

math

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Contents

index	15
I by discipline	17
1 mathematics	19
1.1 tool	19
1.2 discipline	19
2 physics	21
2.1 discipline	21
3 plot	23
4 programming language	25
4.1 discipline	25
4.2 learning map	25
5 machine learning	27
5.1 Shai Ben-David	27
II by date	29
6 A Minimal Book Example	31
6.1 About	31
6.1.1 Usage	31
6.1.2 Render book	31
6.1.3 Preview book	31
6.2 Hello bookdown	32
6.2.1 A section	32
An unnumbered section	32
6.3 Cross-references	32
6.3.1 Chapters and sub-chapters	32
6.3.2 Captioned figures and tables	32
6.4 Parts	34
6.5 Footnotes and citations	34
6.5.1 Footnotes	34
6.5.2 Citations	34
6.6 Blocks	34

6.6.1	Equations	34
6.6.2	Theorems and proofs	34
6.6.3	Callout blocks	35
6.7	Sharing your book	35
6.7.1	Publishing	35
6.7.2	404 pages	35
6.7.3	Metadata for sharing	35
7	test	37
7.1	RStudio	37
7.1.1	writer options	37
7.1.1.1	line wrapping	37
7.1.1.2	ensuring the same markdown between source / visual mode	37
7.1.2	Rtools	37
7.1.3	addins	38
7.1.4	Git	38
7.2	RMarkdown	38
7.2.1	Pandoc link	38
7.2.2	URL	38
7.2.3	arrow	39
7.2.4	superscript and subscript	39
7.2.4.1	LaTeX	39
7.2.5	equation	39
7.2.5.1	proof QED	39
7.2.6	image	39
7.2.6.1	DiagrammeR / mermaid flowchart	40
7.2.6.2	multiple images / figures in the same line	40
7.2.6.3	figure size	42
7.2.6.3.1	knitr	44
7.2.6.3.2	out.width vs. fig.width	45
7.2.6.4	dynamic knitr plot width and height	47
7.2.6.5	web image in PDF	47
7.2.6.6	SVG	48
7.2.7	horizontal rule	50
7.2.8	footnote	50
7.2.9	hyperlink	50
7.2.10	code chunk	50
7.2.10.1	code folding	50
7.2.11	xaringan	50
7.3	Bookdown	51
7.3.1	system locale	51
7.3.2	render_book()	51
7.3.3	serve_book()	51
7.3.4	LaTeX	51
7.3.4.1	hyperlink, URL, href	51
7.3.4.2	ugly mathptmx \sum	51
7.3.4.3	LaTeX package in HTML document	52
7.3.5	depth of table of contents toc_depth	52
7.3.6	multi-column layout / two columns	52
7.3.6.1	for both HTML and PDF	53
7.3.6.2	multi-column fig.cap must use fig.pos="H"	54
7.3.6.3	caption above figure	55

7.3.6.4	for only HTML	55
7.3.6.4.1	CSS flex	55
7.3.6.4.2	CSS grid	56
7.4	conditional block/chunk for either HTML or PDF, and Chinese issue	57
7.5	video embedding	57
7.5.1	timestamp	58
7.6	equation term coloring	58
7.6.1	font color	58
7.6.2	background color	59
7.7	link and reference	60
7.8	number and reference equations	61
7.9	footnote	61
7.10	citation	61
7.10.1	citation in <code>fig.cap</code>	62
7.10.2	backreference	62
7.11	environment for definition, theorem, proof	62
7.12	slide or presentation	63
7.12.1	Xaringan and Infinite Moon Reader	63
7.12.2	ioslides	63
7.12.3	PowerPoint	65
8	test2	67
8.1	verbatim	67
9	partition	69
10	equivalence class	71
11	equivalence relation	73
12	Python	75
12.1	using Python in R / RMarkdown	75
12.2	SoloLearn	77
12.3	list comprehension	77
12.4	functional programming	77
12.5	object-oriented programming = OOP	78
13	TikZ	79
13.1	2D	80
13.2	3D	88
13.3	plots of functions	91
13.4	PGFplots	92
13.4.1	the axis environments	92
13.4.2	axis descriptions	93
13.4.2.1	placement of axis descriptions	93
13.4.2.1.1	coordinate system <code>axis description cs</code>	93
13.4.2.1.2	legend	95
13.4.2.1.3	tick option	95
13.4.3	<code>declare function</code>	95
13.4.3.1	<code>pgfmathparse</code>	96
13.4.3.2	<code>pgfmathdeclarefunction</code>	96
13.4.4	<code> -</code> and <code>- </code> in TikZ	98
13.4.5	<code>pgfplotsinvokeforeach</code>	98

13.4.6	interpolation dashed lines	99
13.4.7	Zewbie	99
13.4.7.1	coordinate axis/axes fine-tuing	100
13.4.7.1.1	range	100
13.4.7.1.2	scaling	100
13.4.7.1.3	direction vector	101
13.4.7.1.4	axis style	102
13.4.7.1.5	axis discontinuity	104
13.4.7.1.6	tick	105
13.4.7.2	<code>addplot+</code>	108
13.4.7.3	point	108
13.4.7.4	line	113
13.4.7.5	plane	115
13.4.7.6	polar coordinate	116
13.4.8	Arnav Bandekar: Using pgfplots to make economic graphs in LaTeX	117
13.4.9	PGFplots gallery	117
13.5	TikZplotLib / tikzplotlib	118
13.6	animation	121
14	xy-pic	123
15	statistics	125
15.1	Hung Hung	125
15.1.1	probability theory	128
15.1.1.1	probability function	128
15.1.1.2	conditional probability	131
15.1.2	univariable distribution	131
15.1.2.1	cumulative distribution function	131
15.1.2.2	probability density function	132
15.1.2.3	range vs. support	133
15.1.2.4	continuous monotone transformation	133
15.1.2.5	discrete monotone transformation	136
15.1.2.6	expected value	138
15.1.2.7	moment	145
15.1.2.7.1	moment generating function	149
15.1.2.7.2	characteristic function	151
15.1.2.8	common families of distributions	152
15.1.2.8.1	discrete distribution	152
15.1.2.8.2	continuous distribution	156
15.1.2.9	exponential family	158
15.1.2.9.1	binomial distribution with known n	159
15.1.2.9.2	continuous uniform distribution not in exponential family	160
15.1.2.9.3	normal distribution is in exponential family	160
15.1.2.9.4	normal distribution with unknown equal mean and standard deviation in curved exponential family	161
15.1.2.9.5	properties of exponential family	163
15.1.3	multivariable distribution	170
15.2	Chen, Lin-An	170
16	covariance matrix	171
16.1	covariance matrix	171
16.1.1	calculation	171

16.1.2 $V[\mathbf{X} + \mathbf{b}] = V[\mathbf{X}]$	171
16.1.3 $V[\mathbf{A}\mathbf{X}] = AV[\mathbf{X}]A^T$	172
16.1.4 $V[\mathbf{A}\mathbf{X} + \mathbf{b}] = AV[\mathbf{X}]A^T$	172
17 Gosper algorithm	173
18 Lorentz transformation	175
18.1 Einstein	175
18.2 Bondi k -calculus	175
18.3 wordline in Minkowski space	175
18.3.1 Wick rotation	175
18.3.1.1 Osterwalder-Schrader reconstruction theorem	175
19 R	177
19.1 TonyKuoYJ	177
19.1.1 quick intro	177
19.1.1.1 function	178
19.1.2 R style	178
19.1.3 data workflow or forward pipe	178
19.1.3.1 <code>%>%</code> operator	178
19.1.4 data processing with <code>dplyr</code>	179
19.1.5 visualization statically with <code>ggplot2</code>	182
19.1.6 loop	188
19.1.7 variable type	189
19.1.7.1 date	189
19.1.7.2 time	189
19.1.7.3 quotient <code>%%</code> operator	190
19.1.8 data type	190
19.1.8.1 vector	190
19.1.8.1.1 logic	191
19.1.8.1.2 <code>rep</code> repeat	191
19.1.8.1.3 <code>seq</code> sequence	191
19.1.8.2 factor	192
19.1.8.3 matrix	192
19.1.8.4 data frame	193
19.1.8.4.1 selecting variable or column	194
19.1.8.4.2 filtering observation or row	194
19.1.8.4.3 check mixed data type	195
19.2 W3School	195
19.2.1 same multiple variable	195
19.2.2 legal variable name	195
19.2.3 complex number	196
19.2.4 escape character	196
19.2.5 global assignment <code><-></code>	196
19.2.6 data type	196
19.2.6.1 array	196
19.2.6.2 list	197
19.3 Apan Liao	197
19.3.1 data input	197
19.3.2 descriptive statistics	197
20 Laplace transform	199

21 conic section	201
21.1 Cartesian coordinate: focus, directrix, eccentricity	202
21.2 two-definition equivalence for ellipse and hyperbola	204
21.2.1 first definition for conic sections including ellipses and hyperbolas	204
21.2.2 second definition for ellipses and hyperbolas	205
21.2.3 eccentricity and its equivalent representation	208
21.3 Cartesian coordinate: standard form / standard equation	208
21.4 parametric equation	210
21.5 polar coordinate	210
21.6 Cartesian coordinate: general form / quadratic equation	214
21.7 homogeneous coordinate	214
22 distance from a point to a line	217
22.1 by shortest $\overline{PP'}$	217
22.2 by perpendicular foot	218
22.3 by normal vector	219
22.4 by Cauchy inequality	220
23 real symmetric matrix diagonalizable	221
24 tangent half-angle formula	225
25 homogeneous coordinate	227
26 Archimedean property	229
26.1 integer Archimedean property	229
26.2 rational Archimedean property	229
26.3 real Archimedean property	229
27 MatPlotLib / matplotlib	231
27.1 Timothy H. Wu	231
27.1.1 functional API	231
27.1.2 object-oriented API	235
27.1.2.1 Configure the figure size and DPI	236
27.1.2.2 subplot	238
27.1.2.3 color and linestyle	239
27.1.2.4 other inputs	239
27.1.2.5 legend	240
27.1.2.6 customize style	240
27.1.2.7 save to file	240
27.1.3 Seaborn	241
27.1.3.1 basic	243
27.1.3.2 data frame	243
27.1.3.3 axis-level plot and figure-level plot	245
27.1.3.4 accessing figure and axes objects	248
27.1.3.5 distribution plot	248
27.1.3.5.1 histogram	248
27.1.3.5.2 ECDF = empirical cumulative distribution function	249
27.1.3.5.3 KDE = kernel density estimation	250
27.1.3.6 categorical plot	252
27.1.3.7 joint plot	253
27.1.3.8 pair plot	253
27.1.3.9 palette	254

27.1.3.10 volcano plot	254
27.1.3.11 heatmap	254
27.2 export	254
27.2.1 .svg	254
27.2.2 .eps	254
28 survial analysis	257
28.1 Python package <code>tableone</code>	257
28.2 Python package <code>lifelines</code>	257
29 Manim	259
29.1 VSCode extension: Manim Sideview	259
29.2 installation	259
29.2.1 Conda	259
29.3 quickstart	259
30 ggplot2	261
30.1 geom	261
30.1.1 basic plot system decomposition	266
30.2 statistic	268
30.3 scale	269
30.4 coordinate system	270
30.5 facet	271
30.6 jitter	271
30.7 font	271
31 notational system for design	273
31.1 graphic notation	273
31.2 pre-experimental design	273
31.2.1 one-shot case study	274
31.2.2 one-group pretest-posttest design	274
31.2.3 static-group comparison	274
31.3 true experimental design	277
31.3.1 posttest-only control group design	277
31.3.2 pretest-posttest control group design	278
31.3.3 Solomon four-group design	278
31.4 quasi-experimental design	278
31.5 correlational and ex post facto designs	278
31.6 graphic notation, advanced	278
32 design of experiment	281
32.1 notational system for design ^[31]	281
32.2 terminology	281
32.2.1 replication vs. subsample	282
32.2.2 replication vs. repeated measurements	282
32.2.3 replication, replicate	282
32.2.3.1 technical replicate, biological replicate	282
32.2.4 Latin square design	283
32.2.5 model assumption and experimental unit, measurement/observational unit	284
32.3 experiment structure	286
32.3.1 treatment structure	286
32.3.2 design structure	286
32.3.3 size of experimental unit	286

32.4 approach to experimentation	286
32.5 sample size estimation	287
32.6 statistical analysis plan	287
32.7 protocol	287
32.8 DoE course with six sigma and Minitab	287
32.8.1 evolution	287
33 quine	289
33.1 %r	289
34 quaternion	291
34.1 TaylorCatAlice	291
34.1.1 complex / dionion / bionion	291
34.1.2 trionion / triernion / triplex / ternion	291
34.1.3 quaternion	292
34.1.3.1 true origin of (dot product & cross product) / (inner product & outer product)	295
34.1.3.2 commutativity vs. anticommutativity	297
34.1.3.2.1 commutativity	297
34.1.3.2.2 anticommutativity	297
34.1.3.3 bracket	297
34.1.3.3.1 self-invented bracket	297
34.1.3.3.2 Poisson bracket	297
34.1.3.3.3 Lagrange bracket	297
34.1.3.3.4 Lie bracket	297
34.1.3.4 triple product	298
34.1.3.5 differential operator	300
34.1.3.5.1 4-differential operator	300
34.1.3.5.2 nabla	301
34.1.3.5.3 Laplace operator	301
34.1.3.5.4 d'Alembert operator	301
34.1.3.6 electromagnetism	301
34.1.3.6.1 4-potential	301
34.1.3.6.2 Maxwell compromise for both quaternion and 3-vector	303
34.1.3.7 Joule heat vs. Thomson heat (Kelvin heat?)	304
34.1.3.7.1 thermoelectric effect	304
34.1.3.8 source term	304
34.1.4 quaternion group	304
34.1.4.1 2D rotation	305
34.1.4.1.1 matrix	305
34.1.4.1.2 complex	307
34.1.4.1.3 $SO(2) \cong U(1)$	307
34.1.4.2 3D rotation	307
34.1.4.2.1 matrix	307
34.1.4.2.2 quaternion	311
34.1.5 octonion	313
34.2 Krasjet	313
34.2.1 Rodrigues rotation	313
34.2.2 quaternion operation	315
34.2.3 matrix form	323
34.2.4 exponential form	325
34.2.5 double cover	326

34.2.6 right-hand vs. left-hand	326
34.2.7 gimbal lock	326
34.2.8 Lie group	326
34.2.8.1 special unitary group	326
34.2.9 geometric algebra and Clifford algebra	326
34.2.10 dual quaternion	327
34.2.11 interpolation	327
34.2.11.1 Lerp	327
34.2.11.2 Nlerp	327
34.2.11.3 Slerp	327
34.3 3Blue1Brown	327
34.3.1 Ben Eater	327
34.3.2 3B1B	327
34.3.3 Sutrabla	327
34.4 CCJou: LA Revelation	327
35 DICOM	329
35.1 Innopolis: DICOM Standard Browser	329
35.2 David Clunie: Medical Image Format Site	329
36 tendon pathophysiology	331
36.1 histology	331
37 group theory	333
37.1 matrix group	333
37.2 group definition and basic theorem	333
37.3 Polya enumeration theorem	334
37.4 complex group representation	334
37.4.1 complex basis group	334
37.4.2 $\mathbb{C} \rightarrow \mathcal{M}_{2 \times 2}(\mathbb{R})$	335
37.4.3 (determinant of complex group representation) equivalent to (squared modulus of complex number)	336
37.4.3.1 Lagrange identity	336
37.4.4 Euler formula proved by complex group representation	337
37.5 quaternion group representation	338
37.5.1 $\mathbb{H} \rightarrow \mathcal{M}_{2 \times 2}(\mathbb{C})$	338
37.5.1.1 Euler identity	340
37.5.2 $\mathbb{H} \rightarrow \mathcal{M}_{4 \times 4}(\mathbb{R})$	342
38 tensor	345
38.1 Einstein summation convention	345
38.1.1 dummy index	345
38.1.2 free index	345
38.2 Elliot Schneider	345
38.2.1 Fundamentals of Cartesian Tensors	345
38.2.2 Fundamentals of Curvilinear Tensors	345
38.2.3 Fundamentals of Spacetime Tensors	345
39 dual space	347
39.1 linear equations	347
39.2 matrix multiplication	348
39.3 functional	349
39.4 definition of linear functional	352

39.5 set of all linear transformations is a vector space	353
39.6 definition of dual space	356
39.7 double dual	356
40 vector space	357
40.1 What is a vector?	357
40.2 vector space definition	357
40.2.1 commutative group structure of vector space	358
40.2.2 scalar distributivity	359
40.3 linearity	360
40.3.1 linear structure of vector space	360
40.3.2 linear transformation or linear map	360
40.4 vector space example	360
40.4.1 reciprocal space	361
40.4.1.1 Kronecker delta	361
40.4.1.2 double dual concept	363
40.5 field	365
40.6 module	365
40.7 subspace	365
41 df	367
41.1 df decomposed with partials as a set of basis in vector space	367
41.2 dual space of span of partials	368
41.3 directional derivative	369
41.4 coefficient of linear combination for vector space and dual space	369
41.5 change of basis / change of coordinate	370
42 determinant	371
42.1 induction of determinant axioms	371
42.2 determinant axioms	371
42.3 determinant theorems or properties	371
42.4 ellipse area	371
42.5 Cramer rule geometry perspective	371
43 hypergeometric function	373
43.1 linear space of function	373
43.2 beta function	373
43.3 gamma function	373
43.4 recursion	373
43.5 mean and variance of discrete probability distributions	373
44 Feynman method	375
44.1 Feynman method of derivative	375
44.2 Feynman method of integral	375
44.3 path integral	375
45 Hilbert space	377
45.1 Taylor expansion or Taylor series	377
45.1.1 Elliot Schneider	384
45.1.1.1 making complicated equation simple	386
45.1.1.2 non-relativistic limit	386
45.1.1.3 quantum momentum operator	386
45.2 Dirac delta function	387

45.3 Fourier expansion or Fourier series	387
45.4 Hilbert space	387
45.5 Dirac bracket	387
45.6 quantum operator	387
45.7 Gram-Schmidt algorithm to find orthonormal basis	387
45.8 Hermite polynomials and Legendre polynomials	387
46 Lagrange inversion	389
47 quantum color dynamics	391
48 Lagrangian	393
49 Hamiltonian	395
50 Fourier analysis	397
50.1 Simon Xu	397
50.1.1 DFT = discrete Fourier transform	397
50.1.2 FFT = fast Fourier transform	397
50.1.3 wavelet	397
51 axiom of choice	399
51.1 Zorn lemma	399
52 linear algebra	401
52.1 CCJou	401
52.2 Chi, Chen-Yu	401
53 analysis	403
53.1 Chi, Chen-Yu	403
53.2 Chen, Jin-Tzu	403
54 matrix calculus	405
54.1 vector-by-scalar	405
54.2 scalar-by-vector	405
54.3 vector-by-vector	406
54.3.1 numerator-layout notation	406
54.3.2 denominator-layout notation	406
55 genetics	407
55.1 term	407
55.2 marker	407
55.3 genome project	407
55.4 linkage analysis	408
55.4.1 PLA = parametric linkage analysis	409
55.4.2 VCLA = variance component linkage analysis	410
55.5 association analysis	410
56 multivariate normal distribution	411
56.1 bivariate normal distribution	419
57 logic	421
57.1 Shai Ben-David	421

58 algorithm	423
58.1 Chen, Vivian	423
58.2 The Bubble Sort Curve	423
59 computer graphics	425
59.1 Cem Yuksel	425
60 autoregression in time series	427
60.1 AR(1) = 1 st -order autoregressive model = first-order autoregressive model	429
60.2 AR(2) = 2 nd -order autoregressive model = second-order autoregressive model	431
60.3 AR(p) = p^{th} -order autoregressive model	432
60.4 MA(q) = q^{th} -order moving-average model	432
60.5 ARMA(p,q) = $p^{\text{th}}, q^{\text{th}}$ -order autoregressive-moving-average model	432
61 conductivity	433
61.1 resistance	433
61.2 semiconductor	433
references	435

index

math on bookdown started on 2024/01/28

Part I

by discipline

Chapter 1

mathematics

1.1 tool

- formula typesetting
 - TeX
 - * LaTeX
 - pdfTeX
 - XeTeX
 - editor/tool:
 - LyX
 - OverLeaf
 - MathPix Snip
 - Microsoft Office Word
 - WordTeX <https://tomwildenhain.com/wordtex/>
 - Pandoc dependent
 - <https://superuser.com/questions/1114697/select-a-different-math-font-in-microsoft-word>
 - https://www.youtube.com/watch?v=jIX_pThh7z8
 - Microsoft Office PowerPoint
 - IguanaTeX <https://www.jonathanleroux.org/software/iguanatex/>
 - MathML
 - MathJax: JavaScript
 - plot^[3]
 - symbolic computing
 - Maple: by MapleSoft
 - Mathematica: by Wolfram
 - numeric computing
 - MatLab: by MathWorks

equivalence relation^[11]

equivalence class^[10]

partition^[9]

1.2 discipline

Chapter 2

physics

2.1 discipline

- relativity
 - special relativity
 - * Lorentz transformation^[18]
 - general relativity
- analytic mechanics
 - Lagrangian mechanics
 - Hamiltonian mechanics
- electromagnetism
- quantum mechanics
- field theory

Chapter 3

plot

- LaTeX
 - [TikZ](#)^[13]
 - * <https://tikz.dev/>
 - * TikZ-3Dplot
 - * [PGFplots](#)^[13.4]
 - <https://tikz.dev/pgfplots/>
 - <https://pgfplots.sourceforge.net/gallery.html>
 - <https://pgfplots.net/>
 - * editor / export
 - <https://zhuanlan.zhihu.com/p/660371706>
 - offline
 - [TikzEdt](#): WYSIWYG and live preview
 - [TikZiT](#)
 - online
 - OverLeaf
 - MathCha
 - GeoGebra Classic
 - Python
 - [TikZplotLib](#) / [tikzplotlib](#)^[13.5]
 - matplotlib export to TikZ .tex
 - [PyPI](#)
 - [GitHub](#)
 - R
 - [TikZDevice](#) / [tikzDevice](#)
 - r chunk engine='tikz' knitr out.width=if (knitr:::is_html_output()) '100%'
 - [CRAN](#)
 - [reference manual](#)
 - vignette: [TikZDevice - LaTeX Graphics for R](#)
 - [GitHub](#)
 - * [TikZ library](#)
 - [xypic](#) = [xy-pic](#)^[14]
- [OverLeaf](#)
- [MathCha](#)
- [GeoGebra](#)
 - [GeoGebra Classic](#): to export TikZ

- GeoGebra Calculator Suite
- Python
 - Matplotlib / matplotlib^[27]
 - Seaborn / seaborn^[27.1.3]
 - Plotly
 - Manim
- R
 - Modern Statistical Graphics
 - ggplot2^[30]
 - * Modern Statistical Graphics [section 5.1](#)
 - GraphViz .gv
 - Mermaid .mmd
 - * **about**
 - * JavaScript based diagramming and charting tool that renders Markdown-inspired text definitions to create and modify diagrams dynamically
 - Shiny
 - * R Markdown Guide [section 5.1](#)
 - tool
 - * Jamovi

neural network plot/draw <https://github.com/ashishpatel26/Tools-to-Design-or-Visualize-Architecture-of-Neural-Network>

Chapter 4

programming language

4.1 discipline

- [Python](#)^[12]
- JavaScript
- SQL = structured query language
- [R](#)^[19]
 - RMarkdown
 - * Bookdown
 - knitr: engine
 - * [TikZ](#)^[13]
 - reticulate: Python
 - Jamovi
- C#
 - web
 - * MVC
 - * .NET
 - desktop
 - * UWP = Universal Windows Platform
 - * WPF = Windows Presentation Foundation
 - * WinForms = Windows Forms
 - 3D/game
 - * Unity

4.2 learning map

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

Chapter 5

machine learning

我妻幸長

5.1 Shai Ben-David

<https://www.youtube.com/playlist?list=PLPW2keNyw-usgymR7FTQ3ZRjfLs5jT4BO>

Part II

by date

Chapter 6

A Minimal Book Example

6.1 About

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

6.1.1 Usage

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

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

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

6.1.2 Render book

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

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

Or build the book from the R console:

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

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

6.1.3 Preview book

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

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

6.2 Hello bookdown

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

6.2.1 A section

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

An unnumbered section

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

6.3 Cross-references

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

6.3.1 Chapters and sub-chapters

There are two steps to cross-reference any heading:

1. Label the heading: # Hello world {#nice-label}.
 - Leave the label off if you like the automated heading generated based on your heading title: for example, # Hello world = # Hello world {#hello-world}.
 - To label an un-numbered heading, use: # Hello world {-#nice-label} or {# Hello world .unnumbered}.
2. Next, reference the labeled heading anywhere in the text using \@ref(nice-label); for example, please see Chapter 6.3.
 - If you prefer text as the link instead of a numbered reference use: [any text you want can go here](#).

6.3.2 Captioned figures and tables

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

See Figure 6.1.

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

Don't miss Table 6.1.

