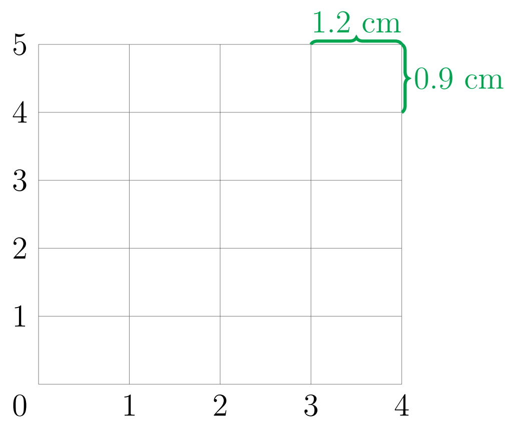


Figure 9.1: Cartesian coordinate system transformation.

```
\draw[decorate, decoration={brace, mirror}, very thick, Green] (4,4)
   -- (4,5) node [midway, right] {$0.9$ cm};
\end{tikzpicture}
```

Be reminded that after the scale transformation, we have to supply `step = (1,1)` so that the grid lines are drawn in the new units. We have also used the `brace` and `mirror` decorations, which are not hard to understand.

Coordinate Rotation Another simple way to transform the coordinate axes is via rotation. It is extremely straightforward and immediately done in Figure 9.2.

```
\begin{tikzpicture}[x=1.2cm, y=0.9cm, rotate=20]
\draw[help lines, step = {(1,1)}] (0,0) grid (4,5);
\end{tikzpicture}
```

9.1.2 3D Plotting

3D Coordinate Axes To initiate a 3D TikZ plot, the easiest automatic way is to write the drawing code just as usual, but now with the coordinates being 3D. We

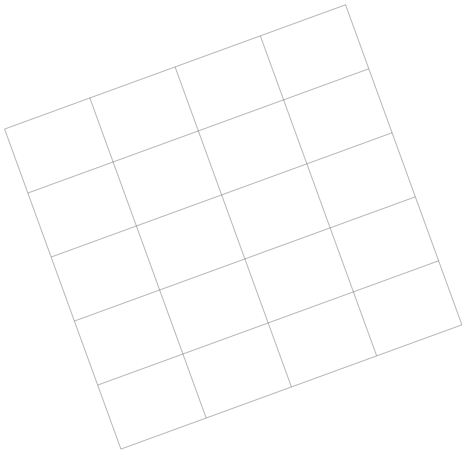


Figure 9.2: Same as Figure 9.1 but with an anti-clockwise rotation applied to the frame.

can also control the axis scales, like in the 2D scenario, where we can specify the direction of each axis displayed on the page. This is demonstrated in Figure 9.3.

```
\begin{tikzpicture}[x={(-1cm, -1.5cm)}, y={(1.5cm, -0.75cm)}, z={(0cm
   , 1.8cm)}, every path/.append style={>=Latex}]
\draw [->] (0,0,0) -- (3,0,0) node [below left] {$x$};
\draw [->] (0,0,0) -- (0,3,0) node [below right] {$y$};
\draw [->] (0,0,0) -- (0,0,3) node [above] {$z$};
\draw [->, very thick, Red] (0,0,0) -- (1,0,0) node [left] {$\hat{\
   imath} = (1,0,0)^T$};
\draw [->, very thick, Red] (0,0,0) -- (0,1,0) node [above right,
   midway] {$\hat{\jmath} = (0,1,0)^T$} ;
\draw [->, very thick, Red] (0,0,0) -- (0,0,1) node [left] {$\hat{k}
   = (0,0,1)^T$};
\draw [Gray, dashed] (1,2,0) -- (1,0,0) node[below, midway, sloped]{$
   y=2$};
\draw [Gray, dashed] (1,2,0) -- (0,2,0) node[below, midway, sloped]{$
   x=1$};
\draw [Gray, dashed] (1,2,0) -- (1,2,2.5) node[midway, right]{$z
   =2.5$};
\draw [->, blue, line width=1.2] (0,0,0) -- (1,2,2.5) node [right]
   {$\vec{v} = (1,2,2.5)^T$};
```

```
\end{tikzpicture}
```