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

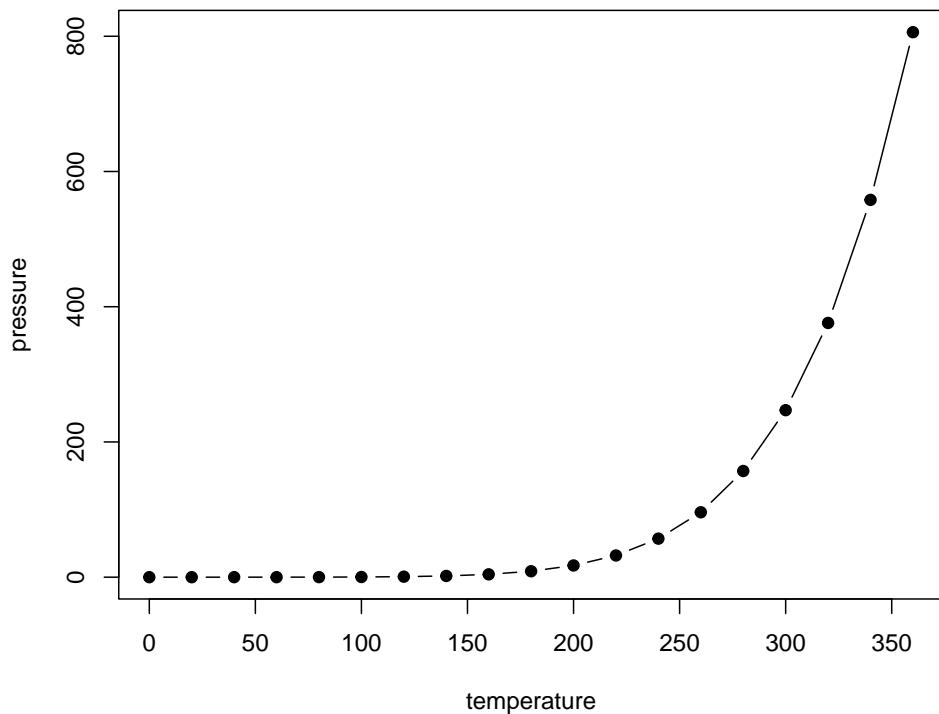


Figure 6.1: Here is a nice figure!

Table 6.1: Here is a nice table!

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

6.4 Parts

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

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

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

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

6.5 Footnotes and citations

6.5.1 Footnotes

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

6.5.2 Citations

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

For example, we are using the `bookdown` package¹ (check out the last code chunk in index.Rmd to see how this citation key was added) in this sample book, which was built on top of R Markdown and `knitr`² (this citation was added manually in an external file book.bib). Note that the `.bib` files need to be listed in the index.Rmd with the YAML `bibliography` key.

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

6.6 Blocks

6.6.1 Equations

Here is an equation.

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

You may refer to using `\@ref(eq:binom)`, like see Equation (6.1).

6.6.2 Theorems and proofs

Labeled theorems can be referenced in text using `\@ref(thm:tri)`, for example, check out this smart theorem 6.1.

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

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

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

¹This is a footnote.

6.6.3 Callout blocks

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

6.7 Sharing your book

6.7.1 Publishing

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

6.7.2 404 pages

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

6.7.3 Metadata for sharing

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

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

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

Read more about the features of this output format here:

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

Or use:

```
?bookdown::gitbook
```


Chapter 7

test

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

7.1 RStudio

7.1.1 writer options

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

7.1.1.1 line wrapping

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

7.1.1.2 ensuring the same markdown between source / visual mode

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

canonical mode

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

```
---
```

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

7.1.2 Rtools

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

7.1.3 addins

```
https://github.com/rstudio/addinexamples

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

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

7.1.4 Git

commit: filename or extension is too long

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

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

7.2 RMarkdown

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

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

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

7.2.1 Pandoc link

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

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

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

7.2.2 URL

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

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

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

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

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

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

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

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

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

```
[1]: http://slashdot.org
[link text itself]: http://www.reddit.com
```

7.2.3 arrow

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

Up arrow: ↑

Down arrow: ↓

Left arrow: ←

Right arrow: →

Double headed arrow: ↔

7.2.4 superscript and subscript

script^{superscript}_{subscript}

script^{superscript}[^]

script^{superscript}

\sim subscript \sim

script_{subscript}

7.2.4.1 LaTeX

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

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

7.2.5 equation

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

7.2.5.1 proof QED

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

\tag*{\$\Box\$}

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

□

\tag*{\$\blacksquare\$}

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

■

7.2.6 image

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

7.2.6.1 DiagrammeR / mermaid flowchart

Error: Functions that produce HTML output found in document targeting latex output.
 Please change the output type of this document to HTML.
 If you're aiming to have some HTML widgets shown in non-HTML format as a screenshot,
 please install webshot or webshot2 R package for knitr to do the screenshot.
 Alternatively, you can allow HTML output in non-HTML formats
 by adding this option to the YAML front-matter of
 your rmarkdown file:

```
always_allow_html: true
```

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

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

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

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

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

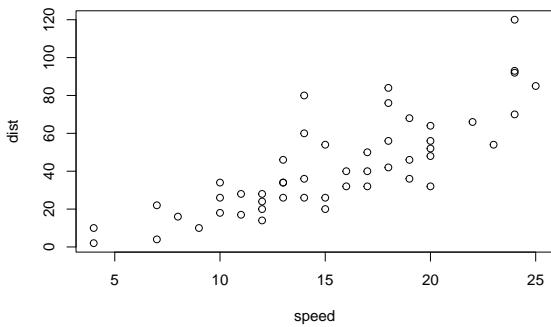
<https://stackoverflow.com/questions/55994210/how-to-solve-diagrammer-waste-of-space-issue-in-rmarkdown>

7.2.6.2 multiple images / figures in the same line

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

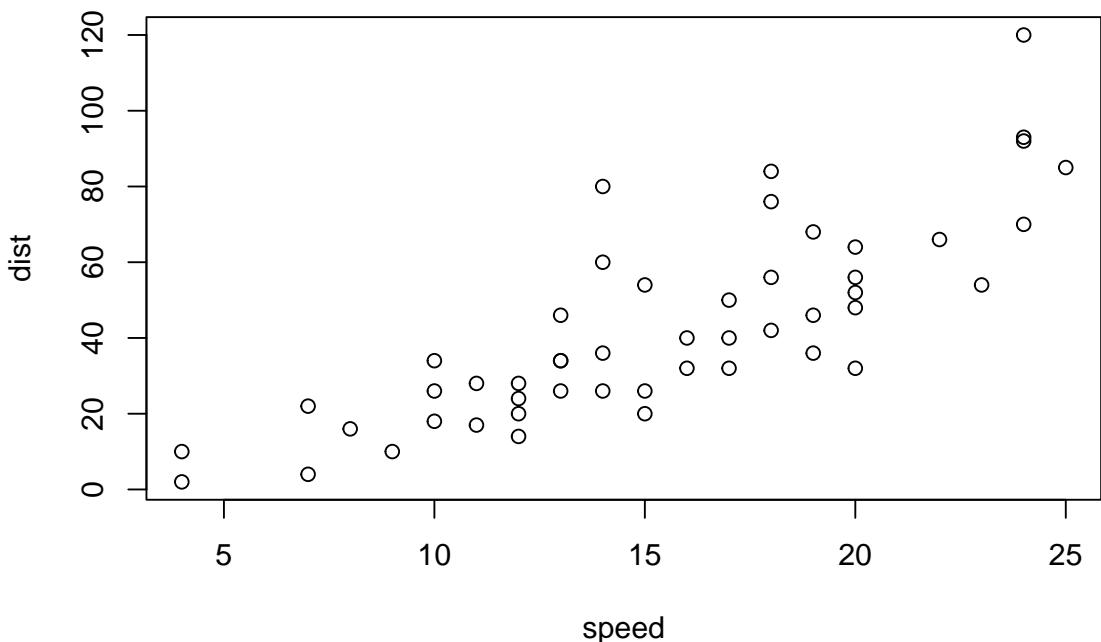
```
{r, fig.show = "hold", out.width = "50%"}
plot(cars)
plot(nhtemp)

plot(cars)
plot(nhtemp)
```

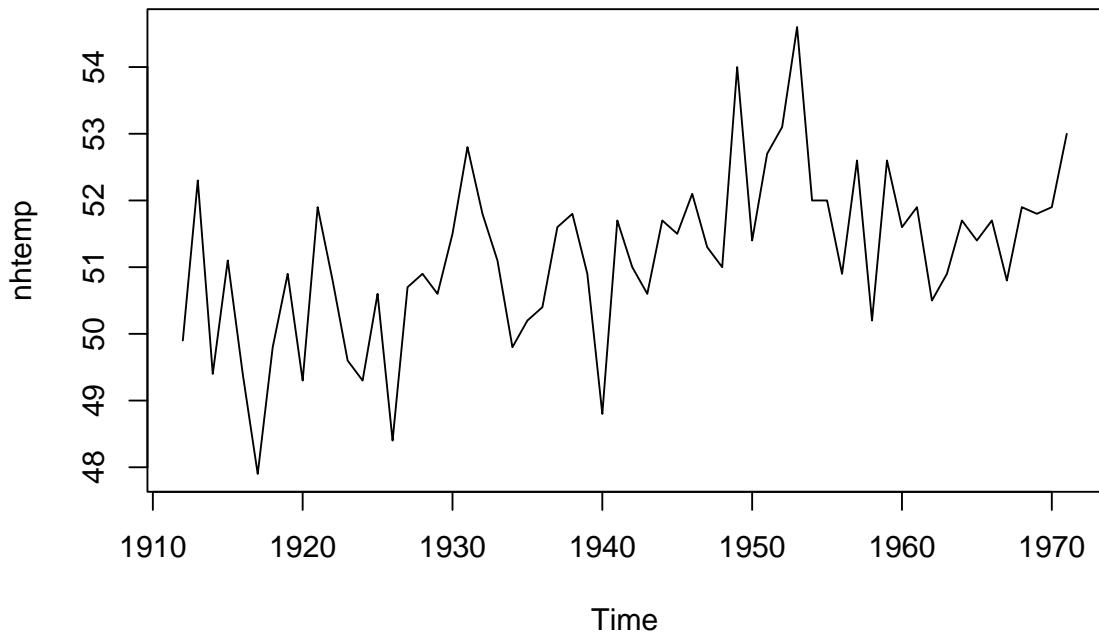


cf.

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



```
plot(nhtemp)
```



7.2.6.3 figure size

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

YAML in index.Rmd

```
---
```

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

first R-chunk in your RMD document

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

width, height and options

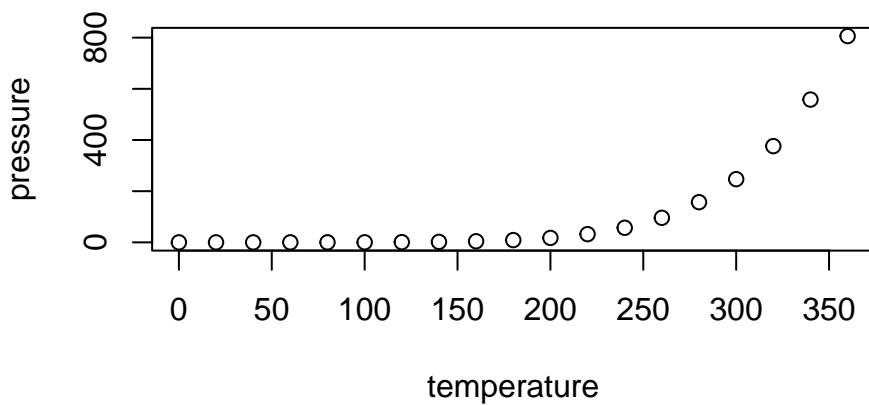
```
```{r fig.height = 3, fig.width = 5}
```

```
plot(pressure)
```

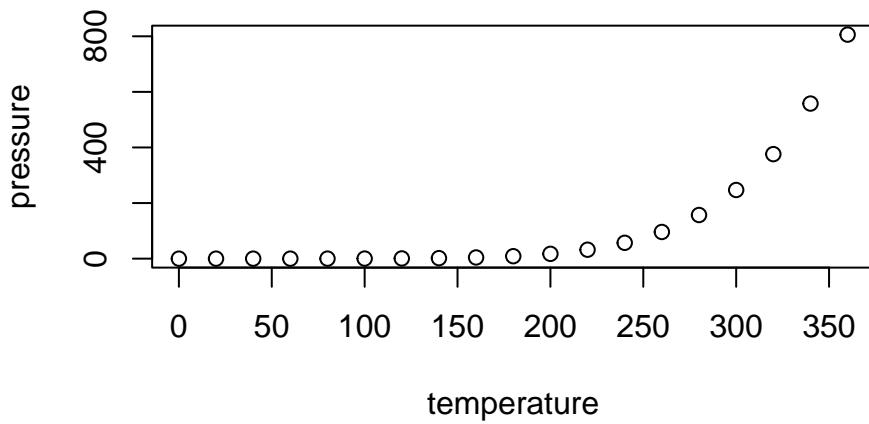
```
```
```

```
{r fig.height = 3, fig.width = 5}
```

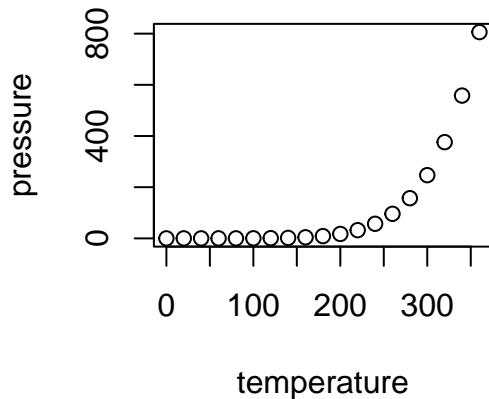
```
plot(pressure)
```



```
{r fig.height = 3, fig.width = 3, fig.align = "center"
plot(pressure)}
```



```
{r fig.width = 5, fig.asp = .62
plot(pressure)}
```

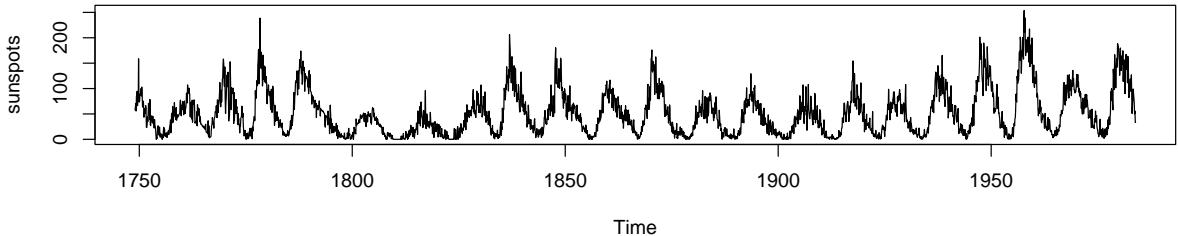


```
<center>
! [] (https://bookdown.org/yihui/rmarkdown-cookbook/images/cover.png){width=20%}
</center>
```

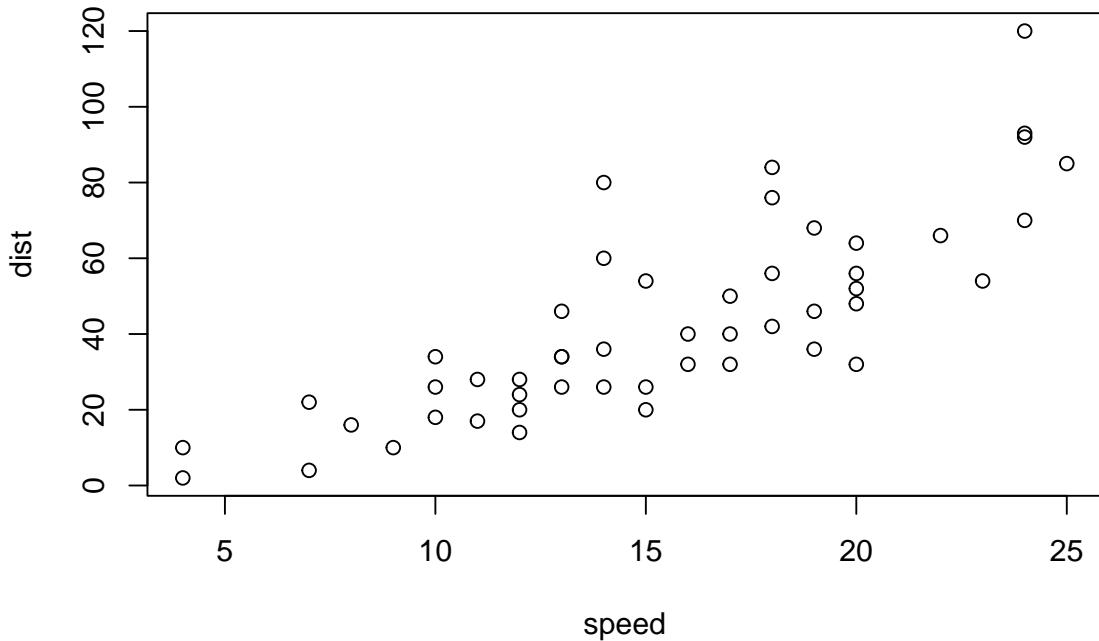
7.2.6.3.1 knitr <https://yihui.org/knitr/options/>

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

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



```
plot(cars)
```



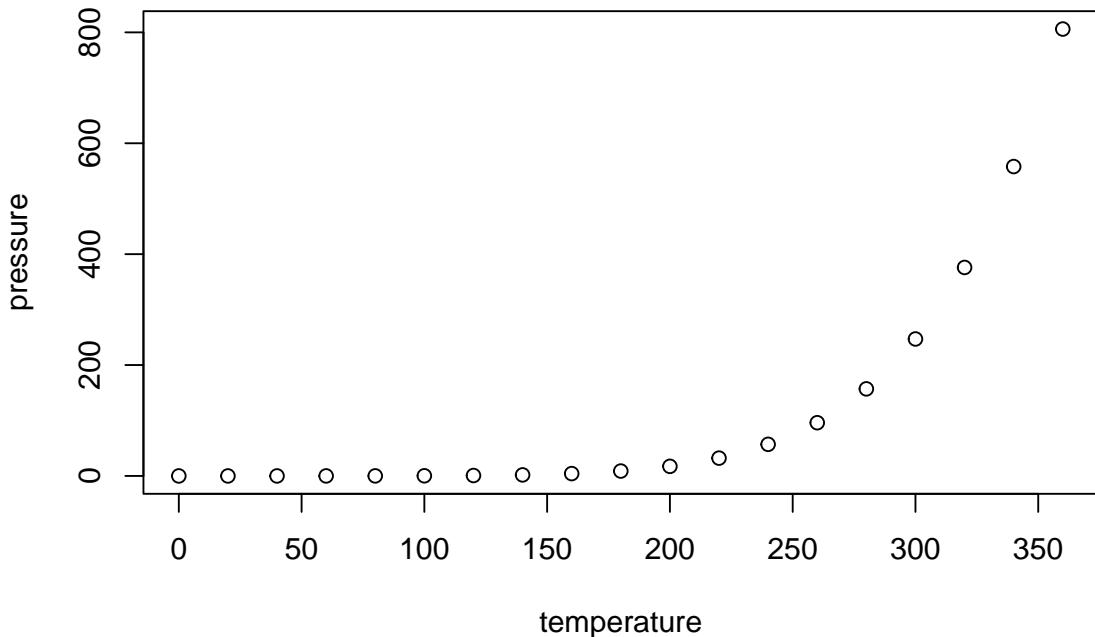
We know from the first fundamental theorem of calculus that
for x in $[a, b]$:

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

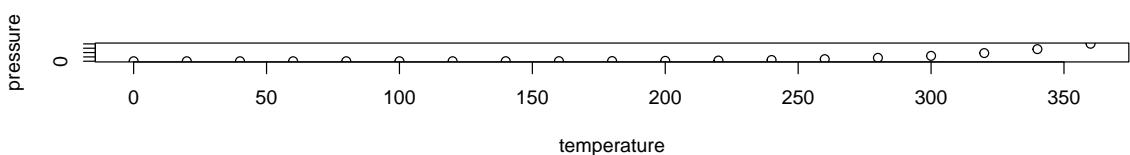
7.2.6.3.2 `out.width` vs. `fig.width` <https://stackoverflow.com/questions/29657777/how-to-make-fig-width-and-out-width-consistent-with-knitr>

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

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



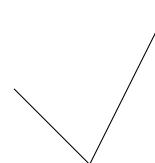
```
plot(pressure)
```



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

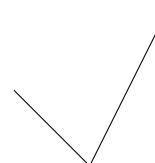
solution: `out.width=if (knitr:::is_html_output()) '100%'`

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



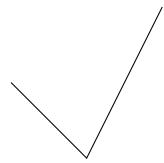
`fig.width=10, fig.height=2`

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



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

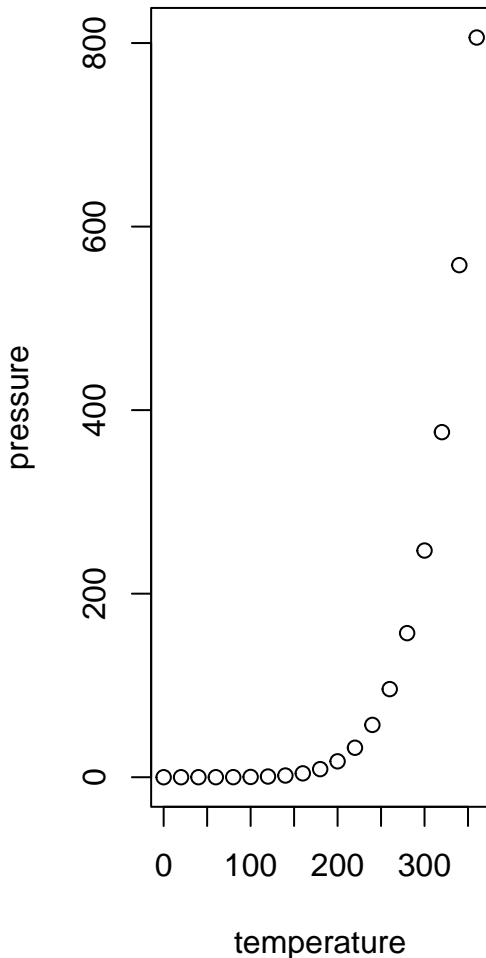
```
\begin{tikzpicture}
  \draw (-1,1)--(0,0)--(1,2);
\end{tikzpicture}
```



7.2.6.4 dynamic knitr plot width and height

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

```
plot(pressure)
```



7.2.6.5 web image in PDF

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

```

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

```

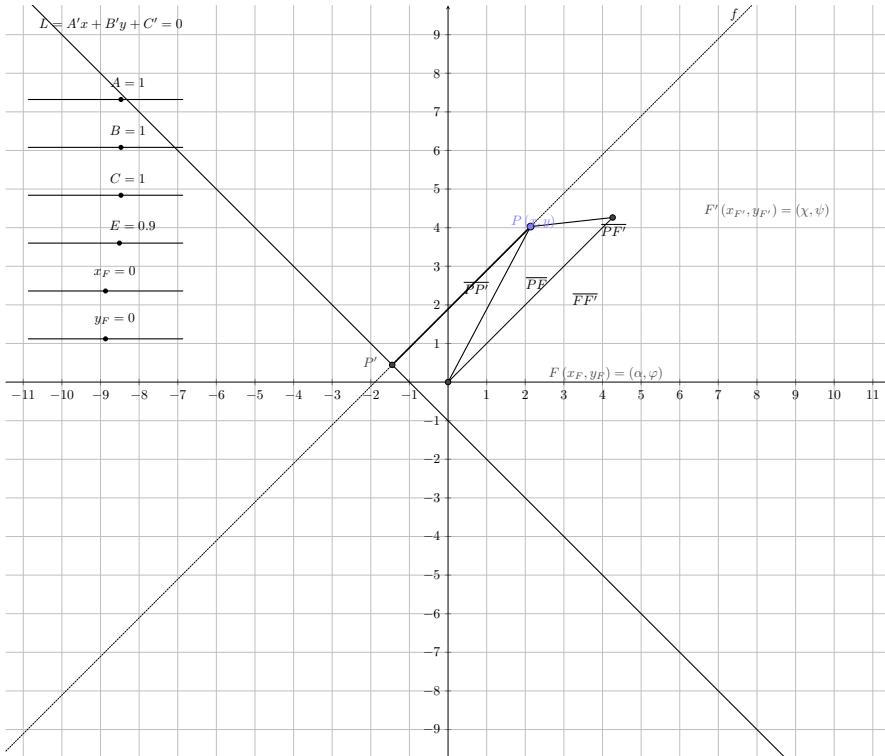


Figure 7.1: conic sections

7.2.6.6 SVG

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

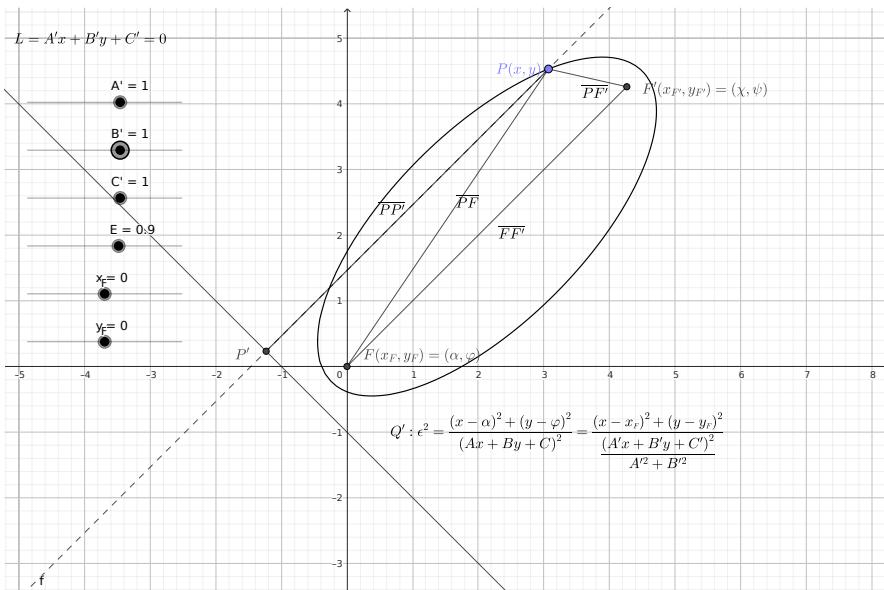
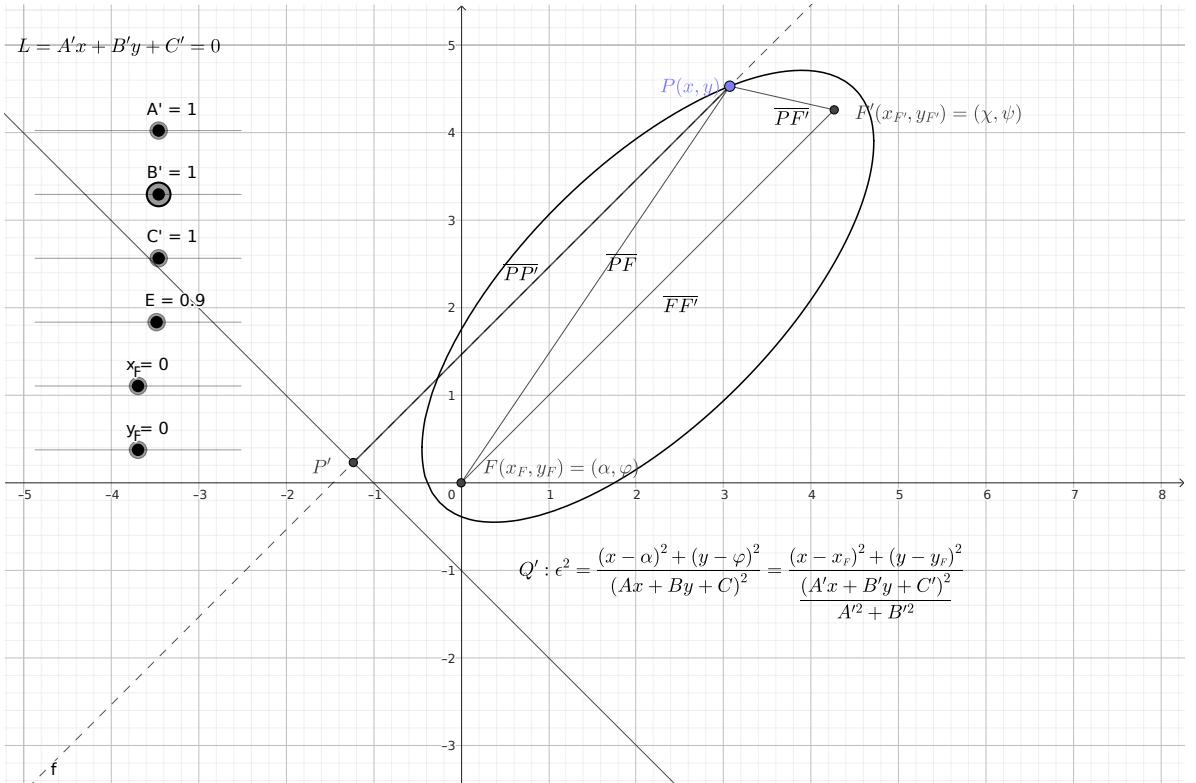


Figure 7.2: conic sections

7.2.7 horizontal rule

horizontal rule (or slide break)

```
dim(iris)
```

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

7.2.8 footnote

7.2.9 hyperlink

PDF pandoc internal link will lose focus

equivalence relation [11] equivalence relation¹ equivalence relation^[11]

equivalence class [10] equivalence class² equivalence class^[10]

partition [9] partition³ partition^[9]

- LaTeX
 - TikZ^[13]
 - * TikZ-3Dplot
 - * PGFplots
 - xypic = **xy-pic**⁴
- OverLeaf
- MathCha
- GeoGebra
- Python
 - MatPlotLib
 - Seaborn
 - Plotly

7.2.10 code chunk

7.2.10.1 code folding

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

7.2.11 xaringan

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

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

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

¹{11} equivalence relation

²{10} equivalence class

³{9} partition

⁴{14} xy-pic

7.3 Bookdown

7.3.1 system locale

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

Sys.getlocale()

Windows

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

MacOS

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

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

7.3.2 render_book()

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

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

7.3.3 serve_book()

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

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

7.3.4 LaTeX

7.3.4.1 hyperlink, URL, href

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

<https://www.omidte.com/> 小技巧讓facebook和line顯示中文網址，網址不再變亂碼/

7.3.4.2 ugly mathptmx \sum

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

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

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

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

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

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

In `preamble.tex`, add

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

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

7.3.4.3 LaTeX package in HTML document

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

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

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

\cancel{x}

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

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

7.3.5 depth of table of contents `toc_depth`

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

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

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

```
toc:
  collapse: section
```

7.3.6 multi-column layout / two columns

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

7.3.6.1 for both HTML and PDF

figure size^[7.2.6.3]

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

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

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

::: {.col data-latex="{0.05\textwidth}"}
\

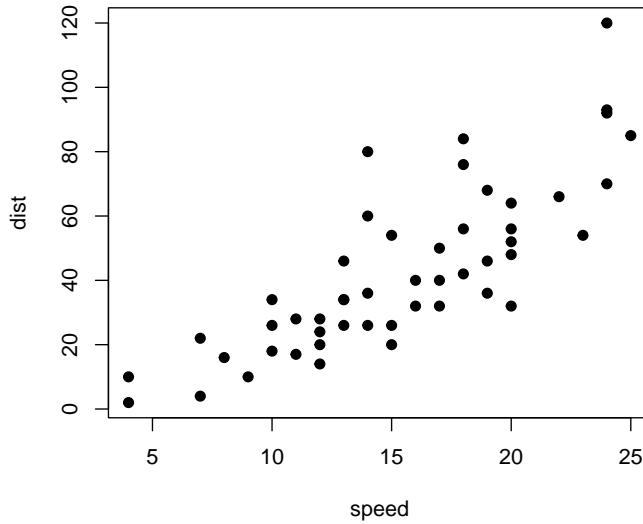
<!-- an empty Div (with a white space), serving as
a column separator -->
:::

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

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

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

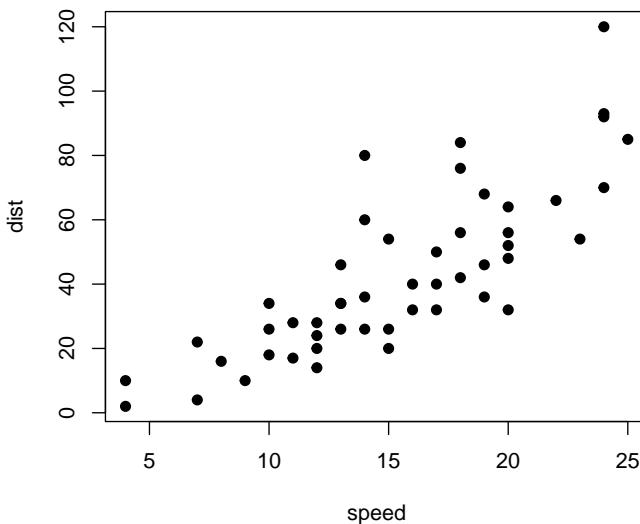
```
{r, echo=FALSE, fig.width=5, fig.height=4}
```



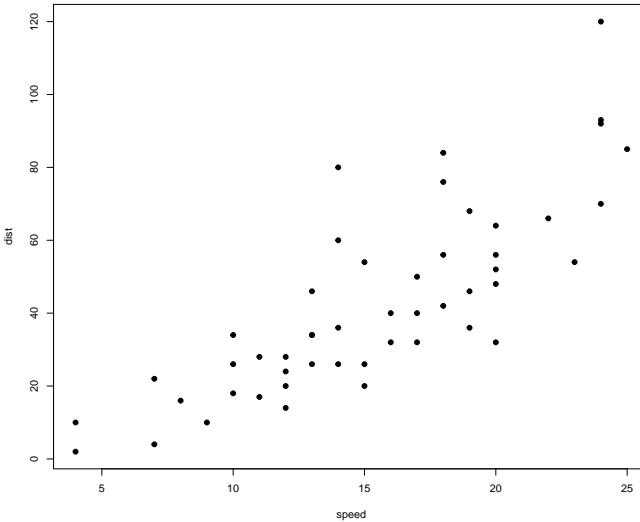
The figure on the left-hand side shows the cars data.

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

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



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



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

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

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

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

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

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

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

to avoid `\LaTeX` Error: Not in outer `par` mode for caption in multi-column `\LaTeX` PDF

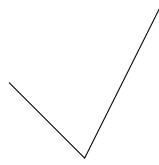
in `output.yml` add `extra_dependencies: ["float"]` under `bookdown::pdf_book:`

include first chunk `knitr::opts_chunk$set(fig.pos = "H", out.extra = "")` in `.Rmd`

add `out.width=if (knitr:::is_html_output()) '50%'` for TikZ chunk

thus complete chunk beginning with `{r, echo=FALSE, cache=TRUE, engine='tikz', fig.ext=if (knitr:::is_latex_output()) 'pdf' else 'png', fig.width=10, fig.height=2, out.width=if (knitr:::is_html_output()) '100%', fig.cap=''`

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



LaTeX package `caption`

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

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

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

side-by-side table

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

R ternary operator

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

7.3.6.3 caption above figure

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

`fig.topcaption=TRUE`

7.3.6.4 for only HTML

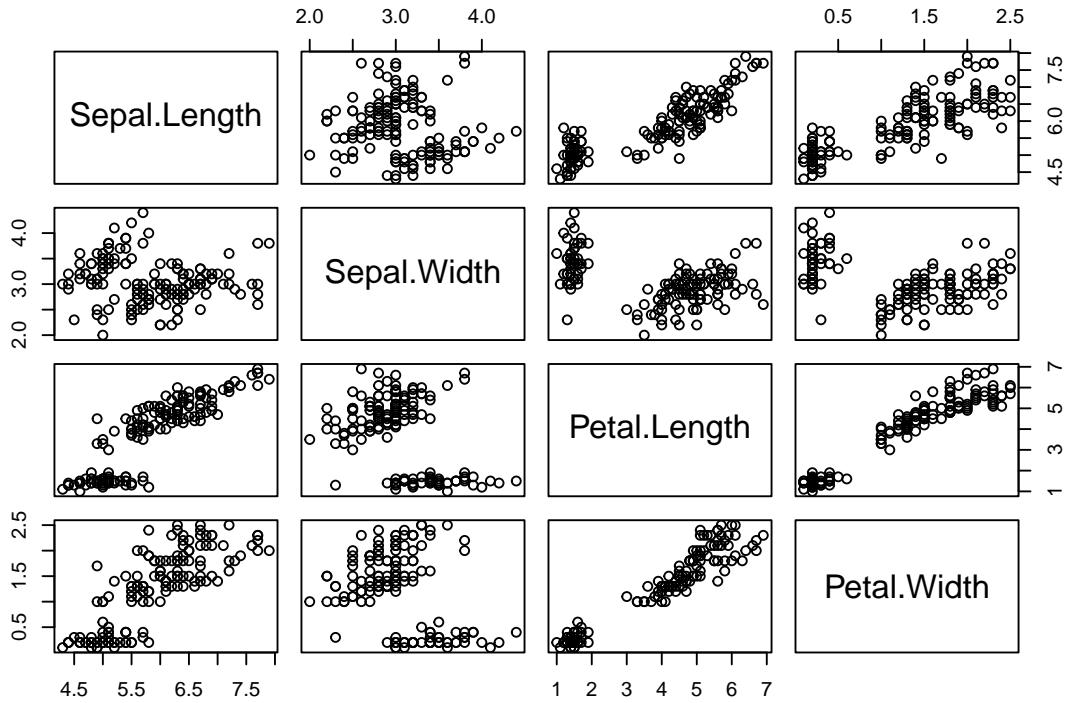
7.3.6.4.1 CSS flex Here is the **first** Div.

```
str(iris)
```

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

And this block will be put on the right:

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



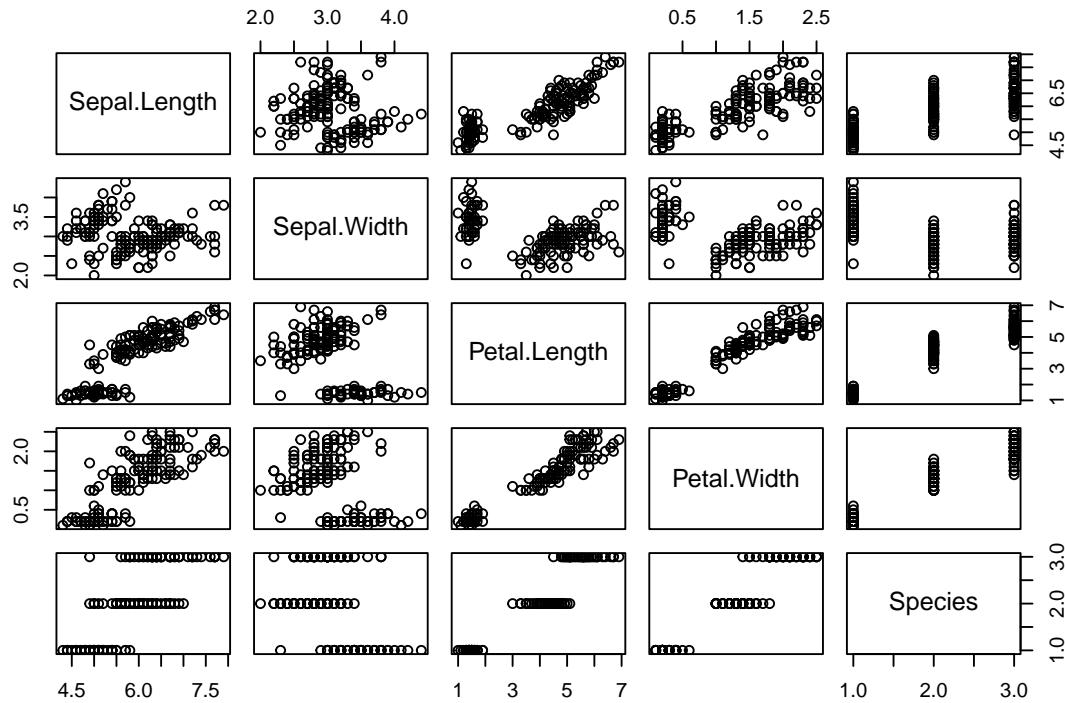
7.3.6.4.2 CSS grid <https://github.com/yihui/knitr/issues/1743>

<https://medium.com/enjoy-life-enjoy-coding/css-所以我說那個版能不能好切一點-grid-基本用法-cd763091cf70>

```
head(iris)
```

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

```
plot(iris)
```



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

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

等價關係 equivalence relation

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

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

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

7.5 video embedding

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

always_allow_html: true

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

however webshot not work

Error: cannot find bilibili.com

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

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

```
## embed_youtube("0LFg5dvP0oc")
```

7.5.1 timestamp

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

7.6 equation term coloring

7.6.1 font color

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

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

\color{orange}x=y

x = y

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

\color{cyan}{x=y}

x = y

\color{cyan}{x=y}

x = y

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

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

:::
```

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

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

:::
```

7.6.2 background color

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

LaTex color

<https://latexcolor.com/>

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

<https://latex-tutorial.com/color-latex/#%3A:text=To%20summarize%2C%20pyellow!50efined%20colors%20in,w>

LaTex color methods

color frame

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

color box

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

color box with round corners

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

highlighting

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

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

LyX

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

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

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

$$F = ma$$

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

$$F = ma$$

$$F = F$$

$$F = ma$$

(7.1)

$$F = ma$$

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

7.7 link and reference

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

$$E = mc^2 \quad (7.2)$$

```
\@ref(nice-label) 7.8
[link to partition] [partition] link to partition
[partition] \@ref(partition)
partition [#partition] (9) @ref(#partition)
[equivalence class] \@ref(equivalence-class)
equivalence class (10)
equivalence class [#equivalence class] (@ref(equivalence class)) @ref(#equivalence class)
[equivalence-class] [#equivalence-class] (10) @ref(#equivalence-class)
X [equivalence-class.html] [equivalence-class.html#equivalence-class] (@ref(equivalence-class.html))
@ref(equivalence-class.html#equivalence-class)
equivalence relation [#equivalence relation] (@ref(equivalence relation)) @ref(#equivalence relation)
[equivalence-relation] [#equivalence-relation] (11) @ref(#equivalence-relation)
X [equivalence-relation.html] [equivalence-relation.html#equivalence-relation] (@ref(equivalence-relation.html))
@ref(equivalence-relation.html#equivalence-relation)
```

7.8 number and reference equations

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

[\#eq:emc \@ref\(eq:emc\)](https://bookdown.org/yihui/rmarkdown/bookdown-markdown.html#equations)

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

C is an equivalence class of a on A

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

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

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

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

This cross reference is the Fig. 7.4

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

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

7.9 footnote

```
noun5 [This is a footnote]
noun[^202401260000-test-cross-link-1]
[^202401260000-test-cross-link-1]: This is a footnote.
```

noun⁵

7.10 citation

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

citation 1³ citation 2³

citation 3⁴ citation 4⁴

⁵This is a footnote.

7.10.1 citation in fig.cap

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

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

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

Figure 7.3: pre- and true experimental designs (⁵ p.8)

7.10.2 backreference

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

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

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

7.11 environment for definition, theorem, proof

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

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

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

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

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

Proof Name. Here is my proof. □

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

$$a^2 + b^2 \stackrel{7.2}{=} c^2$$

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

number and reference equations

(7.3)

(7.2)

7.2

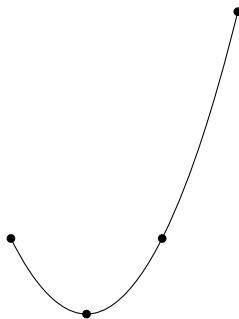


Figure 7.4: parabola arc with points

7.12 slide or presentation

7.12.1 Xaringan and Infinite Moon Reader

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

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

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

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

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

7.12.2 ioslides

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

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

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

```
---
```

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

```
/* theorem environment _ plain */

/*
.theorem {
  display: block;
  font-style: italic;
  font-size: 24px;
  font-family: "Times New Roman";
  color: black;
}
.theorem::before {
  content: "Theorem. ";
  font-weight: bold;
  font-style: normal;
}
.theorem[text]::before {
  content: "Theorem (" attr(text) ") ";
}
.theorem p {
  display: inline;
}
*/
/* theorem environment _ Copenhagen style */

/*
.theorem {
  display: block;
  font-style: italic;
  font-size: 24px;
  font-family: "Times New Roman";
  color: black;
  border-radius: 10px;
  background-color: rgb(222,222,231);
  box-shadow: 5px 10px 8px #888888;
}
.theorem::before {
  content: "Theorem. ";
  font-weight: bold;
  font-style: normal;
  display: inline-block;
  width: -webkit-fill-available;
  color: white;
```

```
border-radius: 10px 10px 0 0;  
padding: 10px 5px 5px 15px;  
background-color: rgb(38, 38, 134);  
}  
.theorem p {  
    padding: 15px 15px 15px 15px;  
}  
*/
```

7.12.3 PowerPoint

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

Chapter 8

test2

8.1 verbatim

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

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

```
```r  
1 + 1
[1] 2
```

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

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

The content can contain inline code like
78.5398163, too.

Chapter 9

partition

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

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

Chapter 10

equivalence class

C is an equivalence class of a on A

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

where the definition of **equivalence relation** can be found in 11.

Chapter 11

equivalence relation

等價關係 equivalence relation

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

$$\Leftrightarrow \left\{ \begin{array}{l} R = \sim = \{\langle x, y \rangle | x \sim y\} \subseteq A \times B \\ \vdots \end{array} \right. \quad (\text{e}) \text{ equivalence 等價}$$

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

Chapter 12

Python

12.1 using Python in R / RMarkdown

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

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

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

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

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

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

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

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

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

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

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

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

# use_virtualenv("r-reticulate")

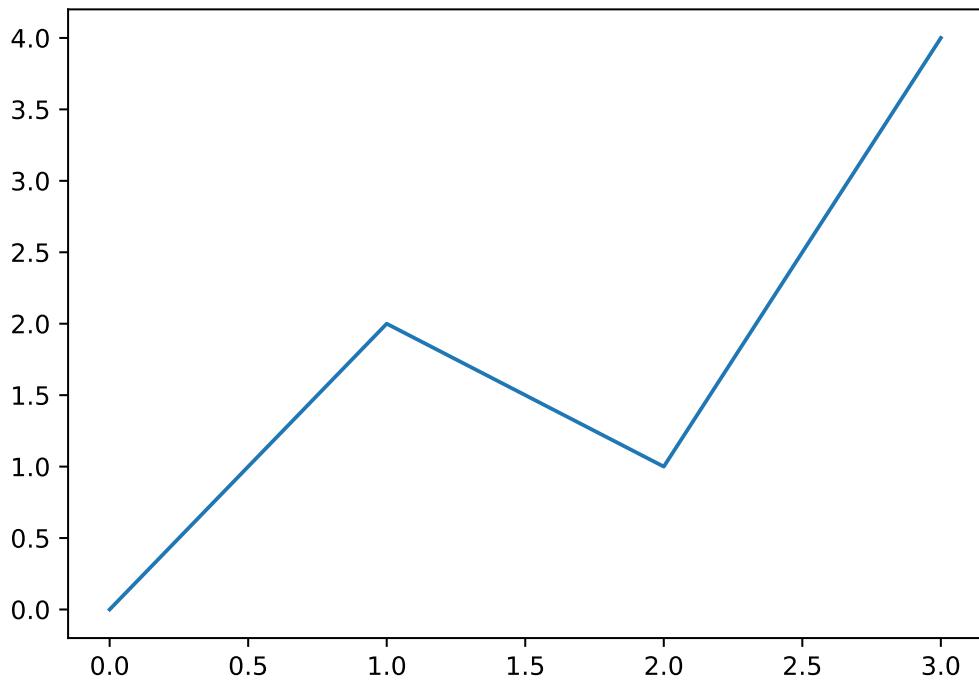
## install Matplotlib
# virtualenv_install("r-reticulate", "matplotlib")

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

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

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

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



12.2 SoloLearn

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

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

12.3 list comprehension

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

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

12.4 functional programming

- pure function
- lambda
- map
- filter
- generator
- decorator
- recursion
- *args

- `**kwargs`

12.5 object-oriented programming = OOP

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

Chapter 13

TikZ

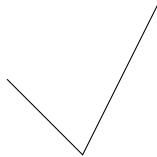
- TikZ
 - PGFplots^[13.4]
 - tikzplotlib^[13.5]: Python^[12] matplotlib^[27] export to TikZ^[13].tex

multi-column 7.3.6

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

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

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



How to speed up bookdown generation?

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

TikZ and PGFplots

What's the relation between packages PGFplots and TikZ?