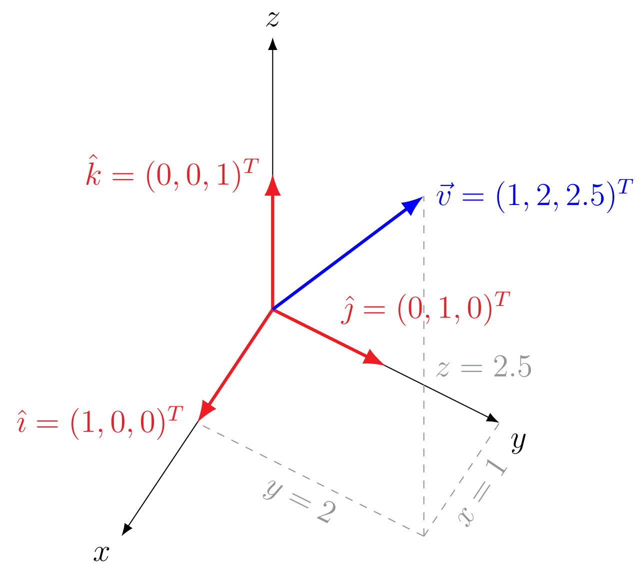


Figure 9.3: A vector in three-dimensional space.

Notice that we have utilized the `append style` function to add the requirement that all arrow tips will use the `LaTeX` type.

Surface Plots Moving from 2D to 3D, we may now want to draw surface plots instead of just curves. This can be done by declaring a normal axis scope and using the `\addplot3` command with the `surf` keyword on the level equation. Figure 9.4 below serves as an example.

```
\begin{tikzpicture}
\begin{axis}[grid=major,colormap/viridis,zmin=-0.25]
\addplot3[surf,samples=20,domain=-2:2,y domain=-1:1] {exp(-(x^2+y^2))
   };
\end{axis}
\end{tikzpicture}
```

We can add a mesh grid and choose the color map (viridis here) at the start of the axis environment. It is also possible to provide a `colorbar`. To draw a

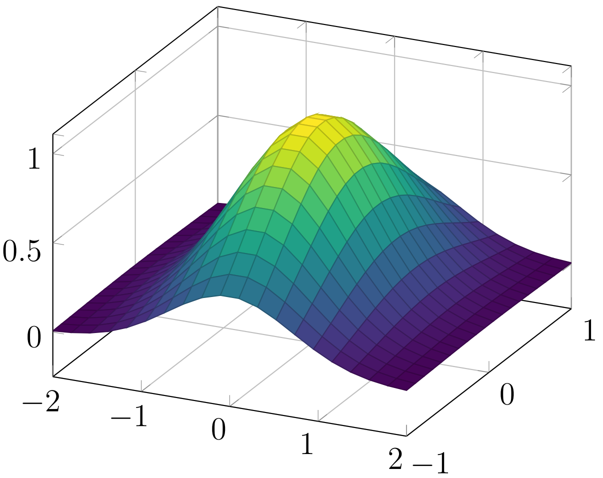


Figure 9.4: A 2D Gaussian surface plot.

contour plot instead, we simply replace `surf` by `contour gnuplot`[1] and use the `view={0}{90}` trick introduced at the end of the last chapter.

3D Spheres and Arcs To construct a 3D sphere and draw arcs on it, we need to import the `tikz-3dplot` package (requires `\usepackage{tikz-3dplot}` [2] this time). Drawing only the sphere is not hard (plus the `ball color` option). Meanwhile, drawing the arcs requires us to first locate the center as well as the two ends of each of them via `\tdplotdefinepoints`, and then actually execute that with `\tdplotdrawpolytopearc`. The whole procedure is illustrated by Figure 9.5.

```
\tdplotsetmaincoords{70}{110}
\begin{tikzpicture}[scale=2.5,tdplot_main_coords,rotate=15]
\coordinate (O) at (0,0,0);
\draw [ball color=white,very thin] (O) circle (1cm);
\tdplotdefinepoints(0,0,0)(0,0,1)(3^0.5/2,0,0.5)
```

[1] Or `contour lua` if you are using LuaLaTeX.

[2] A positive side effect is that it also loads the smaller `3d` TikZ library, which allows the user to write in cylindrical/spherical coordinates.

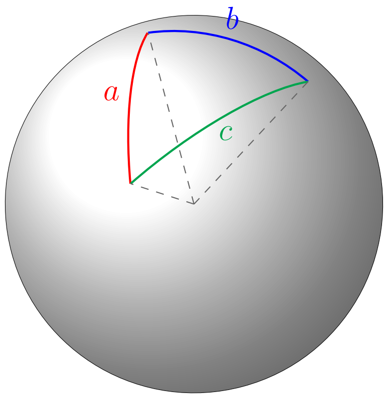


Figure 9.5: Drawing a sphere with a spherical triangle on it.

```
\tdplotdrawpolytopearc[thick, red]{1}{left, red}{$a$}
\tdplotdefinepoints(0,0,0)(0,0,1)(0,0.8,0.6)
\tdplotdrawpolytopearc[thick, blue]{1}{above, blue}{$b$}
\tdplotdefinepoints(0,0,0)(0,0.8,0.6)(3^0.5/2,0,0.5)
\tdplotdrawpolytopearc[thick, Green]{1}{below, Green}{$c$}
\draw[dashed, color=black!60] (O) -- (0,0,1) node(C){};
\draw[dashed, color=black!60] (O) -- (3^0.5/2,0,0.5) node(B){};
\draw[dashed, color=black!60] (O) -- (0,0.8,0.6) node(A){};
\end{tikzpicture}
```

Note that we also call `\tdplotsetmaincoords` and deploy `tdplot_main_coords` to adjust the viewing angle. Furthermore, we have used the `rotate` option as a workaround to tune the orientation.

9.2 Data Visualization

Line Charts There are many other types of plots that we can make with TikZ. The most basic one will probably be line charts, and we will use the Mauna Loa CO_2 concentration data (downloaded from https://gml.noaa.gov/webdata/ccgg/trends/co2/co2_annmean_mlo.csv) as an example. As before, the `\addplot` command is called, and it can accept and read a `.csv` (comma-separated values) file. We will supply the one downloaded from the link above, while providing the respective header names for the `x` and `y` axes. The result is shown in Figure 9.6 above.

```
\begin{tikzpicture}
\begin{axis}[width=0.95\textwidth, height=0.65\textwidth, x tick
   label style={rotate=45,/pgf/number format/.cd,set thousands
   separator={}}, enlarge x limits={abs=2}, xlabel=year, ylabel=$\
   text{CO}_2$ concentration (ppm), title=Mauna Loa Observatory
   Measurement, xlabel style={yshift=-15pt}]
\addplot[Green, mark=*] table [x=year, y=mean, col sep=comma] {co2_
   annmean_mlo.csv};
\end{axis}
\end{tikzpicture}
```

Some noticeable points include that if we change the graph color, we have to explicitly append `mark=*` to get back the dot marks along the curve. Removing it will produce only the curve. We enforce `enlarge x limits` to take `abs=2` so that the x-domain extends by 2 years. We also rotate the x-axis ticks by 45° and use some options to format out the `,` originally in the year numbers. (Try removing them to see what happens!) Accounting for that, we also shift the x-axis label downward by 15 pt.

Bar Plots Bar plots are another commonly seen plot type. To construct a bar plot, we either declare `xbar` or `ybar` in the `axis` option at the start and call the `\addplot` command for each set of bars, or put the keyword directly after `\addplot`. A small example is given as Figure 9.7.

```
\begin{tikzpicture}
\begin{axis}[title=Class Subject Performance,
    ybar,
    enlargelimits=0.15,
    legend style={at={(0.5,-0.15)},anchor=north,legend columns=-1},
    ylabel=Score,
    symbolic x coords={Class A,Class B,Class C},
```