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

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

<https://www.youtube.com/watch?v=ft4Kg9emK1k&list=PLg5nrpKdkk2DWcg3scb75AknF7DJXs81k&index=18>

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

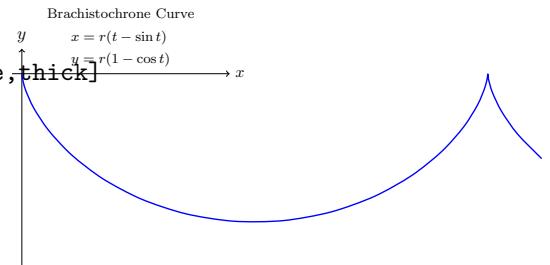


Figure 13.1: Brachistochrone Curve

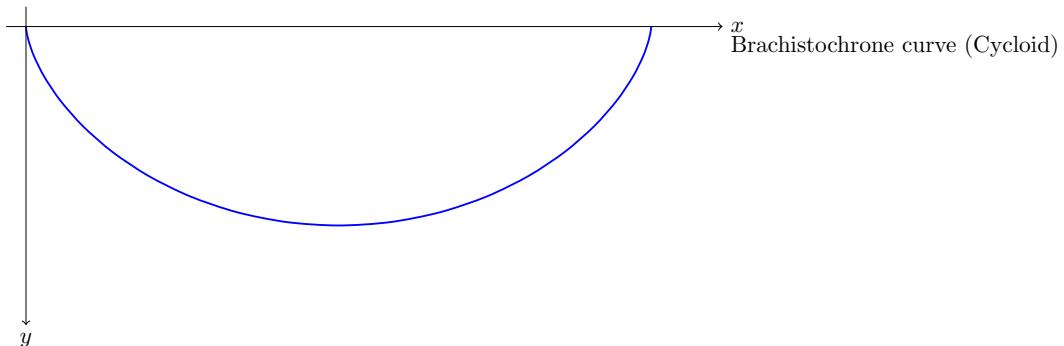


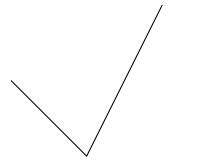
Figure 13.2: Brachistochrone Curve

13.1 2D

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

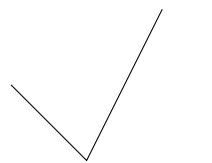
```
\begin{tikzpicture}
\draw (-1,1)--(0,0)--(1,2);
\end{tikzpicture}
```

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



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

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



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

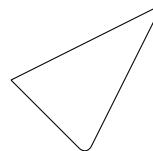


Figure 13.3: rounded corner pseudo-closed triangle

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

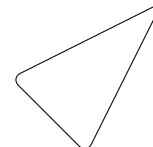


Figure 13.4: rounded corner triangle

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

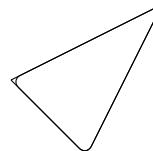


Figure 13.5: triangle vs. pseudo-closed triangle

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



Figure 13.6: rectangle

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



Figure 13.7: square

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

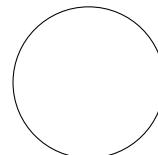


Figure 13.8: circle

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

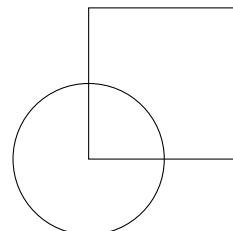


Figure 13.9: circle and square

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

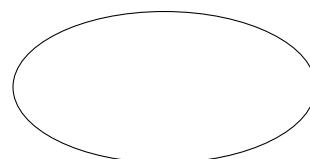


Figure 13.10: ellipse

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

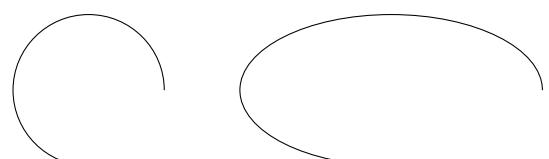


Figure 13.11: circle and ellipse arcs

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

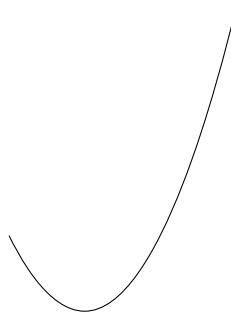


Figure 13.12: parabola arc

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

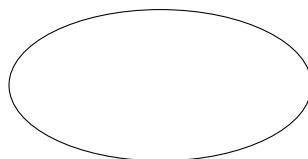


Figure 13.13: parabola arc with points

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

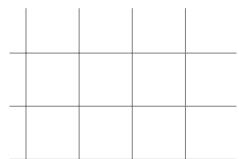
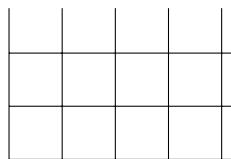


Figure 13.14: grid and help lines

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

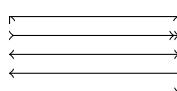


Figure 13.15: arrows

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

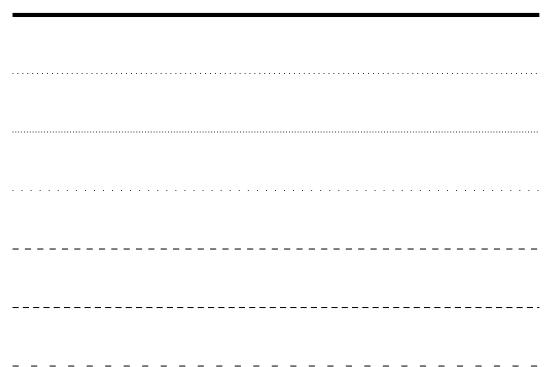


Figure 13.16: lines

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



Figure 13.17: head styling

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

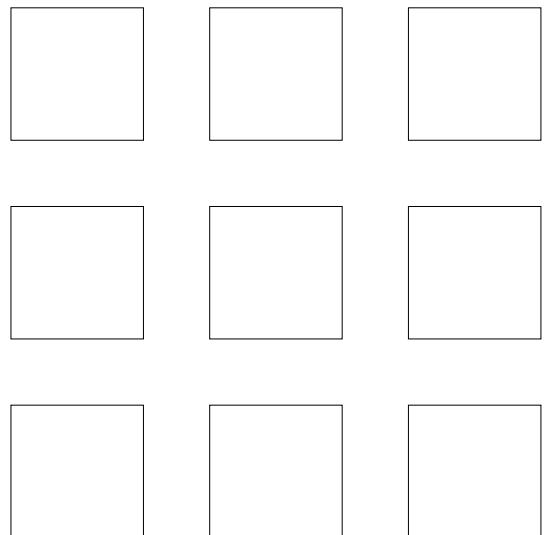


Figure 13.18: transform: shift

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

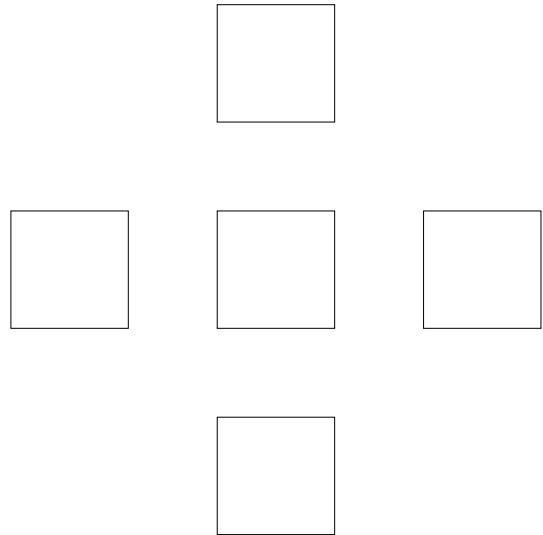


Figure 13.19: transform: shift x, y

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

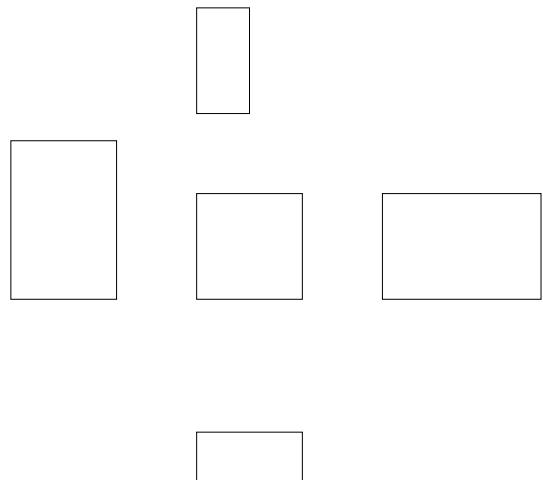


Figure 13.20: transform: scale x, y

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

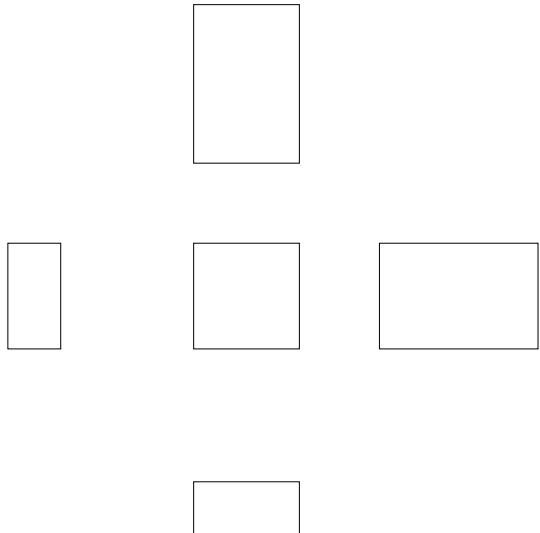


Figure 13.21: transform: scale

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

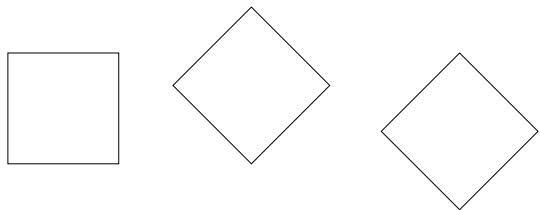


Figure 13.22: transform: rotate

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

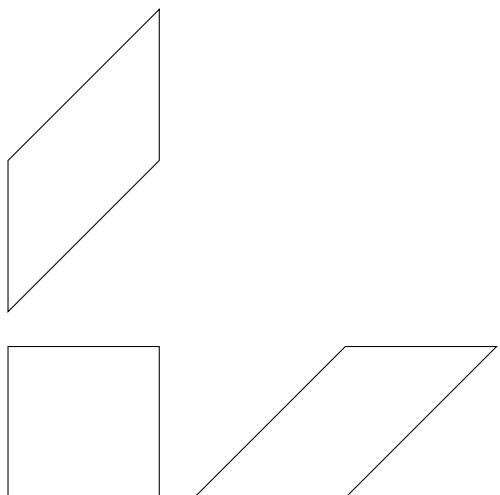


Figure 13.23: transform: slant

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

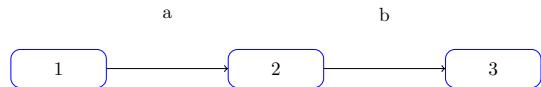


Figure 13.24: flowchart

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

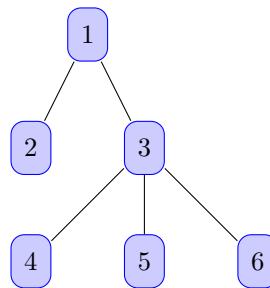


Figure 13.25: tree

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

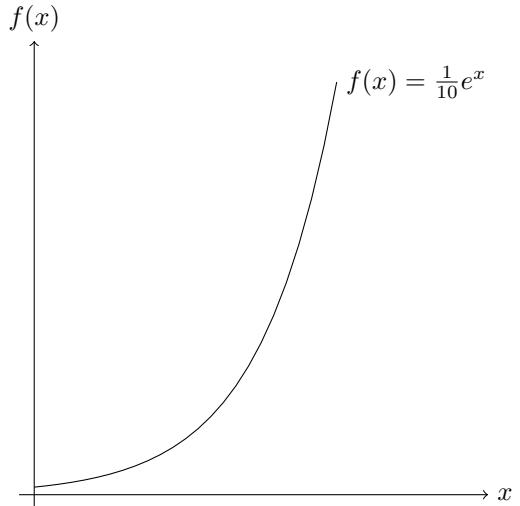


Figure 13.26: function plot

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

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

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

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

13.2 3D

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

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

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

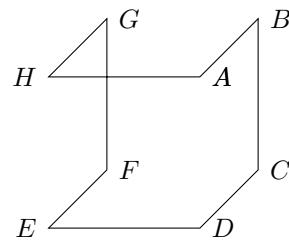


Figure 13.27: cube

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

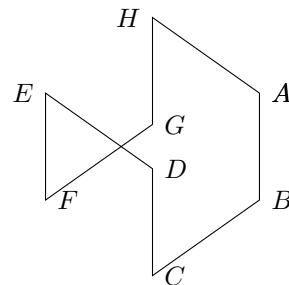


Figure 13.28: cube rotate

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

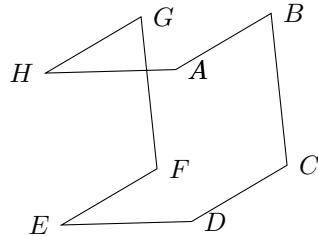


Figure 13.29: cube rotate around

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

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

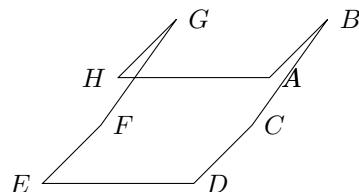


Figure 13.30: cube perspective slant

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

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



Figure 13.31: modern statistics plot skills

13.3 plots of functions

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

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

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

```
\begin{tikzpicture}[domain=0:4]
  \draw[very thin,color=gray]
    (-0.1,-1.1) grid (3.9,3.9);
  \draw[->] (-0.2,0) -- (4.2,0)
    node[right] {$x$};
  \draw[->] (0,-1.2) -- (0,4.2)
    node[above] {$f(x)$};

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

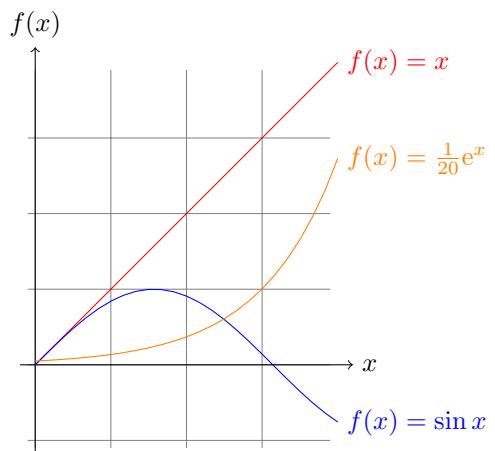


Figure 13.32: plots of functions

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

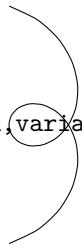


Figure 13.33: 2D parametric function

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



Figure 13.34: 3D parametric function

13.4 PGFplots

axis similar to matplotlib figure anatomy, see Fig: 27.1

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

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

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

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

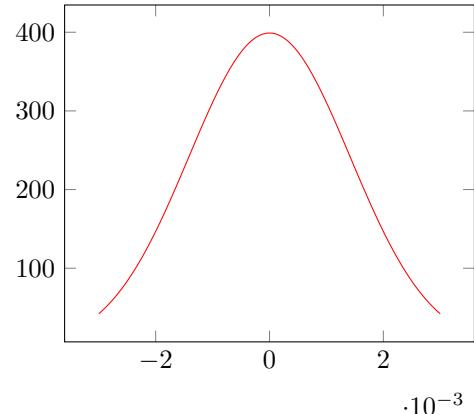


Figure 13.35: PGFplots: normal distribution

13.4.1 the axis environments

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

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

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

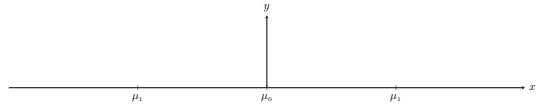


Figure 13.36: beginaxis

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

No, there is no difference.

13.4.2 axis descriptions

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

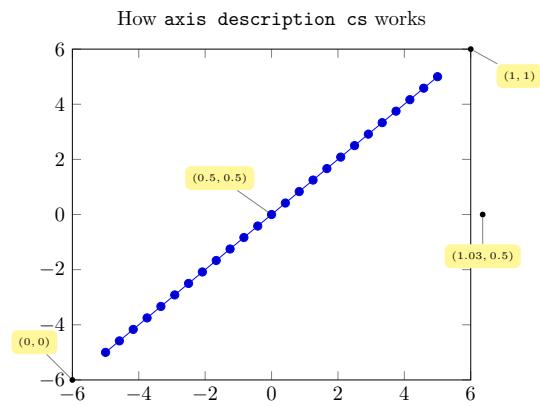
13.4.2.1 placement of axis descriptions

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

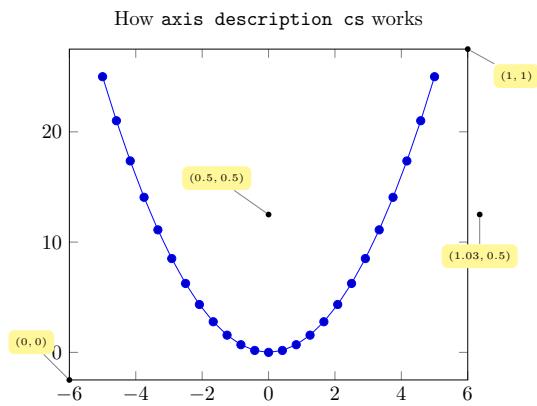
\addplot {x}; can change to \addplot {x^2}; still with auto blue dots

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

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

Figure 13.37: PGFplots: x

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

Figure 13.38: PGFplots: x^2

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

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

13.4.3 declare function

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

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

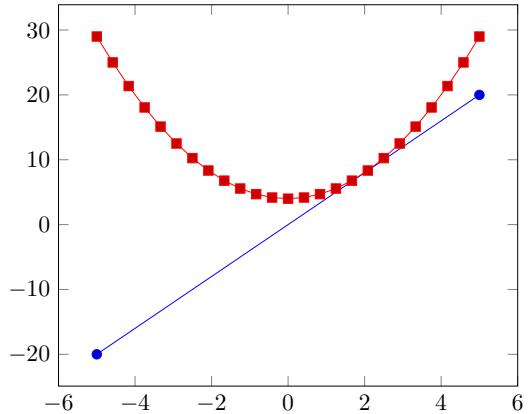


Figure 13.39: declare function

13.4.3.1 pgfmathparse

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

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

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

```
\pgfmathsqrt{x} = \pgfmathparse{sqrt(x)}
\pgfmathln{x} = \pgfmathparse{ln(x)}
...
...
```

13.4.3.2 pgfmathdeclarefunction

like `pgfplotsinvokeforeach`

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

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

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

\begin{tikzpicture}
\begin{axis}[
    no markers,
```

```

axis x line = center,
axis y line = center,
xlabel = {$x$}, xlabel style = {right},
ylabel = {$y$}, ylabel style = {above},
xmin = -8, xmax = 8,
ymin = 0, ymax = 0.45,
hide obscured x ticks=false, % for origin x tick label i.e. xtick = {0}
xtick={-4, 0, 4},
xticklabels={$\mu_{\scriptscriptstyle 1}$, $\mu_{\scriptscriptstyle 0}$, $\mu_{\scriptscriptstyle 1}$},
%extra x ticks={0},
ytick = \emptyset,
x = 1cm, y = 5cm, % x y scaling
%grid = major,
domain = -10:10,
samples = 1000
]
\addplot [fill=cyan!20, draw=none, domain=-10:-2] {gauss(-4, 1)}
\closedcycle;
\addplot [fill=cyan!20, draw=none, domain= 2:10] {gauss( 4, 1)}
\closedcycle;
\addplot [very thick, cyan!50!black] {gauss(-4, 1)};
\addplot [very thick, cyan!50!black] {gauss( 0, 1)};
\addplot [very thick, cyan!50!black] {gauss( 4, 1)};
%\node [anchor=north] at (axis cs: 0, -0.01) {$\mu$};
%\node at (axis cs: -4, -0.02) {$\mu_1$};
\draw [dashed, thin] (axis cs: -4, 0) -- (axis cs: -4, 1);
\draw [dashed, thin] (axis cs: 4, 0) -- (axis cs: 4, 1);
\end{axis}
\end{tikzpicture}

```

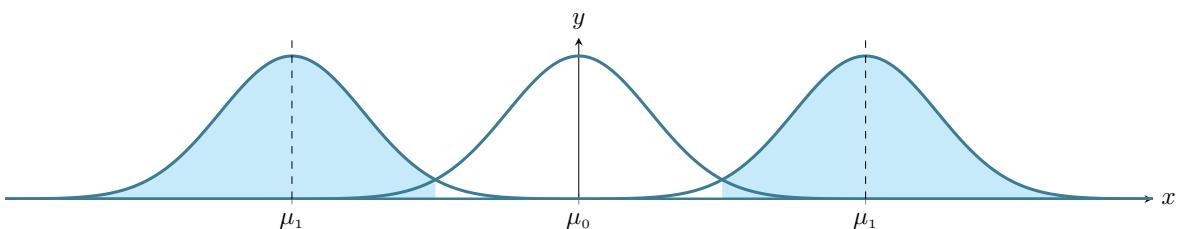


Figure 13.40: PGFmathDeclareFunction: normal distributions hypothesis testing

<https://tex.stackexchange.com/questions/43610/plotting-bell-shaped-curve-in-tikz-pgf>

```

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

```

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

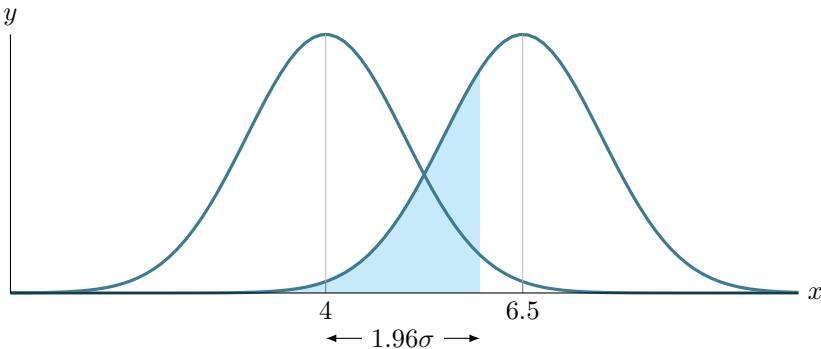


Figure 13.41: PGFmathDeclareFunction: normal distributions

13.4.4 |- and -| in TikZ

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

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

13.4.5 pgfplotsinvokeforeach

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

like `\foreach` in TikZ

A variant of `\pgfplotsforeachungrouped` (and such also of `\foreach`) which replaces any occurrence of `#1` inside of (math image)command(math image) once for every element in

(math image)list(math image). Thus, it actually assumes that (math image)command(math image) is like a \newcommand body.

13.4.6 interpolation dashed lines

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

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

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

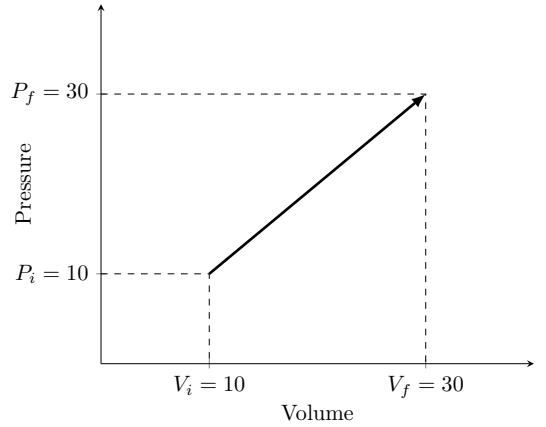


Figure 13.42: tick texts and interpolation dashed lines

13.4.7 Zewbie

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

axis similar to matplotlib figure anatomy, see Fig: 27.1

13.4.7.1 coordinate axis/axes fine-tuing

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

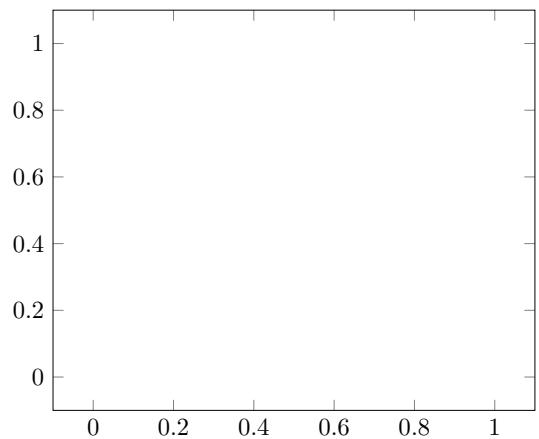


Figure 13.43: PGFplots: 2D axis/axes

13.4.7.1.1 range

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

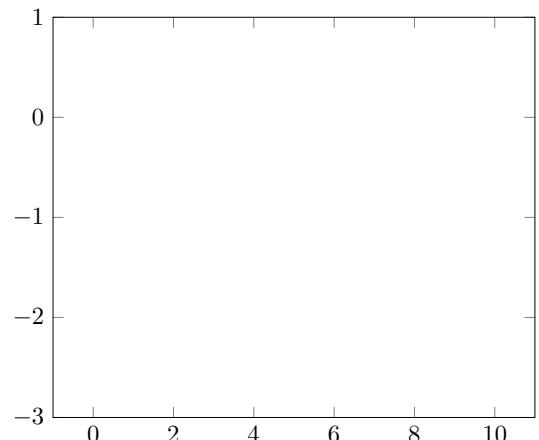


Figure 13.44: PGFplots: axis/axes range

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

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

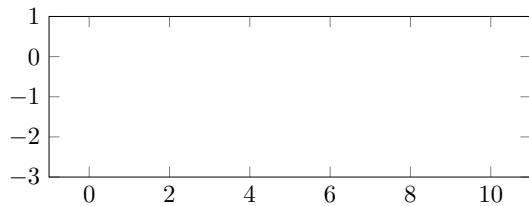


Figure 13.45: PGFplots: axis/axes range

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

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

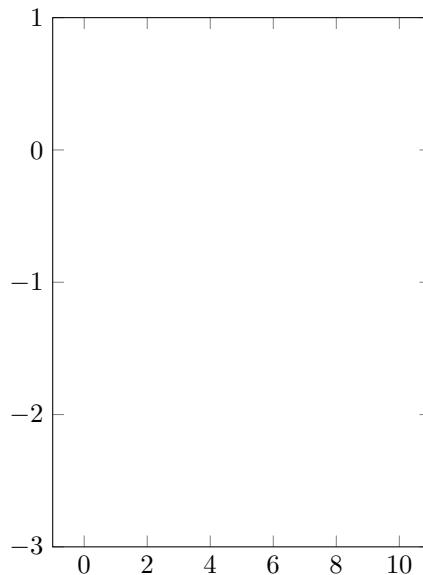


Figure 13.46: PGFplots: axis/axes range

x x unit vector length, y y unit vector length

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

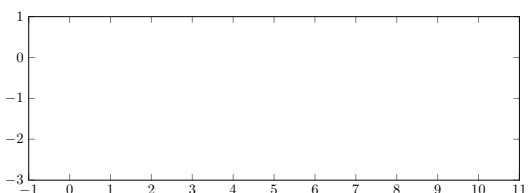


Figure 13.47: PGFplots: axis/axes range

13.4.7.1.3 direction vector

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

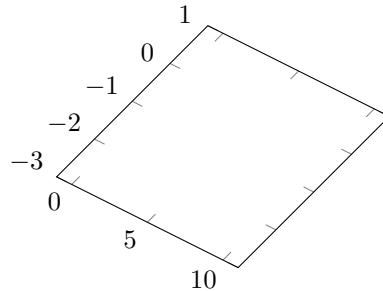


Figure 13.48: PGFplots: axis/axes range

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

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

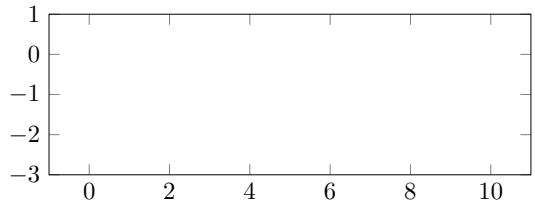


Figure 13.49: PGFplots: axis/axes range

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

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

```
axis lines = center:
```

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

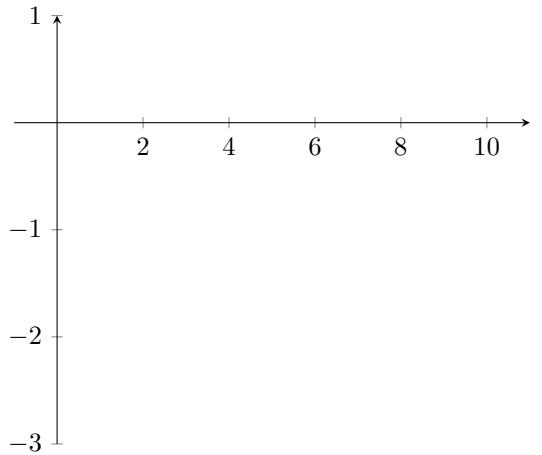


Figure 13.50: PGFplots: axis/axes range

`axis lines *= center:`

x axis line without arrow, y axis box

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

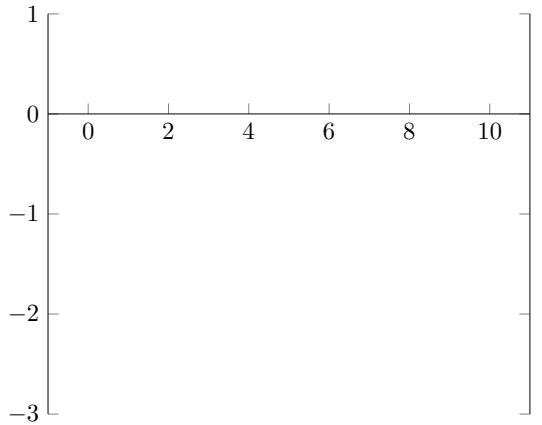


Figure 13.51: PGFplots: axis/axes range

x axis line with arrow, y axis line without arrow

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

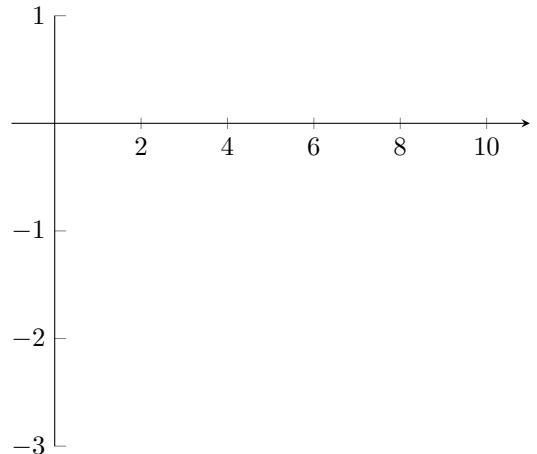


Figure 13.52: PGFplots: axis/axes range

13.4.7.1.5 axis discontinuity crunch, parallel, none

crunch

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

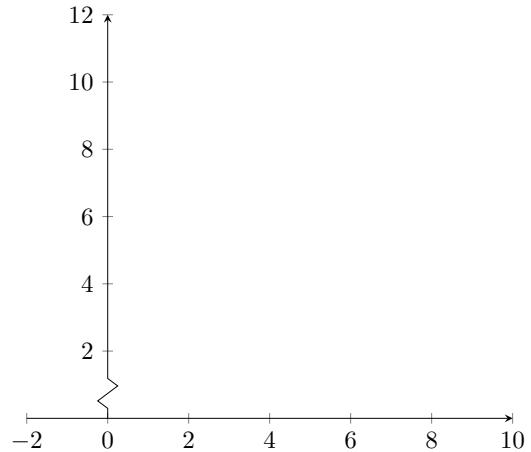


Figure 13.53: PGFplots: axis/axes range

parallel

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

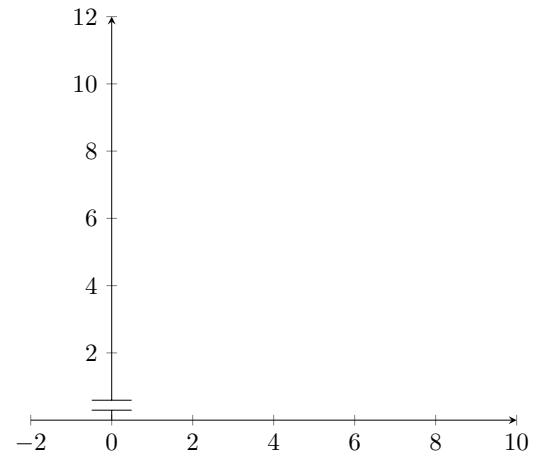


Figure 13.54: PGFplots: axis/axes range

13.4.7.1.6 tick tick pos ticklabel pos

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

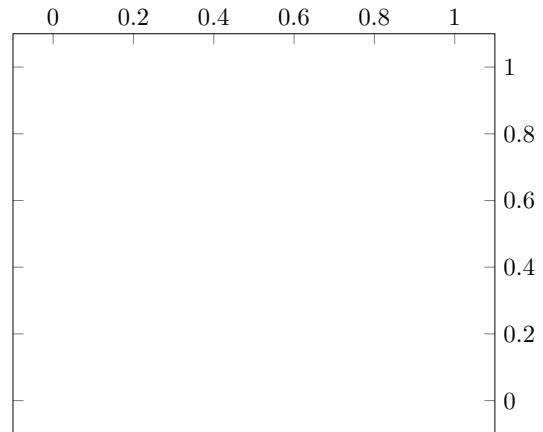


Figure 13.55: PGFplots: axis/axes range

tick distance

tick align: inside, center, outside

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

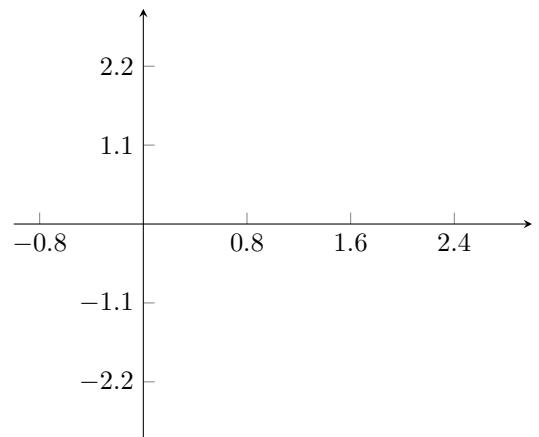


Figure 13.56: PGFplots: axis/axes range

minor tick num

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



Figure 13.57: PGFplots: axis/axes range

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

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

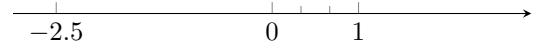


Figure 13.58: PGFplots: axis/axes range

`extra x ticks={<coordinates>}`

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

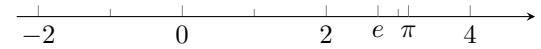


Figure 13.59: PGFplots: axis/axes range

`ticklabels={<labels>} extra x tick labels={<labels>}`

`hide obscured x ticks = false` for origin x tick label

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

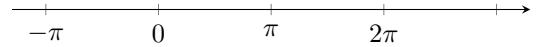


Figure 13.60: PGFplots: axis/axes range

13.4.7.2 addplot+

What does addplot+ do exactly?

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

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

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

13.4.7.3 point

`only marks` only points without lines

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

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



Figure 13.61: PGFplots: 1D points with pins

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

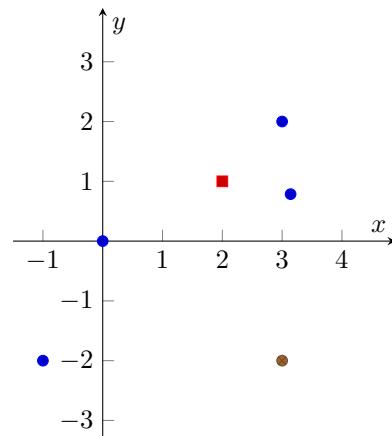


Figure 13.62: PGFplots: 2D points

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

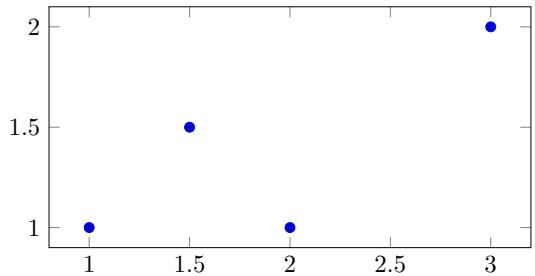


Figure 13.63: PGFplots: data points

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

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

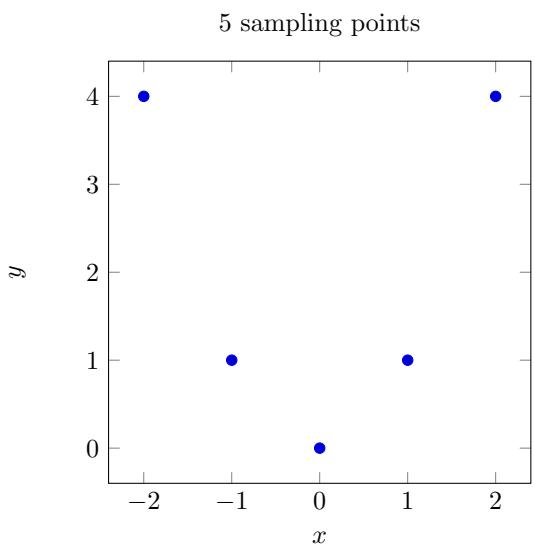


Figure 13.64: PGFplots: function sampling 5 points

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

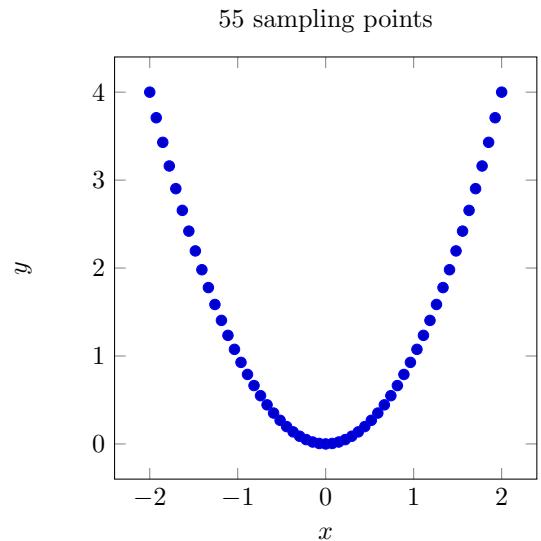


Figure 13.65: PGFplots: function sampling 55 points

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

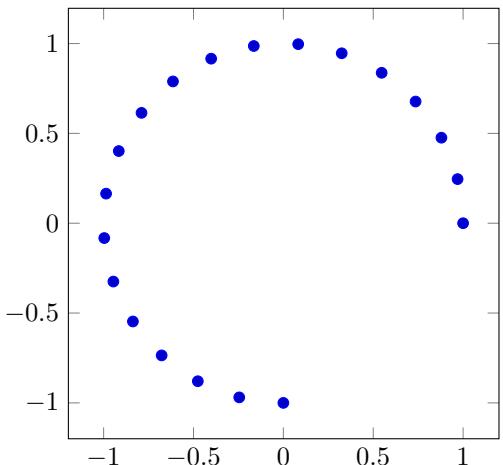


Figure 13.66: PGFplots: parametric function sampling

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



Figure 13.67: PGFplots: 3D points

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

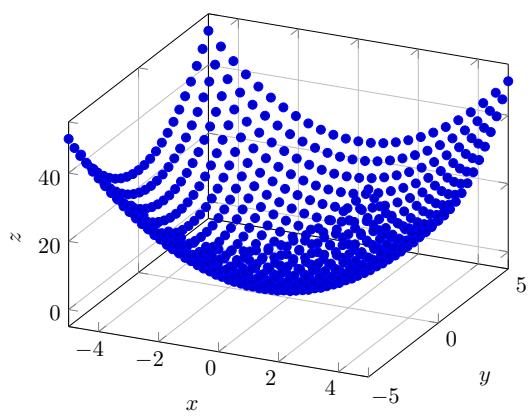


Figure 13.68: PGFplots: 3D function sampling points

13.4.7.4 line

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

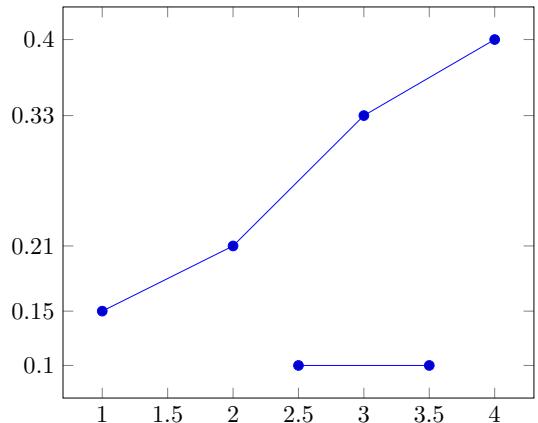


Figure 13.69: lines connecting adjacent points

`smooth` to make smooth curves or lines

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

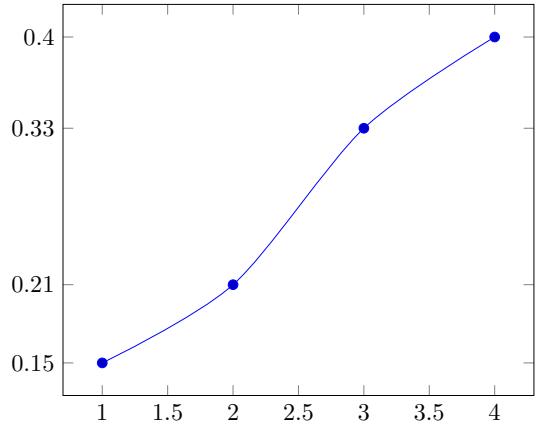
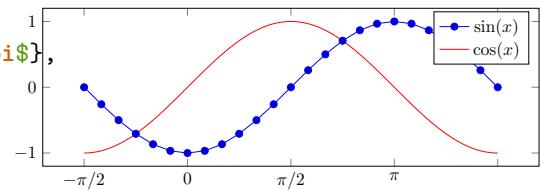


Figure 13.70: smooth lines connecting adjacent points

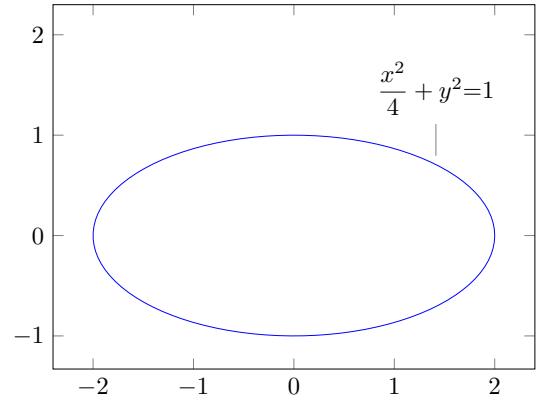
`no markers` to make no markers or points on the curves or lines

`\addlegendentry` to add legends

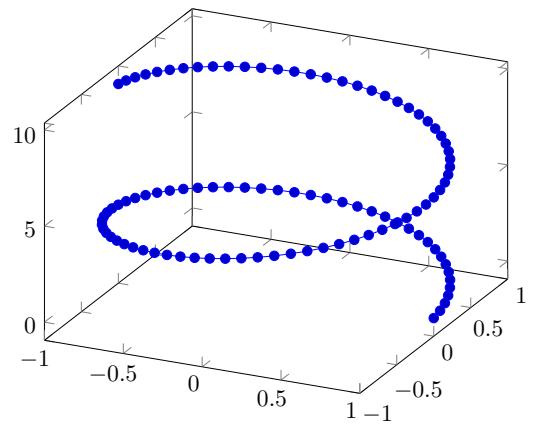
```
\begin{tikzpicture}
\begin{axis}[
    trig format plots=rad,
    xtick distance=pi/2, ytick
    distance=1,
    xticklabels={-$-\pi$,$-\pi/2$,0,$\pi/2$,$\pi$},
    width=10cm, scale only axis,
    axis equal image]
\addplot+ [domain=-pi:pi]
    {sin(x)};
\addlegendentry{$\sin(x)$}
\addplot+ [no
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

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

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

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

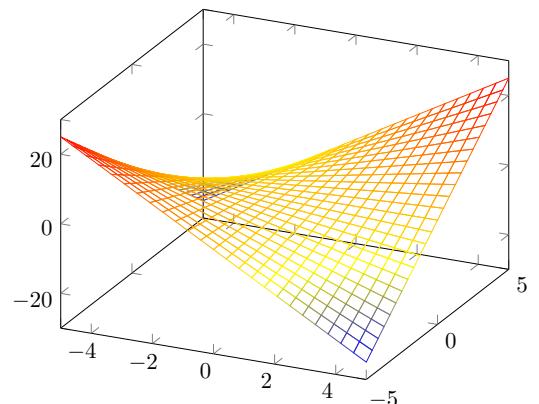
```
\begin{tikzpicture}
\begin{axis}[trig format
    ↵ plots=rad]
\addplot3+ [variable=t,
    domain=0:3*pi,
    samples=100,
    samples y=0]
    ({cos(t)},{sin(t)},{t});
\end{axis}
\end{tikzpicture}
```

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

13.4.7.5 plane

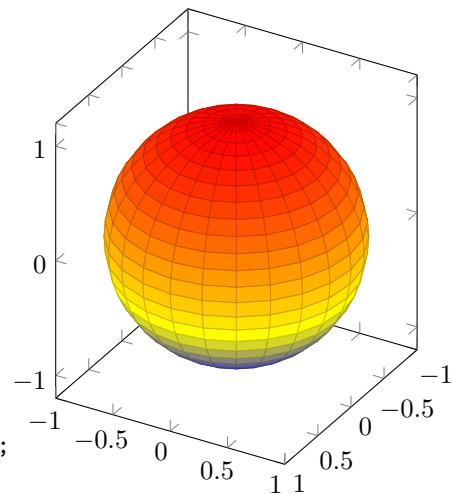
[mesh]

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

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

[surf] surface

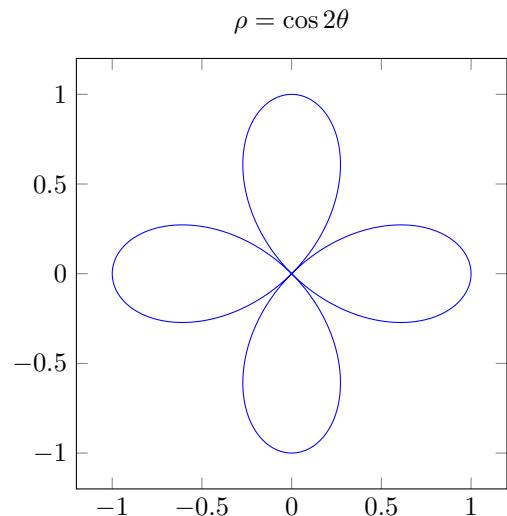
```
\begin{tikzpicture}
\begin{axis}[
    view={120}{30},
    trig format plots=rad,
    width=10cm,
    scale only axis,
    axis equal image
]
\addplot3+ [no markers,
            surf,
            domain=0:2*pi,
            domain y=0:pi]
    ({sin(y)*cos(x)},{sin(y)*sin(x)},{cos(y)});
\end{axis}
\end{tikzpicture}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

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

13.4.7.6 polar coordinate

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

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

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

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

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

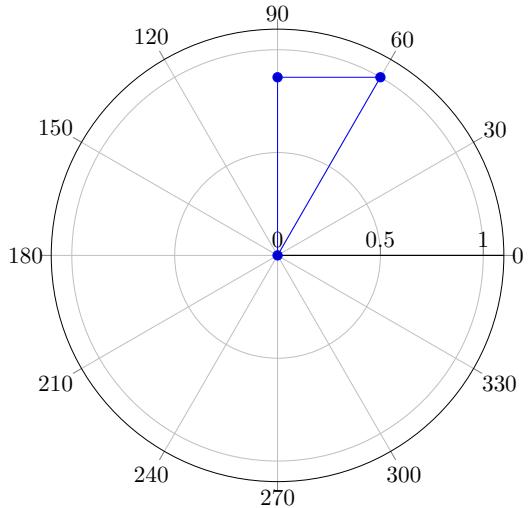


Figure 13.77: polar coordinate axes

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

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

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

13.4.9 PGFplots gallery

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

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

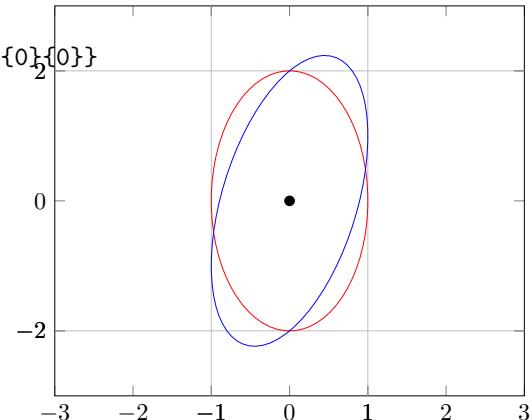


Figure 13.78: declare function

13.5 TikZplotLib / tikzplotlib

Python^[12]

```
library(reticulate)

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

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

# conda_list()
use_condaenv(condaenv = 'sandbox-3.9')

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

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

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

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

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

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

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

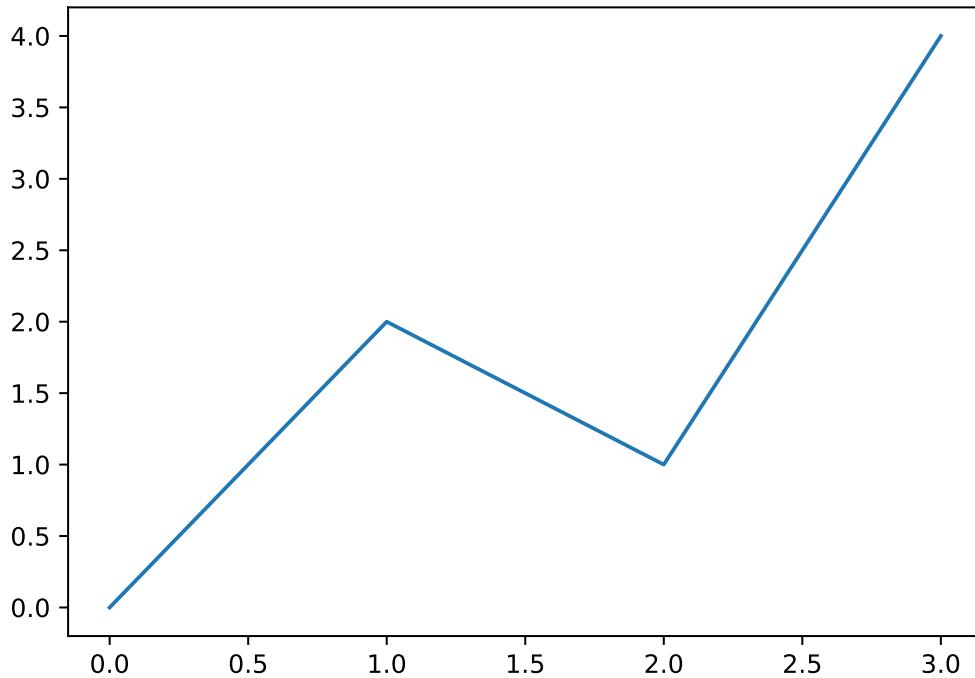
```
reticulate::conda_list()
```

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

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