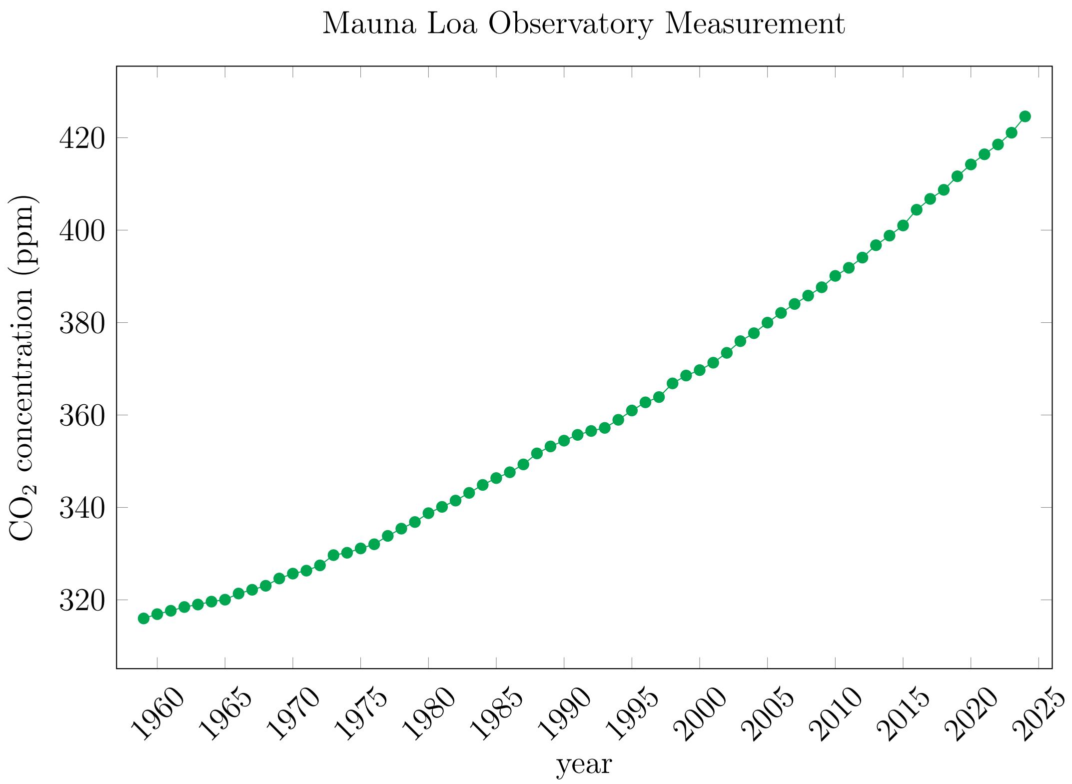


Figure 9.6: The time-series of CO_2 concentration recorded at Mauna Loa Observatory from 1959 to 2024.

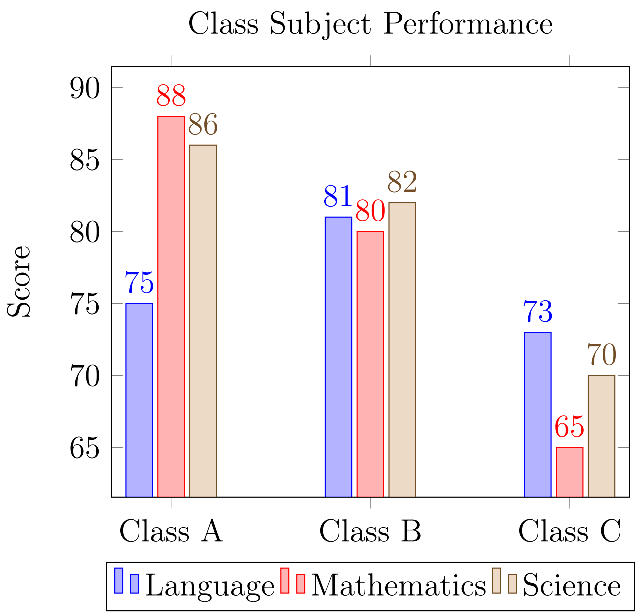


Figure 9.7: A toy dataset about the scores of three classes in three different subjects.

```
    xtick=data,
    nodes near coords,
    nodes near coords align=vertical]
\addplot coordinates {(Class A,75) (Class B,81) (Class C,73)};
\addplot coordinates {(Class A,88) (Class B,80) (Class C,65)};
\addplot coordinates {(Class A,86) (Class B,82) (Class C,70)};
\legend{Language,Mathematics,Science}
\end{axis}
\end{tikzpicture}
```

Here we use `symbolic x coords` to tell the `axis` that the x-coordinates should be treated as strings, and `xtick=data` guarantees that the ticks will be as the input data. `nodes near coords` produces the numbers above the bars. Last but not least, we have tweaked the style for the legend, particularly `legend columns=-1` to arrange the entries horizontally.

9.3 Referencing between TikZ Pictures

Remembering Names and Overlay Sometimes we need to combine multiple TikZ pictures, and share name labels between them so that they can refer to objects in each other. We can enable this functionality by setting the `remember picture` option for them. This is demonstrated by the rather lengthy example of different phase portraits in Figure 9.8.

```
\tikzset{decorated arrows/.style={postaction=decorate,
        decoration={markings,mark={at position 0.5 with {\arrow{
            stealth}}}}}}
% Main Classifying Diagram
\begin{tikzpicture}[remember picture]
\draw[thick, ->] (-6,0) -- (6,0) node[right]{$\tr(A)$};
\draw[thick, ->] (0,-6) -- (0,6) node[above]{$\det(A)$};
\node[below left] (O) at (0,0) {$O$};
\draw[gray, thick] plot[domain=-4.5:4.5,samples=100] (\x, {(\x)^2/4})
    ;
\node[gray, rotate=-60] at (-3.5,2.5) {$\Delta = \tr(A)^2 - 4\det(A)
    = 0$};
\node[gray, rotate=60] at (3,3) {Complex};
\node[gray, rotate=60] at (3.5,2.5) {Real};
\node[anchor=center, Green, rotate=90] at (-6, 5) {\large Stable};
\node[anchor=center, Red, rotate=-90] at (6, 5) {\large Unstable};
% Defining the named coordinates
\coordinate (saddle) at (0,-3);
\node[anchor=center, blue] at (0,-5) {Saddle Point};
\coordinate (center) at (0,3);
\node[anchor=center, blue] at (0, 1) {Center};
... % omitted other cases
\end{tikzpicture}
% Saddle Point
\begin{tikzpicture}[remember picture, overlay]
\begin{axis}[at=(saddle), anchor=center, scale=0.5, xmin=-2, xmax=2,
    ymin=-2, ymax=2, axis lines=center, hide axis]
```

```
\addplot[domain=-1:1.5,samples=50,blue,decorated arrows] ({0.5*e^(x)
    + 0.5*e^(-x)},{0.5*e^(x) - 1*e^(-x)});
\addplot[domain=-1.5:2,samples=50,blue,decorated arrows] ({0.3*e^(x)
    + 0.3*e^(-x)},{0.3*e^(x) - 0.6*e^(-x)});
\addplot[domain=-1:1.5,samples=50,blue,decorated arrows] ({0.5*e^(x)
    - 0.5*e^(-x)},{0.5*e^(x) + 1*e^(-x)});
\addplot[domain=-1.5:2,samples=50,blue,decorated arrows] ({0.3*e^(x)
    - 0.3*e^(-x)},{0.3*e^(x) + 0.6*e^(-x)});
...
\end{axis}
\end{tikzpicture}
% Center
\begin{tikzpicture}[remember picture, overlay]
\begin{axis}[at=(center), anchor=center, scale=0.5, xmin=-2, xmax=2,
    ymin=-2, ymax=2, axis lines=center, hide axis]
\addplot[domain=0:360,samples=50,blue,decorated arrows] ({1*(cos(x))
    + 0.8*(sin(x))},{-1*(cos(x)) + 1*(sin(x))});
\addplot[domain=0:360,samples=50,blue,decorated arrows] ({2/3*(cos(x)
    ) + 1.6/3*(sin(x))},{-2/3*(cos(x)) + 2/3*(sin(x))});
\addplot[domain=0:360,samples=50,blue,decorated arrows] ({1/3*(cos(x)
    ) + 0.8/3*(sin(x))},{-1/3*(cos(x)) + 1/3*(sin(x))});
\end{axis}
\end{tikzpicture}
...
```

(The full code can be checked from the source file.) In the main procedure, the underlying axes and parabola are drawn, and the coordinates at which each phase portrait will be placed are marked and named. Then, a smaller TikZ picture is initiated for each type over the main diagram with the `overlay` option. The axis containing the phase lines is then centered at the marked coordinates by filling the `at` option with the shared name.