```
import matplotlib.pyplot as plt
```

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



```
import tikzplotlib

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

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

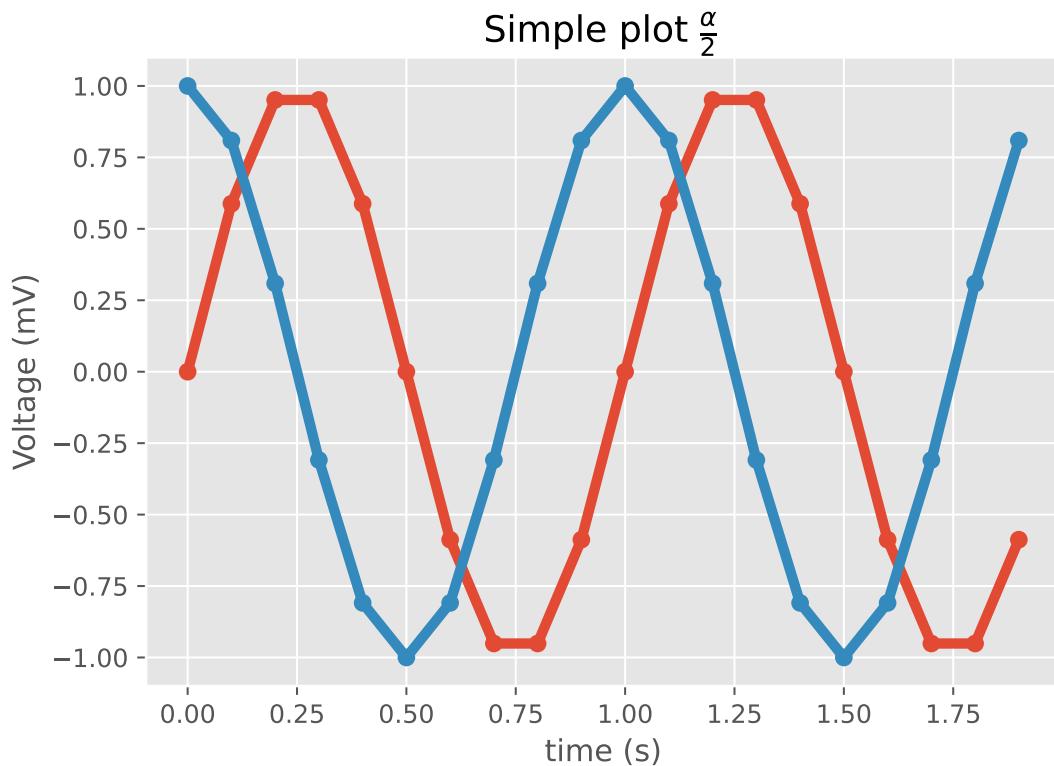
```
import matplotlib.pyplot as plt

plt.close()

import matplotlib.pyplot as plt
import numpy as np

plt.style.use("ggplot")

t = np.arange(0.0, 2.0, 0.1)
s = np.sin(2 * np.pi * t)
s2 = np.cos(2 * np.pi * t)
plt.plot(t, s, "o-", lw=4.1)
plt.plot(t, s2, "o-", lw=4.1)
plt.xlabel("time (s)")
plt.ylabel("Voltage (mV)")
plt.title("Simple plot $\\frac{\\alpha}{2}$")
plt.grid(True)
plt.show()
```



```
import tikzplotlib

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

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

13.6 animation

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

Chapter 14

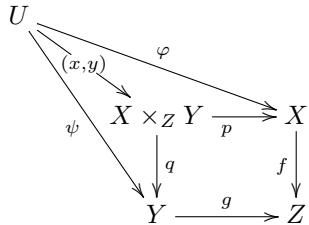
xy-pic

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

`tinytex::install_tinytex()`

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

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



Chapter 15

statistics

15.1 Hung Hung

population

普查 vs. 統計

random variable

X

sample has randomness

probability function

$$P_x(E) \in [0, 1]$$

event = subset of sample space

E

input event with output probability in 0 to 1

$$P_x : \{E_i\}_{i \in I} \rightarrow [0, 1]$$

target of interest

- probability function

but events are hard to be listed or enumerated

$$X : \{\omega_i\}_{i \in I} \rightarrow \mathbb{R}$$

CDF = cumulative distribution function

$$F_X(x) = P_x((-\infty, x]) = P_x(X \leq x)$$

real function is much easier to be operable, there is differentiation or difference operation target of interest

- CDF = cumulative distribution function
- probability function

target of interest

- $P_x(\cdot)$ PF = probability function
 - $f_x(x) = P_x(X = x)$ PMF = probability mass function
 - $f_x(x) = \frac{d}{dx} P_x(X \leq x)$ PDF = probability density function
- $F_x(x)$ CDF = cumulative distribution function^[15.1.2.1]
- $M_x(\xi)$ MGF = moment generating function^[15.1.2.7.1]
- $\varphi_x(\xi)$ CF = characteristic function^[15.1.2.7.2]

$$\begin{array}{ccccccc} X & \sim & F_x(x) & \xleftrightarrow{\text{FToC}} & f_x(x) & \leftrightarrow & P_x \\ \text{inversion formula : } & \downarrow & \forall \xi \approx 0 [M_x(\xi) \in \mathbb{R}] \wedge & & \uparrow \downarrow & \searrow \nearrow & \leftarrow \rho \wedge \text{supp}(f_x) \text{ is bounded} \\ & \varphi_x(\xi) & \xleftrightarrow{} & M_x(\xi) & \rightarrow & & \{\mu_n | n \in \mathbb{N}\} \end{array}$$

In population,

$$X \sim F_x(x)$$

by sampling,

$$X_1, \dots, X_i, \dots, X_n = X_i \sim F_x(x)$$

or

$$X_1, \dots, X_i, \dots, X_n = X_i \stackrel{\text{i.i.d.}}{\sim} F_x(x)$$

i.i.d. = independently identically distributed

and inference back

parametrically

$$\hat{X} \sim \hat{F}_x(x) = \hat{F}_x(x|\theta)$$

or nonparametrically

$$\hat{X} \sim \hat{F}_x(x)$$

inference is function of samples, or called random function, to estimate unknown parameters

$$\hat{\Theta} \leftarrow (X_1, \dots, X_i, \dots, X_n) = T(X_1, \dots, X_n) = T(\dots, X_i, \dots) = T(X_i)$$

corresponding CDF for inference or estimation function of sampling random variables

$$T(X_1, \dots, X_n) = T \sim F_T(t)$$

wish to be unbiased and consistent

$$\begin{cases} E(\hat{\theta}) = \theta \Leftrightarrow E(\hat{\theta}) - \theta = 0 & \text{unbiasedness} \\ V(\hat{\theta}) = 0 & \text{consistency} \end{cases}$$

unbiasedness usually harder than consistency, thus usually first considered consistency.
modeling or parameterizing with unknown parameter θ

$$F_X(x) \stackrel{M}{=} F_X(x|\theta) = F_X(x;\theta)$$

parameterization is to reduce unknown parameters from infinite ones to finite ones
e.g. for normally distributed data

$$f_X(x) \stackrel{M}{=} f_X(x|\theta) = \frac{e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}}{\sqrt{2\pi\sigma^2}} = f_X(x|\mu, \sigma^2) = f_X(x|\mu, \sigma)$$

the price of parameterization is guess wrong model.

For some non-negative data, instead of normal distribution, consider distributions skewed to the right

- [gamma](#)
- [exponential](#)
- [Weibull](#)
- [log-normal](#)

topics

1. P_x probability theory
2. $f_X(x) \stackrel{M}{=} f_X(x|\theta) = f_X(x;\theta)$ various univariable distribution
3. $f_{\mathbf{X}}(\mathbf{x}) \stackrel{M}{=} f_{\mathbf{X}}(\mathbf{x}|\boldsymbol{\theta}) = f_{\mathbf{X}}(\mathbf{x};\boldsymbol{\theta})$ multivariable distribution
4. $T(X_1, \dots, X_n)$ inference

- point estimation

$$\hat{\mu} = \begin{cases} \bar{X} & \rightarrow \mu \\ \text{median}(X_1, \dots, X_n) & \rightarrow \mu \\ \vdots \end{cases}$$

- interval estimation = hypothesis testing

$$\begin{cases} H_0 : \theta = \theta_0 & \leftarrow T \in \{0, 1\} \\ H_1 : \theta \neq \theta_0 \end{cases}$$

5. how to find T
6. behavior of random function $T(X_1, \dots, X_n) = T \sim F_T(t)$
 - statistical properties of T
 - asymptotic properties

$$n \rightarrow \infty \begin{cases} \text{CLT} = \text{central limit theorem} \\ \text{LLN} = \text{law of large number} \end{cases}$$

15.1.1 probability theory

Definition 15.1. sample space: The set S of all possible outcomes of an experiment is called the sample space

$$S = \{\omega_i\}_{i \in I}$$

Definition 15.2. event: An event E is any collection of possible outcomes of an experiment, i.e. any subset of S

$$E \subseteq S$$

set operation

commutativity, associativity, distributivity

De Morgan law

pairwise disjoint = mutually exclusive

partition

15.1.1.1 probability function

probability function axioms = probability function definition

Kolmogorov axioms of probability⁶ p.72

Definition 15.3. probability function: Given a sample space S and its event E , a probability function is a function P satisfying

$$\begin{cases} P(S) = 1 \\ \forall E \subseteq S (P(E) \geq 0) \\ E_1, \dots, E_i, \dots \text{ are pairwise disjoint} \Rightarrow P\left(\bigcup_{i \in I} E_i\right) = \sum_{i \in I} P(E_i) \end{cases}$$

tossing a dice

theorems

$$P(\emptyset) = 0$$

$$P(E) \leq 1$$

$$P(E^C) = P(\overline{E}) = 1 - P(E)$$

$$P(E_2 \cap \overline{E}_1) = P(E_2) - P(E_2 \cap E_1)$$

$$E_1 \subseteq E_2 \Rightarrow P(E_1) \leq P(E_2)$$

addition rule⁶ p.75 and extended addition rule⁶ p.76

inclusion-exclusion principle = sieve principle

$$P(E_1 \cup E_2) = P(E_1) + P(E_2) - P(E_1 \cap E_2)$$

$$P(E_1 \cup E_2 \cup E_3) = P(E_1) + P(E_2) + P(E_3) - P(E_1 \cap E_2) - P(E_2 \cap E_3) - P(E_3 \cap E_1) + P(E_1 \cap E_2 \cap E_3)$$

$$P\left(\bigcup_{i=1}^n E_i\right) = \sum_{k=1}^n \left((-1)^{k-1} \sum_{1 \leq i_1 < \dots < i_k \leq n} P\left(\bigcap_{i \in \{i_1, \dots, i_k\}} E_i\right) \right)$$

symmetric difference⁶ p.75

union probability upper-bounded by sum of individual probability

$$P(E_1 \cup E_2) = P(E_1) + P(E_2) - P(E_1 \cap E_2) \leq P(E_1) + P(E_2)$$

$$E_1 \cap E_2 = \emptyset \Leftrightarrow P(E_1 \cup E_2) = P(E_1) + P(E_2)$$

Boole inequality

$$P\left(\bigcup_{i \in I} E_i\right) \leq \sum_{i \in I} P(E_i)$$

$$P\left(\widehat{H_0} \mid H_0\right) = P(\text{reject } H_0 \mid H_0 \text{ is true}) = \alpha = \text{type 1 error}$$

multiple hypothesis testing

How to control the family-wise error rate?

Ideally,

FWER = family-wise error rate

$$\begin{aligned}
\alpha &= P \left(\overbrace{H_0^1 \cup \dots \cup H_0^m}^{} \middle| H_0^1 \cap \dots \cap H_0^m \right) = P(\text{reject any } H_0^i \mid \text{any } H_0^j \text{ is true}) \\
&= P \left(\bigcup_{i=1}^m \overbrace{H_0^i}^{} \middle| \bigcap_{j=1}^m H_0^j \right) = 1 - P \left(\bigcup_{i=1}^m \overbrace{H_0^i}^{} \middle| \bigcap_{j=1}^m H_0^j \right) \\
&= 1 - P \left(\bigcap_{i=1}^m \overbrace{H_0^i}^{} \middle| \bigcap_{j=1}^m H_0^j \right) = 1 - P \left(\text{not to reject any } H_0^i \middle| \bigcap_{j=1}^m H_0^j \right) \\
&\stackrel{H_0^j \text{ pairwise independent}}{=} 1 - \prod_{i=1}^m P \left(\overbrace{H_0^i}^{} \middle| \bigcap_{j=1}^m H_0^j \right) = 1 - \prod_{i=1}^m \left(1 - P \left(\overbrace{H_0^i}^{} \middle| \bigcap_{j=1}^m H_0^j \right) \right) \\
&\stackrel{\forall i, j \left[P \left(\overbrace{H_0^i}^{} \middle| \bigcap_{j=1}^m H_0^j \right) = \alpha_0 \right]}{=} 1 - \prod_{i=1}^m (1 - \alpha_0) = 1 - (1 - \alpha_0)^m \\
\alpha &= 1 - (1 - \alpha_0)^m \\
\alpha_0 &= 1 - (1 - \alpha)^{\frac{1}{m}} = 1 - \sqrt[m]{1 - \alpha} \\
&\Downarrow \\
\text{set } P \left(\overbrace{H_0^i}^{} \middle| \bigcap_{j=1}^m H_0^j \right) &= \alpha_0 = 1 - \sqrt[m]{1 - \alpha}
\end{aligned}$$

But condition H_0^j pairwise independent is too strong.

Practically,

$$\begin{aligned}
\alpha &= P \left(\overbrace{H_0^1 \cup \dots \cup H_0^m}^{} \middle| H_0^1 \cap \dots \cap H_0^m \right) = P(\text{reject any } H_0^i \mid \text{any } H_0^j \text{ is true}) \\
&= P \left(\bigcup_{i=1}^m \overbrace{H_0^i}^{} \middle| \bigcap_{j=1}^m H_0^j \right) \stackrel{P \left(\bigcup_{i \in I} E_i \right) \leq \sum_{i \in I} E_i}{\leq} \stackrel{\text{Boole inequality}}{\leq} \sum_{i=1}^m P \left(\overbrace{H_0^i}^{} \middle| \bigcap_{j=1}^m H_0^j \right) \stackrel{\uparrow}{=} \sum_{i=1}^m \alpha_0 = m\alpha_0 \stackrel{\Downarrow}{=} \alpha \\
\text{let } \forall i, j \left[P \left(\overbrace{H_0^i}^{} \middle| \bigcap_{j=1}^m H_0^j \right) = \alpha_0 \right] &\Rightarrow \sum_{i=1}^m P \left(\overbrace{H_0^i}^{} \middle| \bigcap_{j=1}^m H_0^j \right) = \sum_{i=1}^m \alpha_0 = m\alpha_0 \Rightarrow \alpha_0 = \frac{\alpha}{m} \\
&\Downarrow \\
\text{set } P \left(\overbrace{H_0^i}^{} \middle| \bigcap_{j=1}^m H_0^j \right) &= \alpha_0 = \frac{\alpha}{m}
\end{aligned}$$

Bonferroni correction

$$P \left(\overbrace{H_0^i}^{} \middle| \bigcap_{j=1}^m H_0^j \right) = \frac{\alpha}{m} \Rightarrow P \left(\bigcup_{i=1}^m \overbrace{H_0^i}^{} \middle| \bigcap_{j=1}^m H_0^j \right) \leq \alpha$$

Bonferroni inequality⁶ p.77

Bonferroni inequality and Boole inequality are equivalent inequalities
birthday problem⁶ p.78

15.1.1.2 conditional probability

15.1.2 univariable distribution

$$\begin{aligned} & \left\{ \begin{array}{ll} P_x(X \in E) & \forall E \subseteq S \\ P_x(X \leq x) & \forall x \in \mathbb{R} \end{array} \right. \\ & \left\{ \begin{array}{ll} P_x(X \in E) & \forall E \subseteq S \\ P_x(X \leq x) = P_x((-\infty, x]) = F_x(x) & \forall x \in \mathbb{R} \end{array} \right. \\ & P_x(X \leq x) = P_x((-\infty, x]) \\ & = P_x\left(\bigcup_{\epsilon>0}(-\infty, x-\epsilon]\right) = \lim_{\epsilon \rightarrow 0} P_x((-\infty, x-\epsilon]) \\ & \leftrightarrow P_x((-\infty, x)) = P_x(E), E = (-\infty, x) \end{aligned}$$

15.1.2.1 cumulative distribution function

CDF = cumulative distribution function

$$\begin{aligned} F_x(x) &= P_x((-\infty, x]) = P_x(X \leq x) \\ X \sim P_x &\leftrightarrow F_x(x) \end{aligned}$$

$$X \sim F_x(x) \leftrightarrow P_x$$

Definition 15.4. CDF = cumulative distribution function: A cumulative distribution function is a function $F : \mathbb{R} \rightarrow [0, 1]$ satisfying

$$F_x(x) = P_x((-\infty, x]) = P_x(X \leq x)$$

Theorem 15.1. CDF = cumulative distribution function: $F(x)$ is a cumulative distribution function iff

$$\begin{cases} \begin{aligned} & \lim_{x \rightarrow -\infty} F(x) = 0 & \lim_{x \rightarrow +\infty} F(x) = 1 & (01) [0, 1] \\ & \forall x_1 < x_2 [F(x_1) \leq F(x_2)] & & (nd) \text{ non-decreasing} \end{aligned} \\ \begin{aligned} & \lim_{x \rightarrow x_0^+} F(x) = F(x_0) & & (rc) \text{ right-continuous} \end{aligned} \end{cases}$$

Definition 15.5. RV = r.v. = random variable

$$\begin{cases} X \text{ is a continuous RV} & \lim_{x \rightarrow x_0} F_x(x) = F_x(x_0) \\ X \text{ is a discrete RV} & F_x \text{ is a step function of } x \end{cases}$$

⁶ p.103

Definition 15.6. RV = r.v. = random variable

⁶ p.104

Definition 15.7. range of r.v. = range of RV = the range of a random variable

$$\begin{aligned}\mathcal{R}_X &= \left\{ x \middle| \begin{cases} \omega \in S \\ x \in X(\omega) \end{cases} \right\} \\ &= \{x | \forall \omega \in S [x \in X(\omega)]\} \\ &= \{x | x \in X(\Omega)\} = X(\Omega)\end{aligned}$$

15.1.2.2 probability density function

$$\begin{cases} P_x(X \leq x) = P_x((-\infty, x]) = F_x(x) \\ P_x(X = x) = P_x(x) = ? \end{cases}$$

Definition 15.8. PDF = probability density function

PMF = probability mass function

$$\begin{cases} f_x(x) = \frac{d}{dx} F_x(x) & X \text{ continuous RV} \\ f_x(x) = F_x(x) - F_x(x^-) & X \text{ discrete RV} \end{cases}$$

$$\begin{cases} f_x(x) = \text{derivative of } F_x(x) & X \text{ continuous} \\ f_x(x) = \text{difference of } F_x(x) & X \text{ discrete} \end{cases}$$

$$\begin{cases} f_x(x) = \frac{d}{dx} F_x(x) \Leftrightarrow F_x(x) = \int_{-\infty}^x f_x(t) dt \\ f_x(x) = F_x(x) - F_x(x^-) \Leftrightarrow F_x(x) = \sum_{t \leq x} f_x(t) \end{cases}$$

$$\begin{cases} X \sim P_x \Leftrightarrow F_x(x) \Leftrightarrow f_x(x) & \text{e.g. probability theory} \\ X \sim F_x(x) \Leftrightarrow P_x \Rightarrow F_x(x) \stackrel{M}{=} F_x(x|\theta) & \text{e.g. survival analysis} \\ X \sim f_x(x) \Leftrightarrow F_x(x) \Leftrightarrow P_x \Rightarrow f_x(x) \stackrel{M}{=} f_x(x|\theta) & \text{e.g. general statistics} \end{cases}$$

Theorem 15.2. PDF = probability density function or PMF = probability mass function: $f(x)$ is a probability density function or probability mass function iff

$$\begin{cases} \forall x \in \mathbb{R} [f(x) \geq 0] \\ \begin{cases} \int_{-\infty}^{+\infty} f(x) dx = 1 & t \text{ continuous} \\ \sum_{x \in X(\Omega)} f(x) = 1 & t \text{ discrete} \end{cases} \end{cases}$$

$$\forall E \subseteq S \left[P_x(X \in E) = \begin{cases} \int_{x \in E} f_x(x) dx & X \text{ continuous} \\ \sum_{x \in E} f_x(x) & X \text{ discrete} \end{cases} \right]$$

$$\begin{aligned}
P_X(X = x) &= \lim_{\epsilon \rightarrow 0} P_X([x - \epsilon, x + \epsilon]) \\
&= \lim_{\epsilon \rightarrow 0} P_X(x - \epsilon \leq X \leq x + \epsilon) \\
&= \lim_{\epsilon \rightarrow 0} [F_X(x + \epsilon) - F_X(x - \epsilon)] \\
&= \begin{cases} F_X(x) - F_X(x^-) = 0 & X \text{ continuous} \\ F_X(x) - F_X(x^-) = f_X(x) & X \text{ discrete} \end{cases}
\end{aligned}$$

$$X \sim F_X(x) \Leftrightarrow P_X$$

$$Y = g(X)$$

$$\begin{cases} Y \sim F_Y(y) \Leftrightarrow f_Y(y) & \Rightarrow F_Y(y) \stackrel{M}{=} F_Y(y|\theta) \\ Y \sim f_Y(y) \Leftrightarrow F_Y(y) \Leftrightarrow P_Y & \Rightarrow f_Y(y) \stackrel{M}{=} f_Y(y|\theta) \end{cases}$$

15.1.2.3 range vs. support

Definition 15.9. range of r.v. = range of RV = the range of a random variable

$$\begin{aligned}
\mathcal{R}_X &= \left\{ x \middle| \left\{ \begin{array}{l} \omega \in S \\ x \in X(\omega) \end{array} \right\} \right\} \\
&= \{x | \forall \omega \in S [x \in X(\omega)]\} \\
&= \{x | x \in X(\Omega)\} = X(\Omega)
\end{aligned}$$

Definition 15.10. support

$$\text{supp}(f) = \left\{ x \middle| \left\{ \begin{array}{l} f : D \rightarrow \mathcal{R} \\ x \in D \\ f_x(x) \neq 0 \end{array} \right\} \right\}$$

Definition 15.11. support of r.v. = support of RV = the support of a random variable

$$\text{supp}(f_x) = \left\{ x \middle| \left\{ \begin{array}{l} x \in X(\Omega) \\ f_x(x) \neq 0 \end{array} \right\} \right\} \stackrel{f_x(x) \geq 0}{=} \left\{ x \middle| \left\{ \begin{array}{l} x \in X(\Omega) \\ f_x(x) > 0 \end{array} \right\} \right\}$$

15.1.2.4 continuous monotone transformation

Theorem 15.3. Random variable Y is monotone transformation of random variable X ,

i.e. $\begin{cases} X \sim F_X(x) \Leftrightarrow f_X(x) \\ Y = g(X) \begin{cases} \forall x_1 < x_2 [g(x_1) < g(x_2)] \\ \forall x_1 < x_2 [g(x_1) > g(x_2)] \end{cases} \end{cases} \Rightarrow \exists g^{-1} : Y \rightarrow X, \text{ then}$

$$f_Y(y) = f_X(g^{-1}(y)) \left| \frac{dg^{-1}(y)}{dy} \right|$$

Proof:

$$\begin{aligned} F_Y(y) &= P_Y(Y \leq y) \\ &= P(g(X) \leq y) \begin{cases} \forall x_1 < x_2 [g(x_1) < g(x_2)] \Leftrightarrow \forall g(x_1) < g(x_2) [x_1 < x_2] \\ \forall x_1 < x_2 [g(x_1) > g(x_2)] \Leftrightarrow \forall g(x_1) > g(x_2) [x_1 < x_2] \end{cases} \\ &= \begin{cases} P_X(X \leq g^{-1}(y) = x) & \forall y_1 < y_2 [g^{-1}(y_1) < g^{-1}(y_2)] \\ P_X(X \geq g^{-1}(y) = x) & \forall y_1 > y_2 [g^{-1}(y_1) < g^{-1}(y_2)] \end{cases} \\ &= \begin{cases} P_X(X \leq g^{-1}(y) = x) & \forall y_1 < y_2 [g^{-1}(y_1) < g^{-1}(y_2)] \\ P_X(X \geq g^{-1}(y) = x) & \forall y_1 < y_2 [g^{-1}(y_1) > g^{-1}(y_2)] \end{cases} \\ &= \begin{cases} F_X(g^{-1}(y)) & \forall y_1 < y_2 [g^{-1}(y_1) < g^{-1}(y_2)] \\ 1 - F_X(g^{-1}(y)) & \forall y_1 < y_2 [g^{-1}(y_1) > g^{-1}(y_2)] \end{cases} \\ F_Y(y) &= \begin{cases} F_X(g^{-1}(y)) & \forall y_1 < y_2 [g^{-1}(y_1) < g^{-1}(y_2)] \\ 1 - F_X(g^{-1}(y)) & \forall y_1 < y_2 [g^{-1}(y_1) > g^{-1}(y_2)] \end{cases} \end{aligned}$$

$$\begin{aligned} f_Y(y) &= \frac{d}{dy} F_Y(y) = \begin{cases} \frac{d}{dy} F_X(g^{-1}(y)) & \forall y_1 < y_2 [g^{-1}(y_1) < g^{-1}(y_2)] \\ \frac{d}{dy} [1 - F_X(g^{-1}(y))] & \forall y_1 < y_2 [g^{-1}(y_1) > g^{-1}(y_2)] \end{cases} \\ &= \begin{cases} \frac{dF_X(g^{-1}(y))}{dg^{-1}(y)} \frac{dg^{-1}(y)}{dy} & \forall y_1 < y_2 [g^{-1}(y_1) < g^{-1}(y_2)] \\ \frac{-dF_X(g^{-1}(y))}{dg^{-1}(y)} \frac{dg^{-1}(y)}{dy} & \forall y_1 < y_2 [g^{-1}(y_1) > g^{-1}(y_2)] \end{cases} \\ &= \begin{cases} \frac{dF_X(g^{-1}(y))}{dg^{-1}(y)} \frac{dg^{-1}(y)}{dy} & \forall y_1 < y_2 [g^{-1}(y_1) < g^{-1}(y_2)] \\ \frac{dF_X(g^{-1}(y))}{dg^{-1}(y)} - \frac{dg^{-1}(y)}{dy} & \forall y_1 < y_2 [g^{-1}(y_1) > g^{-1}(y_2)] \end{cases} \\ &= \begin{cases} f_X(g^{-1}(y)) \frac{dg^{-1}(y)}{dy} & \begin{cases} \frac{dg^{-1}(y)}{dy} \geq 0 \\ f_X(g^{-1}(y)) \geq 0 \end{cases} \Rightarrow f_Y(y) \geq 0 \\ f_X(g^{-1}(y)) \frac{-dg^{-1}(y)}{dy} & \begin{cases} \frac{-dg^{-1}(y)}{dy} \geq 0 \\ f_X(g^{-1}(y)) \geq 0 \end{cases} \Rightarrow f_Y(y) \geq 0 \end{cases} \\ f_Y(y) &= \begin{cases} f_X(g^{-1}(y)) \frac{dg^{-1}(y)}{dy} & \frac{dg^{-1}(y)}{dy} \geq 0 \\ f_X(g^{-1}(y)) \frac{-dg^{-1}(y)}{dy} & \frac{-dg^{-1}(y)}{dy} \geq 0 \end{cases} \\ f_Y(y) &= f_X(g^{-1}(y)) \left| \frac{dg^{-1}(y)}{dy} \right| \end{aligned}$$

□

segment $g(X)$ into monotone functions

For example, $\begin{cases} g(x) = x^2 \\ Y = g(X) \end{cases} \Rightarrow Y = g(X) = X^2,$

$$\begin{cases} Y = g(X) = X^2 \\ X \in (-\infty, +\infty) \end{cases}$$

$$\begin{aligned} & Y = g(X) = X^2 \\ \Rightarrow & Y = \begin{cases} X^2 = g(X) & X \geq 0 \Leftrightarrow X \in [0, +\infty) \Rightarrow \forall X_1 < X_2 [X_1^2 < X_2^2] \\ X^2 = g(X) & X < 0 \Leftrightarrow X \in (-\infty, 0) \Rightarrow \forall X_1 < X_2 [X_1^2 > X_2^2] \end{cases} \\ \Rightarrow & X = \begin{cases} \sqrt{Y} = g^{-1}(Y) & X \geq 0 \Rightarrow \forall X_1^2 < X_2^2 [X_1 < X_2] \Rightarrow \forall Y_1 < Y_2 [X_1 < X_2] \\ -\sqrt{Y} = g^{-1}(Y) & X < 0 \Rightarrow \forall X_1^2 < X_2^2 [X_1 > X_2] \Rightarrow \forall Y_1 < Y_2 [X_1 > X_2] \end{cases} \\ \Rightarrow & X = \begin{cases} \sqrt{Y} = g^{-1}(Y) & Y \in [0, \infty) \Rightarrow X \geq 0 \Rightarrow \forall Y_1 < Y_2 [g^{-1}(Y_1) < g^{-1}(Y_2)] \\ -\sqrt{Y} = g^{-1}(Y) & Y \in [0, \infty) \Rightarrow X < 0 \Rightarrow \forall Y_1 < Y_2 [g^{-1}(Y_1) > g^{-1}(Y_2)] \end{cases} \end{aligned}$$

$$\begin{aligned} F_Y(y) &= P_Y(Y \leq y) = P(X^2 \leq y) \\ &= P(\{X^2 \leq y\} \cap (\{X < 0\} \cup \{X \geq 0\})) \\ &= P((\{X^2 \leq y\} \cap \{X < 0\}) \cup (\{X^2 \leq y\} \cap \{X \geq 0\})) \\ &= P(\{X^2 \leq y\} \cap \{X < 0\}) + P(\{X^2 \leq y\} \cap \{X \geq 0\}) \\ &\quad - P((\{X^2 \leq y\} \cap \{X < 0\}) \cap (\{X^2 \leq y\} \cap \{X \geq 0\})) \\ &= P(\{X^2 \leq y\} \cap \{X < 0\}) + P(\{X^2 \leq y\} \cap \{X \geq 0\}) - P(\emptyset) \\ &= P(\{X^2 \leq y\} \cap \{X < 0\}) + P(\{X^2 \leq y\} \cap \{X \geq 0\}) - 0 \\ &= P(\{X^2 \leq y\} \cap \{X < 0\}) + P(\{X^2 \leq y\} \cap \{X \geq 0\}) \\ &= P(\{-X \leq \sqrt{y}\} \cap \{X < 0\}) + P(\{X \leq \sqrt{y}\} \cap \{X \geq 0\}) \\ &= P(\{X \geq -\sqrt{y}\} \cap \{X < 0\}) + P(\{X \leq \sqrt{y}\} \cap \{X \geq 0\}) \\ &= P_X(-\sqrt{y} \leq X < 0) + P_X(0 \leq X \leq \sqrt{y}) \\ &= [F_X(0) - F_X(-\sqrt{y})] + [F_X(\sqrt{y}) - F_X(0)] \\ &= F_X(\sqrt{y}) - F_X(-\sqrt{y}) \end{aligned}$$

□

Another example, $\begin{cases} Y = g(X) = X^2 \\ X \in [-1, \infty) \end{cases},$

$$\begin{aligned}
Y &= g(X) = X^2 \\
\Rightarrow Y &= \begin{cases} X^2 = g(X) & X \geq 0 \Leftrightarrow X \in [0, +\infty) \Rightarrow \forall X_1 < X_2 [X_1^2 < X_2^2] \\ X^2 = g(X) & -1 \leq X < 0 \Leftrightarrow X \in [-1, 0) \Rightarrow \forall X_1 < X_2 [X_1^2 > X_2^2] \end{cases} \\
\Rightarrow X &= \begin{cases} \sqrt{Y} = g^{-1}(Y) & Y \in [0, \infty) \Rightarrow \forall X_1^2 < X_2^2 [X_1 < X_2] \Rightarrow \forall Y_1 < Y_2 [X_1 < X_2] \\ -\sqrt{Y} = g^{-1}(Y) & Y \in [-1, 0) \Rightarrow \forall X_1^2 < X_2^2 [X_1 > X_2] \Rightarrow \forall Y_1 < Y_2 [X_1 > X_2] \end{cases} \\
\Rightarrow X &= \begin{cases} \sqrt{Y} = g^{-1}(Y) & Y \in [0, \infty) \Rightarrow X \in [0, \infty) \Rightarrow \forall Y_1 < Y_2 [g^{-1}(Y_1) < g^{-1}(Y_2)] \\ -\sqrt{Y} = g^{-1}(Y) & Y \in (0, 1] \Rightarrow X \in [-1, 0) \Rightarrow \forall Y_1 < Y_2 [g^{-1}(Y_1) > g^{-1}(Y_2)] \end{cases} \\
\Rightarrow X &= \begin{cases} \sqrt{Y} = g^{-1}(Y) & Y \in (1, \infty) \Rightarrow X \in (1, \infty) \Rightarrow \forall Y_1 < Y_2 [g^{-1}(Y_1) < g^{-1}(Y_2)] \\ \sqrt{Y} = g^{-1}(Y) & Y \in [0, 1] \Rightarrow X \in [0, 1] \Rightarrow \forall Y_1 < Y_2 [g^{-1}(Y_1) < g^{-1}(Y_2)] \\ -\sqrt{Y} = g^{-1}(Y) & Y \in (0, 1] \Rightarrow X \in [-1, 0) \Rightarrow \forall Y_1 < Y_2 [g^{-1}(Y_1) > g^{-1}(Y_2)] \end{cases}
\end{aligned}$$

$$\begin{aligned}
F_Y(y) &= P_Y(Y \leq y) = P(X^2 \leq y) \begin{cases} Y = g(X) = X^2 \\ X \in [-1, \infty) \end{cases} \\
&= P(\{X^2 \leq y\} \cap (\{X < 0\} \cup \{X \geq 0\})) = \dots \text{ as } \begin{cases} Y = g(X) = X^2 \\ X \in (-\infty, +\infty) \end{cases} \\
&= P(\{X^2 \leq y\} \cap \{X < 0\}) + P(\{X^2 \leq y\} \cap \{X \geq 0\}) \\
&= P(\{-X \leq \sqrt{y}\} \cap \{X < 0\}) + P(\{X \leq \sqrt{y}\} \cap \{X \geq 0\}) \\
&= \begin{cases} P(\{-X \leq \sqrt{y}\} \cap \{X < 0\} \cap \{X > 1\}) + P(\{X \leq \sqrt{y}\} \cap \{X \geq 0\} \cap \{X > 1\}) & Y \in (1, \infty) \Rightarrow X \in (1, \infty) \\ P(\{-X \leq \sqrt{y}\} \cap \{X < 0\} \cap \{X \geq -1\}) + P(\{X \leq \sqrt{y}\} \cap \{X \geq 0\} \cap \{X \leq 1\}) & Y \in [0, 1] \Rightarrow \begin{cases} X \in [0, 1] \\ X \in [-1, 0] \end{cases} \end{cases} \\
&= \begin{cases} P(\emptyset) + P_x(1 < X \leq \sqrt{y}) & Y \in (1, \infty) \Rightarrow X \in (1, \infty) \\ P(\{X \geq -\sqrt{y}\} \cap \{X < 0\} \cap \{X \geq -1\}) + P_x(0 \leq X \leq \min\{\sqrt{y}, 1\}) & Y \in [0, 1] \Rightarrow \begin{cases} X \in [0, 1] \\ X \in [-1, 0] \end{cases} \end{cases} \\
&= \begin{cases} 0 + [F_x(\sqrt{y}) - F_x(1)] & Y \in (1, \infty) \Rightarrow X \in (1, \infty) \\ P_x(\max\{-1, -\sqrt{y}\} \leq X < 0) + P_x(0 \leq X \leq \sqrt{y}) & Y \in [0, 1] \Rightarrow \begin{cases} X \in [0, 1] \\ X \in [-1, 0] \end{cases} \end{cases} \\
&= \begin{cases} F_x(\sqrt{y}) - F_x(1) & Y \in (1, \infty) \Rightarrow X \in (1, \infty) \\ P_x(-\sqrt{y} \leq X < 0) + [F_x(\sqrt{y}) - F_x(0)] & Y \in [0, 1] \Rightarrow \begin{cases} X \in [0, 1] \\ X \in [-1, 0] \end{cases} \end{cases} \\
&= \begin{cases} F_x(\sqrt{y}) - F_x(1) & y > 1 \\ F_x(\sqrt{y}) - F_x(-\sqrt{y}) & -1 \leq y \leq 1 \end{cases}
\end{aligned}$$

□

15.1.2.5 discrete monotone transformation

$$\begin{cases} Y = g(X) = X^2 \\ X \text{ discrete} \Rightarrow Y \text{ discrete} \end{cases}$$

$$\begin{aligned}
f_Y(y) &= P_Y(Y = y) \\
&= P(X^2 = y) \\
&= P(\{X = \sqrt{y}\} \cup \{X = -\sqrt{y}\}) \\
&= P(\{X = \sqrt{y}\}) + P(\{X = -\sqrt{y}\}) - P(\{X = \sqrt{y}\} \cap \{X = -\sqrt{y}\}) \\
&= P_X(X = \sqrt{y}) + P_X(X = -\sqrt{y}) - P(\emptyset) \\
&= P_X(X = \sqrt{y}) + P_X(X = -\sqrt{y}) - 0 \\
&= P_X(X = \sqrt{y}) + P_X(X = -\sqrt{y}) \\
&= f_X(\sqrt{y}) + f_X(-\sqrt{y})
\end{aligned}$$

□

Theorem 15.4. *discrete monotone transformation*

$$\begin{array}{c}
\left\{ \begin{array}{l} Y = g(X) \\ X \text{ discrete} \Rightarrow Y \text{ discrete} \end{array} \right. \\
\Downarrow \\
f_Y(y) = \sum_{\{x|g(x)=y\}} f_X(x) = \sum_{\{x|x=g^{-1}(y)\}} f_X(x)
\end{array}$$

Proof:

$$\begin{aligned}
f_Y(y) &= P_Y(Y = y) \\
&= P(g(X) = y) = \sum_{t \in \{x|g(x)=y\}} f_X(t) = \sum_{x \in \{x|g(x)=y\}} f_X(x) = \sum_{\{x|g(x)=y\}} f_X(x) \\
&= P_X(X = g^{-1}(y)) = \sum_{t \in \{x|x=g^{-1}(y)\}} f_X(t) = \sum_{x \in \{x|x=g^{-1}(y)\}} f_X(x) = \sum_{\{x|x=g^{-1}(y)\}} f_X(x) \\
f_Y(y) &= P_Y(Y = y) \\
&= P(g(X) = y) = \sum_{t \in \{x|g(x)=y\}} f_X(t) = \sum_{x \in \{x|g(x)=y\}} f_X(x) = \sum_{\{x|g(x)=y\}} f_X(x) \\
&= P_X(X = g^{-1}(y)) = \sum_{t \in \{x|x=g^{-1}(y)\}} f_X(t) = \sum_{x \in \{x|x=g^{-1}(y)\}} f_X(x) = \sum_{\{x|x=g^{-1}(y)\}} f_X(x)
\end{aligned}$$

□

Theorem 15.5. *probability integral transformation*

$$\begin{array}{c}
\left\{ \begin{array}{l} X \text{ continuous} \quad (c) \\ X \sim F_X(x) \quad (d) \\ Y = F_X(X) \quad (t) \end{array} \right. \\
\Downarrow \\
F_Y(y) = y, \forall y \in [0, 1] \\
\Updownarrow \text{def.} \\
Y \sim U = U(y) \Leftrightarrow Y \sim U(y) \Leftrightarrow Y \text{ is uniformly distributed on } [0, 1]
\end{array}$$

Proof:

$$\begin{aligned}
F_Y(y) &= \Pr_Y(Y \leq y) \stackrel{(t)}{=} \Pr(F_X(X) \leq y), \forall x_1 < x_2 [F_X(x_1) < F_X(x_2)] \Rightarrow \begin{cases} \exists F_X^{-1} : Y \rightarrow X \\ \forall y_1 < y_2 [F_X^{-1}(y_1) < F_X^{-1}(y_2)] \end{cases} \\
&= \Pr_X(X \leq F_X^{-1}(y) = x) = \Pr_X(X \leq x), x = F_X^{-1}(y) \\
&= \Pr_X(X \leq x) = F_X(x) \stackrel{x=F_X^{-1}(y)}{=} F_X(F_X^{-1}(y)) = y \\
F_Y(y) &= y
\end{aligned}$$

□

Note:

According to Theorem 15.5,

$$\begin{aligned}
U &= F_X(X) \stackrel{15.5}{\sim} U(u) \text{ on } [0, 1] \\
\Rightarrow X &= F_X^{-1}(U) \wedge X \sim F_X(x) \Rightarrow F_X^{-1}(U) = X \sim F_X(x) \Rightarrow F_X^{-1}(U) \sim F_X(x) \\
\Rightarrow X &= F_X^{-1}(U) \sim F_X(x) \\
&\text{i.e. uniform random variables substituted into the inverse of } F_X, \\
&\text{we can get random variables follow } F_X(x)
\end{aligned}$$

15.1.2.6 expected value

$$\mathbb{E}(g(X)) = \mathbb{E}[g(X)] = \mathbb{E}g(X) = \mathbb{E}[g(X)] = \mathbb{E}g(X)$$

Definition 15.12. expected value: The expected value of a random variable $g(X)$ is

$$\mathbb{E}(g(X)) = \mathbb{E}[g(X)] = \begin{cases} \int_{-\infty}^{+\infty} g(x) f_X(x) dx & X \text{ continuous} \\ \sum_{x \in X(\Omega)} g(x) f_X(x) & X \text{ discrete} \end{cases}$$

⁶ p.126

Definition 15.13. expected value or expectation function: The expected value of a random variable X is

$$\mathbb{E}(X) = \mathbb{E}[X] = \begin{cases} \int_{-\infty}^{+\infty} x f_X(x) dx = 1 & X \text{ continuous} \\ \sum_{x \in X(\Omega)} x f_X(x) = 1 & X \text{ discrete} \end{cases}$$

Theorem 15.6. *the rule of the lazy statistician*

the law of the unconscious statistician = the LOTUS

$$\mathbb{E}(g(X)) = \mathbb{E}[g(X)] = \begin{cases} \int_{-\infty}^{+\infty} g(x) f_X(x) dx & X \text{ continuous} \\ \sum_{x \in X(\Omega)} g(x) f_X(x) & X \text{ discrete} \end{cases}$$

Proof:⁷ p.162 for p.119

Discrete case:

to be proved

Continuous case:

to be proved

□

By linearity of \int and \sum , expected values have the following properties or theorems,

- $E[a_1g_1(X_1) + a_2g_2(X_2) + c] = a_1E[g_1(X_1)] + a_2E[g_2(X_2)] + c$
- $\forall x \in \mathbb{R} [g(x) \geq 0] \Rightarrow E[g(X)] \geq 0$
- $\forall x \in \mathbb{R} [g_1(x) \geq g_2(x)] \Rightarrow E[g_1(X)] \geq E[g_2(X)]$
- $\forall x \in \mathbb{R} [a \leq g(x) \leq b] \Rightarrow a \leq E[g(X)] \leq b$

Theorem 15.7. $E[X]$ minimizes Euclidean distance $E[(X - b)^2]$ over b , i.e.

$$E[X] = \arg \min_b E[(X - b)^2]$$

Proof:

$$\begin{aligned} E[(X - b)^2] &= E[(X - E[X] + E[X] - b)^2] \\ &= E[\{(X - E[X]) + (E[X] - b)\}^2] \\ &= E[(X - E[X])^2 + 2(X - E[X])(E[X] - b) + (E[X] - b)^2] \\ &= E[(X - E[X])^2] + 2(E[X] - b)E[(X - E[X])] + E[(E[X] - b)^2] \\ &= E[(X - E[X])^2] + 2(E[X] - b)E[X - E[X]] + (E[X] - b)^2 \\ &= E[(X - E[X])^2] + 2(E[X] - b)(E[X] - E[X]) + (E[X] - b)^2 \\ &= E[(X - E[X])^2] + 2(E[X] - b)0 + (E[X] - b)^2 \\ &= E[(X - E[X])^2] + 0 + (E[X] - b)^2 \\ &= E[(X - E[X])^2] + (E[X] - b)^2 \stackrel{(E[X]-b)^2 \geq 0}{\geq} E[(X - E[X])^2] \\ E[(X - b)^2] &\geq E[(X - E[X])^2] \\ &\Downarrow \\ E[(X - b)^2] &= E[(X - E[X])^2] \text{ holds if } (E[X] - b)^2 = 0 \Rightarrow b = E[X] \Rightarrow E[X] = \arg \min_b E[(X - b)^2] \end{aligned}$$

□

Note:

When $b = E[X]$, $E[(X - b)^2]$ has minimum loss $E[(X - E[X])^2] = V[X] = V(X)$, i.e. defintion of variance appears.

Theorem 15.8. median $[X]$ minimizes $E[|X - b|]$ over b , i.e.

$$\text{median}[X] = \arg \min_b E[|X - b|]$$

Proof:

to be proved

□

Note:

When $b = \text{median}[X]$, $E[(X - b)^2]$ has minimum loss $E[|X - \text{median}[X]|]$, i.e. defintion of MAD(mean absolute deviation) in robust statistics appears.

Definition 15.14. indicator function

$$\begin{aligned} 1(E) &= 1(x \in E) = 1(\{x \in E\}) = 1(\{x | x \in E\}) = \begin{cases} 1 & \text{if } E \\ 0 & \text{if } \bar{E} = E^C \end{cases} \\ &= \begin{cases} 1 & \text{if event } E \text{ occurs} \\ 0 & \text{if event } E \text{ does not occur} \end{cases} \end{aligned}$$

Note:

Theorem 15.9. probability as expected value

$$P_x(E) = P(x \in E) = E[1(X \in E)]$$

Proof:

$$\begin{aligned} P_x(E) &= P(x \in E) = \int_{x \in E} f_x(x) dx = \int_E f_x(x) dx \\ &= \int 1(x \in E) f_x(x) dx \\ &= \int g(x) f_x(x) dx, g(x) = 1(x \in E) \\ &= E[g(X)], g(X) = 1(X \in E) \\ &= E[1(X \in E)] \end{aligned}$$

$$P_x(E) = P(x \in E) = E[1(X \in E)]$$

□

Iverson bracket https://en.wikipedia.org/wiki/Iverson_bracket

$$\begin{cases} v(p(x)) = \text{T} & \Leftrightarrow [p(x)] = 1 \\ v(p(x)) = \text{F} & \Leftrightarrow [p(x)] = 0 \end{cases}$$

$$[p(x)] = \begin{cases} 1 & v(p(x)) = \text{T} \\ 0 & v(\neg p(x)) = \text{T} \end{cases} = \begin{cases} 1 & p(x) \\ 0 & \neg p(x) \end{cases}$$

negation = NOT

$$[\neg p] = 1 - [p]$$

in set theory or domain of events,

$$1(\bar{E}) = 1 - 1(E)$$

conjunction = AND

$$[p \wedge q] = [p][q]$$

in set theory or domain of events,

$$1(E_1 \cap E_2) = 1(E_1)1(E_2)$$

disjunction = OR

$$[p \vee q] = [p] + [q] - [p][q] = [p] + [q] - [p \wedge q]$$

Proof:

in set theory or domain of events,

$$\begin{aligned} 1(E_1 \cup E_2) &\stackrel{\text{de Moivre}}{=} 1(\overline{\bar{E}_1 \cap \bar{E}_2}) \\ &= 1 - 1(\bar{E}_1 \cap \bar{E}_2) = 1 - 1(\bar{E}_1)1(\bar{E}_2) \\ &= 1 - [1 - 1(E_1)][1 - 1(E_2)] \\ &= 1 - [1 - 1(E_1)][1 - 1(E_2)] \\ &= 1 - [1 - 1(E_1) - 1(E_2) + 1(E_1)1(E_2)] \\ &= 1(E_1) + 1(E_2) - 1(E_1)1(E_2) \\ &= 1(E_1) + 1(E_2) - 1(E_1 \cap E_2) \end{aligned}$$

$$1(E_1 \cup E_2) = 1(E_1) + 1(E_2) - 1(E_1)1(E_2) = 1(E_1) + 1(E_2) - 1(E_1 \cap E_2)$$

□

implication = conditional

$$\begin{aligned}[p \rightarrow q] &= [\neg p \vee q] \\ &= [\neg p] + [q] - [\neg p][q] \\ &= 1 - [p] + [q] - (1 - [p])[q] \\ &= 1 - [p] + [p][q]\end{aligned}$$

exclusive disjunction = XOR

$$\begin{aligned}[p \vee q] &= [p \oplus q] = |[p] - [q]| = ([p] - [q])^2 \\ &= [p](1 - [q]) + (1 - [p])[q]\end{aligned}$$

biconditional = XNOR

$$[p \leftrightarrow q] = [p \odot q] = [\neg(p \oplus q)] = [\neg(p \vee q)] = ([p] + (1 - [q]))((1 - [p]) + [q])$$

Kronecker delta

$$\delta_{ij} = [i = j]$$

single-argument notation

$$\delta_i = \delta_{i0} = \begin{cases} 1 & i = j = 0 \\ 0 & i \neq j = 0 \end{cases}$$

sign function

$$\operatorname{sgn}(x) = \begin{cases} 1 & x > 0 \\ 0 & x = 0 \\ -1 & x < 0 \end{cases} = [x > 0] - [x < 0]$$

absolute function