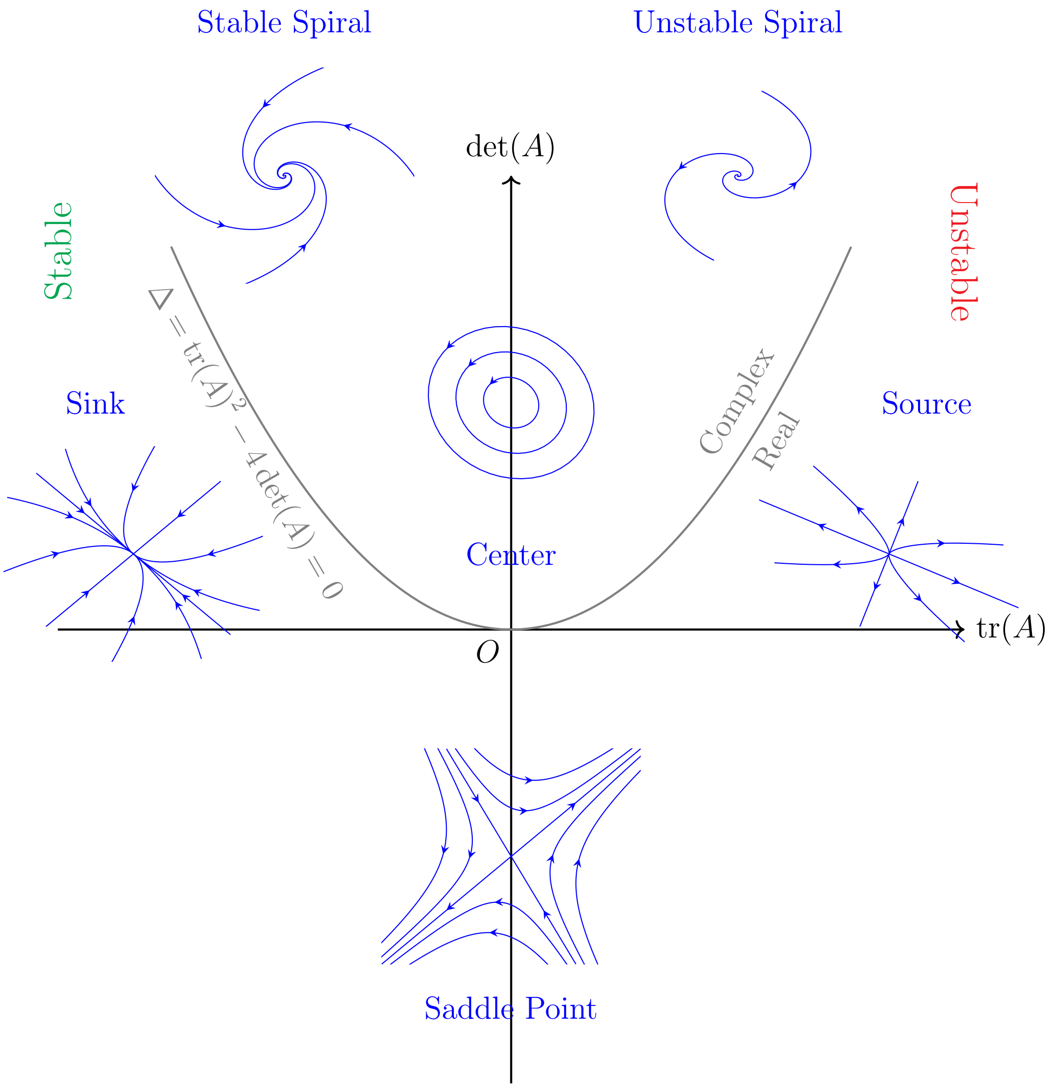


Figure 9.8: Different types of equilibrium points and their representative phase portraits in two-dimensional dynamical systems.

9.4 Matrices in Tikz

Matrices of Nodes To generate a matrix in TikZ that can be marked, we can use the `\matrix` command with the `matrix of math nodes` option. This is illustrated by Figure 9.9 below.

```
\begin{tikzpicture}[remember picture]
\node (A) {$A=$};
\matrix(mymatrix)[matrix of math nodes, left delimiter={[}, right
   delimiter={]}, right=1.5ex of A, row sep=6pt, column sep=6pt,
   inner sep=1.5pt, nodes={text width=16pt, align=center}]
{2 & 1 & 7 & \frac{8}{9} \\
\mathcolor{red}{5} & -\frac{1}{3} & 5 & 0 \\
-3 & \frac{4}{11} & 6 & -\frac{1}{6} \\};
\begin{scope}[on background layer]
\draw [Green, dashed, fill=blue!12, fill opacity=0.5] ($(mymatrix
   -1-1.north west)+(-0.5ex,1ex)$) rectangle ($(mymatrix-3-1.south
   east)+(0.5ex,-1ex)$);
\draw [Green, dashed, fill=blue!12, fill opacity=0.5] ($(mymatrix
   -2-1.north west)+(-0.5ex,1ex)$) rectangle ($(mymatrix-2-4.south
   east)+(0.5ex,-1ex)$);
\end{scope}
\node at (mymatrix-1-1) [above, font=\footnotesize, yshift=10, Green]
    {Col 1};
\node at (mymatrix-2-4) [right, font=\footnotesize, xshift=15, Green]
    {Row 2};
\draw[Red, -Stealth] (pic cs:Ap) to[in=-45, out=-180] (mymatrix-2-1);
\end{tikzpicture}
{\large$\mathcolor{red}{\tikzmark{Ap}A_{21} = 5}$}
```

Particularly, the `left/right delimiter` settings enclose the nodes with the square brackets, and the `right of` syntax puts the matrix to the right of the `A=` part. The positioning of the nodes can be controlled by changing `row sep`, `column sep`, and `inner sep`.

We have also used two additional TikZ libraries. The first one is `backgrounds`

$$A = \begin{array}{ll} \text{Col 1} & \\ \begin{bmatrix} 2 & 1 & 7 & \frac{8}{9} \\ 5 & -\frac{1}{3} & 5 & 0 \\ -3 & \frac{4}{11} & 6 & -\frac{1}{6} \end{bmatrix} & \text{Row 2} \end{array}$$

$$A_{21} = 5$$

Figure 9.9: Typesetting and labeling a TikZ matrix.

to draw blue shadings along the targeted row/column in the background via a `on background layer` scope. The second one is `tikzmark` so that we can place a corresponding `tikzmark` tag at some other location outside the TikZ picture, which can then refer to this tag as `pic cs:<name>` with the help of `remember picture` just introduced before.

9.5 Flow Charts

Flow Charts with Shapes A general TikZ application is to produce flow charts for various processes. This is demonstrated by the bisection algorithm example in Figure 9.10. We will need to load the `shapes.geometric` TikZ library for the shapes representing different components.

```
\begin{tikzpicture}[startend/.style={rectangle, rounded corners,
    minimum width=3cm, minimum height=1cm, draw=black},
io/.style={trapezium, trapezium left angle=70, trapezium right angle
    =110, minimum width=4cm, minimum height=1cm, draw=black},
process/.style={rectangle, minimum width=3cm, minimum height=1cm,
    draw=black},
decision/.style={diamond, minimum width=5cm, minimum height=1cm, draw
    =black}]
\node[startend] (start) {Start};
\node[io,below=1.2cm of start,align=center] (input) {$f(x)$, $a < b$,
     \\ $f(a)<0$, $f(b)>0$};
```

```
\draw[->] (start) -- (input);
\node[process,below=1.2cm of input] (bisect) {$c = (a+b)/2$};
\draw[->] (input) -- (bisect) node[midway] (back) {};
\node[decision,below=1.2cm of bisect] (check1) {$f(c)>0$};
\draw[->] (bisect) -- (check1);
\node[process,below=1.2cm of check1] (moveb) {$b = c$};
\draw[->] (check1) -- (moveb) node[midway,right]{Yes};
\node[process,left=1 of moveb] (movea) {$a = c$};
\draw[->] (check1) -- (check1 -| movea) -- (movea) node[midway,left]{
   No};
\node[decision,below=1.2cm of moveb] (check2) {$\abs{f(c)-0} < \
   varepsilon$};
\draw[->] (moveb) -- (check2);
\draw[->] (movea) -- (check2 -| movea) -- (check2);
\draw[->] (check2.east) --++ (1.4cm,0) |- node[midway,right]{No} (
   back);
\node[startend,below=1.2cm of check2] (end) {End};
\draw[->] (check2) -- (end) node[midway,right]{Yes};
\end{tikzpicture}
```

9.6 Electrical Circuit Diagrams

Electrical Circuits with Components Finally, we can draw electrical circuit diagrams by importing the `circuitikz` package. A small example is given as Figure 9.11.

```
\begin{circuitikz}
\draw (-3,0) to[vsource, l=$E$] (3,0);
\draw (3,0) to[nos,n=S1] (3,-3)
      node[ocirc] at (S1.w) {}
      node[ocirc] at (S1.e) {};
\draw (-3,0) to[R=$R$] (-3,-3);
\draw (-3,-3) to[C=$1/C$] (3,-3);
\draw (-1.5,0) to[L=$L$, *-*] (-1.5,-3);
\end{circuitikz}
```

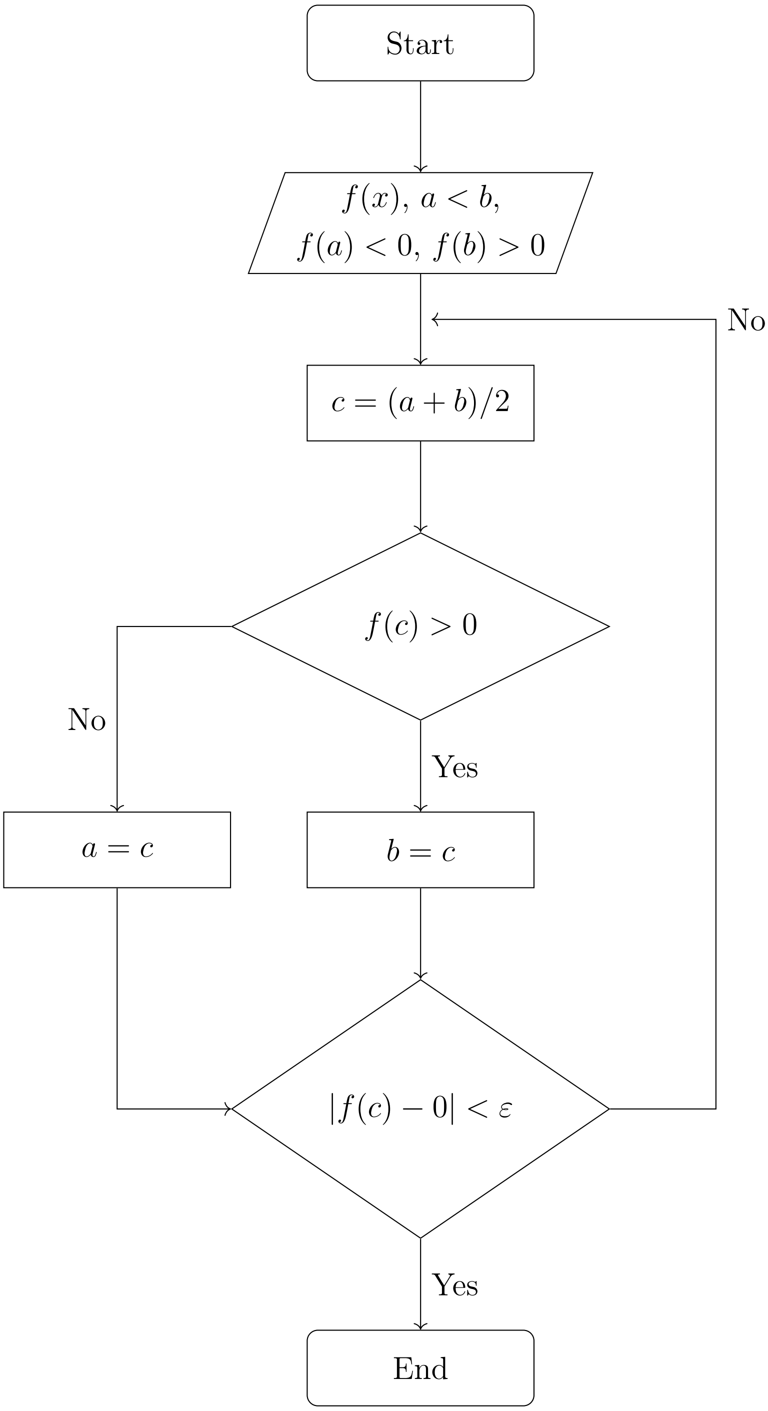


Figure 9.10: The flow chart of the bisection algorithm.

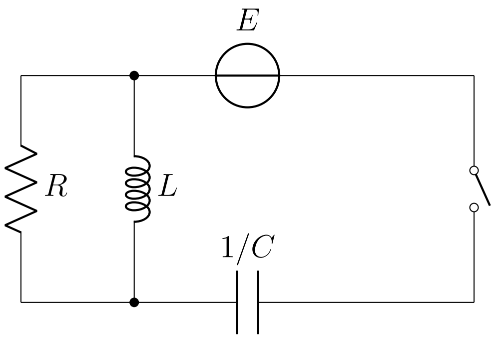


Figure 9.11: A toy circuit with a voltage source, resistor, inductor, and capacitor.

Specifically, the `nos,n=S1` part draws a switch with the internal name `S1`, and the `*-*` syntax produces the junctions around the inductor.

Chapter 10

Miscellaneous

Answers to Exercises

Answers for Chapter 5

5.3)

```
\foreach \x in {1,...,20} {%
\pgfmathsetmacro{\diva}{int(Mod(\x, 3))}%
\pgfmathsetmacro{\divb}{int(Mod(\x, 5))}%
\\ \ifthenelse{\(\diva = 0\) \AND \(\divb = 0\)}{\x{} is
   divisible by both 3 and 5.}{
\ifthenelse{\diva = 0}{\x{} is divisible by 3.}{\x{} is not
   divisible by 3.}
\ifthenelse{\divb = 0}{\x{} is divisible by 5.}{\x{} is not
   divisible by 5.}}}
```