$$\begin{aligned}|x| &= \begin{cases} x & x \geq 0 \\ -x & x < 0 \end{cases} = \begin{cases} x & x > 0 \\ -x & x \leq 0 \end{cases} = \begin{cases} x & x > 0 \\ 0 & x = 0 \\ -x & x < 0 \end{cases} \\ &= \begin{cases} x \cdot 1 & x > 0 \\ x \cdot 0 & x = 0 \\ x \cdot (-1) & x < 0 \end{cases} = \begin{cases} x \cdot \operatorname{sgn}(x) & x > 0 \\ x \cdot \operatorname{sgn}(x) & x = 0 \\ x \cdot \operatorname{sgn}(x) & x < 0 \end{cases} \\ &= x \cdot \operatorname{sgn}(x) = x([x > 0] - [x < 0]) = x[x > 0] - x[x < 0]\end{aligned}$$

binary min and max function

$$\max(x, y) = x [x > y] + y [x \leq y]$$

$$\min(x, y) = x [x \leq y] + y [x > y]$$

binary max function

$$\max(x, y) = \frac{x + y + |x - y|}{2}$$

floor and ceiling functions

floor function

$$\begin{aligned} \lfloor x \rfloor &= n, n \leq x < n + 1 \\ &= \sum_{n \in \mathbb{N}} n [n \leq x < n + 1] \end{aligned}$$

ceiling function

$$\begin{aligned} \lceil x \rceil &= n, n - 1 < x \leq n \\ &= \sum_{n \in \mathbb{N}} n [n - 1 < x \leq n] \end{aligned}$$

Heaviside step function

$$H(x) = \begin{cases} 1 & x > 0 \\ 0 & x \leq 0 \end{cases} = [x > 0] = 1_{(0, \infty)}(x)$$

or conveniently define “unit step function”

$$u(x) = \begin{cases} 1 & x \geq 0 \\ 0 & x < 0 \end{cases} = [x \geq 0] = 1_{[0, \infty)}(x)$$

ramp function = rectified linear unit activation function = ReLU

$$\text{ReLU}(x) = \begin{cases} x & x \geq 0 \\ 0 & x < 0 \end{cases} = x [x \geq 0]$$

indicator function

$$A \subseteq X \Rightarrow \begin{cases} 1_A : X \rightarrow \{0, 1\} & \Leftrightarrow x \in X \xrightarrow{1_A} \{0, 1\} \\ 1_A(x) = \begin{cases} 1 & x \in A \\ 0 & x \notin A \end{cases} & = [x \in A] = \begin{cases} 1 & v(x \in A) = T \\ 0 & v(\neg(x \in A)) = T \end{cases} \end{cases}$$

$A, B \subseteq \Omega$,

$$A = B \Leftrightarrow 1_A = 1_B$$

$$A = \Omega \Leftrightarrow 1_A(x) = 1$$

$$A = \emptyset \Leftrightarrow 1_A(x) = 0$$

Theorem 15.10. *subset indicator order*

$$A \subset B \Rightarrow 1_A(x) \leq 1_B(x)$$

Proof:

$$\begin{aligned} & \forall x (1_A(x) = 1 \Rightarrow 1_B(x) = 1) \\ \Leftrightarrow & \forall x (\neg 1_A(x) = 1 \vee 1_B(x) = 1) \\ \Leftrightarrow & \forall x (\neg (1_A(x) = 1) \wedge \neg 1_B(x) = 1) \\ \Rightarrow & \neg \exists x (1_A(x) = 1 \wedge 1_B(x) = 0) \\ \Rightarrow & \neg \exists x (1_B(x) = 0 < 1 = 1_A(x)) \\ \Rightarrow & \neg \exists x (1_B(x) < 1_A(x)) \\ \Rightarrow & \forall x (1_B(x) \geq 1_A(x)) \end{aligned}$$

□

in set theory or domain of events,

$$1(E_1 \cap E_2) = 1(E_1) 1(E_2)$$

$$1(\overline{E}) = 1 - 1(E)$$

$$1(E_1 \cup E_2) = 1(E_1) + 1(E_2) - 1(E_1) 1(E_2) = 1(E_1) + 1(E_2) - 1(E_1 \cap E_2)$$

expectation in many perspectives

$$Y = g(X)$$

$$\int_{-\infty}^{+\infty} y f_Y(y) dy = E[Y] = E[g(X)] = \int_{-\infty}^{+\infty} g(x) f_X(x) dx$$

$$E_Y[Y] = \int_{-\infty}^{+\infty} y f_Y(y) dy = E[Y] = E[g(X)] = \int_{-\infty}^{+\infty} g(x) f_X(x) dx = E_X[g(X)]$$

$$\mathbb{E}_Y [Y] = \mathbb{E}_X [g(X)]$$

$$\begin{aligned} & \mathbb{E}[a_1 g_1(X_1) + a_2 g_2(X_2) + c], \begin{cases} Y_1 = g_1(X_1) \\ Y_2 = g_2(X_2) \end{cases} \\ &= \mathbb{E}[a_1 Y_1 + a_2 Y_2 + c] \end{aligned}$$

$$\begin{aligned} & \mathbb{E}[a_1 g_1(X_1) + a_2 g_2(X_2) + c] = a_1 \mathbb{E}[g_1(X_1)] + a_2 \mathbb{E}[g_2(X_2)] + c \\ &= \mathbb{E}[a_1 Y_1 + a_2 Y_2 + c] = a_1 \mathbb{E}[Y_1] + a_2 \mathbb{E}[Y_2] + c \end{aligned}$$

$$a_1 \mathbb{E}[g_1(X_1)] + a_2 \mathbb{E}[g_2(X_2)] + c = a_1 \mathbb{E}_{X_1}[g_1(X_1)] + a_2 \mathbb{E}_{X_2}[g_2(X_2)] + c$$

$$a_1 \mathbb{E}[Y_1] + a_2 \mathbb{E}[Y_2] + c = a_1 \mathbb{E}_{Y_1}[Y_1] + a_2 \mathbb{E}_{Y_2}[Y_2] + c$$

$$a_1 \mathbb{E}_{X_1}[g_1(X_1)] + a_2 \mathbb{E}_{X_2}[g_2(X_2)] + c = a_1 \mathbb{E}_{Y_1}[Y_1] + a_2 \mathbb{E}_{Y_2}[Y_2] + c$$

15.1.2.7 moment

Definition 15.15. n^{th} moment: For each integer n , the n^{th} moment of X is $\mathbb{E}[X^n]$.

The n^{th} central moment of X is $\mu_n = \mathbb{E}[(X - \mathbb{E}[X])^n]$.

$$\mathbb{E}[X^n] = \begin{cases} \int_{-\infty}^{+\infty} x^n f_X(x) dx & X \text{ continuous} \\ \sum_{x \in X(\Omega)} x^n f_X(x) & X \text{ discrete} \end{cases}$$

$$\mu = \mathbb{E}[X^1] = \mathbb{E}[X] = \begin{cases} \int_{-\infty}^{+\infty} x^1 f_X(x) dx & X \text{ continuous} \\ \sum_{x \in X(\Omega)} x^1 f_X(x) & X \text{ discrete} \end{cases} = \begin{cases} \int_{-\infty}^{+\infty} x f_X(x) dx & X \text{ continuous} \\ \sum_{x \in X(\Omega)} x f_X(x) & X \text{ discrete} \end{cases}$$

$$\mu_n = \mathbb{E}[(X - \mathbb{E}[X])^n] = \begin{cases} \int_{-\infty}^{+\infty} (x - \mu)^n f_X(x) dx & X \text{ continuous} \\ \sum_{x \in X(\Omega)} (x - \mu)^n f_X(x) & X \text{ discrete} \end{cases}$$

1st moment of X = mean

$$\mu = \mathbb{E}[X^1] = \mathbb{E}[X] = \begin{cases} \int_{-\infty}^{+\infty} x^1 f_X(x) dx & X \text{ continuous} \\ \sum_{x \in X(\Omega)} x^1 f_X(x) & X \text{ discrete} \end{cases} = \begin{cases} \int_{-\infty}^{+\infty} x f_X(x) dx & X \text{ continuous} \\ \sum_{x \in X(\Omega)} x f_X(x) & X \text{ discrete} \end{cases}$$

1st central moment of X = 0

$$\begin{aligned}\mu_1 &= \mathbb{E}[(X - \mathbb{E}[X])^1] = \begin{cases} \int_{-\infty}^{+\infty} (x - \mu)^1 f_x(x) dx & X \text{ continuous} \\ \sum_{x \in X(\Omega)} (x - \mu)^1 f_x(x) & X \text{ discrete} \end{cases} = \begin{cases} \int_{-\infty}^{+\infty} (x - \mu) f_x(x) dx & X \text{ continuous} \\ \sum_{x \in X(\Omega)} (x - \mu) f_x(x) & X \text{ discrete} \end{cases} \\ &= \begin{cases} \int_{-\infty}^{+\infty} x f_x(x) dx - \int_{-\infty}^{+\infty} \mu f_x(x) dx & X \text{ continuous} \\ \sum_{x \in X(\Omega)} x f_x(x) - \sum_{x \in X(\Omega)} \mu f_x(x) & X \text{ discrete} \end{cases} \\ &= \begin{cases} \mathbb{E}[X] - \mu \int_{-\infty}^{+\infty} f_x(x) dx & X \text{ continuous} \\ \mathbb{E}[X] - \mu \sum_{x \in X(\Omega)} f_x(x) & X \text{ discrete} \end{cases} = \begin{cases} \mathbb{E}[X] - \mu \cdot 1 & X \text{ continuous} \\ \mathbb{E}[X] - \mu \cdot 1 & X \text{ discrete} \end{cases} \\ &= \begin{cases} \mathbb{E}[X] - \mu & X \text{ continuous} \\ \mathbb{E}[X] - \mu & X \text{ discrete} \end{cases} = \begin{cases} \mathbb{E}[X] - \mathbb{E}[X] & X \text{ continuous} \\ \mathbb{E}[X] - \mathbb{E}[X] & X \text{ discrete} \end{cases} \\ &= \begin{cases} 0 & X \text{ continuous} \\ 0 & X \text{ discrete} \end{cases} = 0\end{aligned}$$

$$\mathbb{E}[(X - \mathbb{E}[X])] = 0$$

$$\mathbb{E}[X - \mathbb{E}[X]] = 0$$

$$\forall X (\mathbb{E}[X - \mathbb{E}[X]] = 0)$$

For normal distribution, actually for any distribution,

$$\begin{array}{c} X \sim n(0, 1) = \mathcal{N}(0, 1^2) \\ \Downarrow \\ \mathbb{E}[X - \mathbb{E}[X]] = 0 \end{array}$$

2^{nd} central moment of X = variance

$$\begin{aligned}\mu_2 &= \mathbb{E}[(X - \mathbb{E}[X])^2] = \begin{cases} \int_{-\infty}^{+\infty} (x - \mu)^2 f_x(x) dx & X \text{ continuous} \\ \sum_{x \in X(\Omega)} (x - \mu)^2 f_x(x) & X \text{ discrete} \end{cases} \\ &= \mathbb{E}[(X - \mathbb{E}[X])^2] = V[X] = V(X)\end{aligned}$$

For normal distribution,

$$\begin{array}{c} X \sim n(0, 1) = \mathcal{N}(0, 1^2) = \mathcal{N}(\mu = 0, V^2[X] = 1^2) \\ \Downarrow \\ V[X] = V(X) = 1 \end{array}$$

variance properties

$$V[aX + b] = a^2 V[X]$$

Proof:

to be proved

□

3rd central moment of X

$$\mu_3 = E[(X - E[X])^3] = \begin{cases} \int_{-\infty}^{+\infty} (x - \mu)^3 f_x(x) dx & X \text{ continuous} \\ \sum_{x \in X(\Omega)} (x - \mu)^3 f_x(x) & X \text{ discrete} \end{cases}$$

skewness

偏度

$$\begin{aligned} \text{skewness}[X] &= \frac{\mu_3}{\mu_2^{\frac{3}{2}}} = \frac{E[(X - E[X])^3]}{(V[X])^{\frac{3}{2}}} = \frac{E[(X - E[X])^3]}{\left(E[(X - E[X])^2]\right)^{\frac{3}{2}}} \\ &= \begin{cases} \frac{\int_{-\infty}^{+\infty} (x - \mu)^3 f_x(x) dx}{\left(\int_{-\infty}^{+\infty} (x - \mu)^2 f_x(x) dx\right)^{\frac{3}{2}}} & X \text{ continuous} \\ \frac{\sum_{x \in X(\Omega)} (x - \mu)^3 f_x(x)}{\left(\sum_{x \in X(\Omega)} (x - \mu)^2 f_x(x)\right)^{\frac{3}{2}}} & X \text{ discrete} \end{cases} \end{aligned}$$

For normal distribution,

$$\begin{aligned} X \sim n(0, 1) &= \mathcal{N}(0, 1^2) = \mathcal{N}(\mu = 0, V^2[X] = 1^2) \\ \Downarrow \\ \text{skewness}[X] &= \frac{E[(X - E[X])^3]}{(V[X])^{\frac{3}{2}}} = \frac{E[(X - E[X])^3]}{1^{\frac{3}{2}}} = 0 \end{aligned}$$

Proof:

to be proved

□

4^{th} central moment of X

$$\mu_4 = E[(X - E[X])^4] = \begin{cases} \int_{-\infty}^{+\infty} (x - \mu)^4 f_x(x) dx & X \text{ continuous} \\ \sum_{x \in X(\Omega)} (x - \mu)^4 f_x(x) & X \text{ discrete} \end{cases}$$

kurtosis

峰度

$$\begin{aligned} \text{kurtosis}[X] &= \frac{\mu_4}{\mu_2^2} = \frac{E[(X - E[X])^4]}{(V[X])^2} = \frac{E[(X - E[X])^4]}{\left(E[(X - E[X])^2]\right)^2} \\ &= \begin{cases} \frac{\int_{-\infty}^{+\infty} (x - \mu)^4 f_x(x) dx}{\left(\int_{-\infty}^{+\infty} (x - \mu)^2 f_x(x) dx\right)^2} & X \text{ continuous} \\ \frac{\sum_{x \in X(\Omega)} (x - \mu)^4 f_x(x)}{\left(\sum_{x \in X(\Omega)} (x - \mu)^2 f_x(x)\right)^2} & X \text{ discrete} \end{cases} \end{aligned}$$

For normal distribution,

$$\begin{aligned} X \sim n(0, 1) &= \mathcal{N}(0, 1^2) = \mathcal{N}(\mu = 0, V^2[X] = 1^2) \\ \downarrow \\ \text{kurtosis}[X] &= \frac{E[(X - E[X])^4]}{(V[X])^2} = \frac{[(X - E[X])^4]}{1^2} = 3 \end{aligned}$$

Proof:

to be proved

□

For normal distribution,

$$\begin{aligned} X \sim n(0, 1) &= \mathcal{N}(0, 1^2) = \mathcal{N}(\mu = 0, V^2[X] = 1^2) \\ \downarrow \end{aligned}$$

$$\left\{ \begin{array}{ll} \mu = E[X] & = 0 \\ \mu_1 = E[X - E[X]] & = 0 \\ \text{variance}[X] = V[X] = E[(X - E[X])^2] & = 1 \\ \text{skewness}[X] = \frac{E[(X - E[X])^3]}{(V[X])^{\frac{3}{2}}} & = 0 \\ \text{kurtosis}[X] = \frac{E[(X - E[X])^4]}{(V[X])^2} & = 3 \end{array} \right.$$

$$\begin{aligned} \mu &= E[X] = 0 \\ \mu_1 &= E[X - E[X]] = 0 \\ \text{variance}[X] &= V[X] = E[(X - E[X])^2] = 1 \\ \text{skewness}[X] &= \frac{E[(X - E[X])^3]}{(V[X])^{\frac{3}{2}}} = 0 \\ \text{kurtosis}[X] &= \frac{E[(X - E[X])^4]}{(V[X])^2} = 3 \end{aligned}$$

$$X \sim F_x(x) \leftrightarrow f_x(x) \rightarrow \{\mu_n | n \in \mathbb{N}\} = \left\{ \mu_n \left| \begin{cases} n \in \mathbb{N} \\ \mu_n = E[(X - E[X])^n] \end{cases} \right. \right\}$$

15.1.2.7.1 moment generating function

Definition 15.16. MGF = moment generating function: The moment generating function of X is $M(\xi) = M_x(\xi) = E[e^{\xi X}]$, provided that the expression exists for $t \approx 0$.

$$M(t) = M_x(t) = E[e^{tX}]$$

$$M(\xi) = M_x(\xi) = E[e^{\xi X}]$$

Theorem 15.11. moment generating function(MGF) generating moment

$$M_x^{(n)}(\xi) = E[X^n]$$

where

$$M_x^{(n)}(\xi) = \frac{d^n}{d\xi^n} M_x(\xi)$$

Proof:

to be proved

□

$$X \sim F_x(x) \leftrightarrow f_x(x) \rightarrow \{\mu_n | n \in \mathbb{N}\} = \left\{ \mu_n \middle| \begin{cases} n \in \mathbb{N} \\ \mu_n = \mathbb{E}[(X - \mathbb{E}[X])^n] \end{cases} \right\}$$

$$\begin{array}{ccccccc} X & \sim & F_x(x) & \leftrightarrow & f_x(x) & \rightarrow & \{\mu_n | n \in \mathbb{N}\} \\ & & & & \downarrow & \nearrow & \\ & & & & M_x(\xi) & & \end{array}$$

$$\begin{array}{ccccccc} X & \sim & F_x(x) & \leftrightarrow & f_x(x) & & \\ & & & & \downarrow & \searrow & \\ & & & & M_x(\xi) & \rightarrow & \{\mu_n | n \in \mathbb{N}\} \end{array}$$

Theorem 15.12. If X and Y have bounded support, then $\forall u [F_x(u) = F_y(u)]$ iff $\forall n \in \mathbb{N} (\mathbb{E}[X^n] = \mathbb{E}[Y^n])$.

$$\forall u [F_x(u) = F_y(u)] \Rightarrow \forall n \in \mathbb{N} (\mathbb{E}[X^n] = \mathbb{E}[Y^n])$$

$$\left\{ \begin{array}{l} \forall n \in \mathbb{N} (\mathbb{E}[X^n] = \mathbb{E}[Y^n]) \\ \left\{ \begin{array}{l} \text{supp}(f_x) \text{ is bounded} \\ \text{supp}(f_y) \text{ is bounded} \end{array} \right. \Rightarrow \forall u [F_x(u) = F_y(u)] \end{array} \right.$$

Proof:

to be proved

□

Theorem 15.13. If $M_x(t)$ and $M_y(t)$ exist, then $\forall u [F_x(u) = F_y(u)]$ iff $\forall t \approx 0 [M_x(t) = M_y(t)]$.

$$\forall u [F_x(u) = F_y(u)] \Rightarrow \forall t \approx 0 [M_x(t) = M_y(t)]$$

$$\left\{ \begin{array}{l} \forall t \approx 0 [M_x(t) = M_y(t)] \\ \left\{ \begin{array}{l} \exists M_x(t) \in \mathbb{R} \\ \exists M_y(t) \in \mathbb{R} \end{array} \right. \Rightarrow \forall u [F_x(u) = F_y(u)] \end{array} \right.$$

Proof:

to be proved

□

$$\begin{array}{ccccccc} X & \sim & F_x(x) & \leftrightarrow & f_x(x) & & \\ & & \uparrow & \downarrow & \searrow \nwarrow & \leftarrow \wedge \text{ supp}(f_x) \text{ is bounded} & \\ \forall \xi \approx 0 [M_x(\xi) \in \mathbb{R}] & \wedge & M_x(\xi) & \rightarrow & & & \{\mu_n | n \in \mathbb{N}\} \end{array}$$

15.1.2.7.2 characteristic function

Definition 15.17. CF = characteristic function: The characteristic function of X is $\varphi(\xi) = \varphi_x(\xi) = E[e^{i\xi X}]$, provided that the expression always exists.

$$\varphi(t) = \varphi_x(t) = E[e^{itX}]$$

$$\varphi(\xi) = \varphi_x(\xi) = E[e^{i\xi X}]$$

Note:

1. $\varphi(\xi) = \varphi_x(\xi) = E[e^{i\xi X}]$ always exists.

$$\forall X (\varphi(\xi) = \varphi_x(\xi) = E[e^{i\xi X}] \in \mathbb{R})$$

2. moment generating function to characteristic function

$$M(\xi) = M_x(\xi) = E[e^{\xi X}] \in \mathbb{R} \Rightarrow M_x(i\xi) = \varphi_x(\xi)$$

3. inversion theorem or inversion formula

For $a < b$,

$$\begin{aligned} & \lim_{T \rightarrow \infty} \frac{1}{2\pi} \int_{-T}^{+T} \frac{e^{-ita} - e^{-itb}}{it} \varphi_x(t) dt \\ &= P(a < X < b) + \frac{1}{2} [P(X = a) + P(X = b)] \end{aligned}$$

i.e. $\varphi_x(\xi)$ determines $F_x(x)$.

$$\begin{array}{ccccccc} X & \sim & F_x(x) & \leftrightarrow & f_x(x) & & \\ \uparrow & & \forall \xi \approx 0 [M_x(\xi) \in \mathbb{R}] \wedge & \uparrow \downarrow & \searrow \nearrow & \leftrightarrow \rho \wedge \text{supp}(f_x) \text{ is bounded} \\ \varphi_x(\xi) & & \Leftrightarrow & M_x(\xi) & \rightarrow & & \{\mu_n | n \in \mathbb{N}\} \end{array}$$

$$\begin{array}{ccccccc} X & \sim & F_x(x) & \xleftrightarrow{\text{FToC}} & f_x(x) & \leftrightarrow & P_x \\ \text{inversion formula :} & & \downarrow & \forall \xi \approx 0 [M_x(\xi) \in \mathbb{R}] \wedge & \uparrow \downarrow & \searrow \nearrow & \leftrightarrow \rho \wedge \text{supp}(f_x) \text{ is bounded} \\ & & \varphi_x(\xi) & \Leftrightarrow & M_x(\xi) & \rightarrow & \{\mu_n | n \in \mathbb{N}\} \end{array}$$

MGF theorems

<https://www.youtube.com/watch?v=fSbs6im6wqY&t=524s>

Theorem 15.14. If

15.1.2.8 common families of distributions

mean and variance of discrete probability distributions^[43.5]

15.1.2.8.1 discrete distribution

15.1.2.8.1.1 discrete uniform distribution

$$\begin{aligned} X &\sim \mathcal{DU}(1, N) \\ &\Updownarrow \\ \begin{cases} f_x(x|N) = \frac{1}{N} \\ x \in X(\Omega) = \{1, 2, \dots, N\} \end{cases} \\ &\Downarrow \\ \begin{cases} E[X] = \frac{N+1}{2} \\ V[X] = \frac{(N+1)(N-1)}{12} \end{cases} \end{aligned}$$

$$\begin{aligned} E[X] &= \sum_{x \in X(\Omega)} x f_x(x|N) = \sum_{x=1}^N x \frac{1}{N} \\ &= \frac{1}{N} \sum_{x=1}^N x = \frac{1}{N} \frac{N(N+1)}{2} = \frac{N+1}{2} \\ E[X] &= \frac{N+1}{2} \end{aligned}$$

$$\begin{aligned} V[X] &= \sum_{x \in X(\Omega)} (x - E[X])^2 f_x(x|N) = \sum_{x=1}^N \left(x - \frac{N+1}{2} \right)^2 \frac{1}{N} \\ &= \frac{1}{N} \sum_{x=1}^N \left[x^2 - (N+1)x + \left(\frac{N+1}{2} \right)^2 \right] \\ &= \frac{1}{N} \left[\sum_{x=1}^N x^2 - (N+1) \sum_{x=1}^N x + N \left(\frac{N+1}{2} \right)^2 \right] \\ &= \frac{1}{N} \left[\frac{N(N+1)(2N+1)}{6} - (N+1) \frac{N(N+1)}{2} + N \left(\frac{N+1}{2} \right)^2 \right] \\ &= (N+1) \left[\frac{2N+1}{6} - \frac{N+1}{2} + \frac{N+1}{4} \right] = (N+1) \frac{4N+2-(3N+3)}{12} \\ &= \frac{(N+1)(N-1)}{12} \\ V[X] &= \frac{(N+1)(N-1)}{12} \end{aligned}$$

$$X \sim \mathcal{DU}(a, b) \Updownarrow \begin{cases} f_x(x|N) = \frac{1}{N} = \frac{1}{b-a+1} \\ x \in X(\Omega) = \{a, a+1, \dots, b\} \end{cases} \quad N = b - a + 1 \quad \Updownarrow F_x(x|a, b) = \frac{\lfloor x \rfloor - a + 1}{b - a + 1}$$

15.1.2.8.1.2 hypergeometric distribution

$$\begin{aligned}
 X &\sim \mathcal{HG}(N, M, K) \\
 f_X(x|N, M, K) &= \frac{\binom{N-M}{K-x} \binom{M}{x}}{\binom{N}{K}} \\
 x \in X(\Omega) &= \{\max\{0, K - (N - M)\}, \dots, \min\{K, M\}\} \\
 &\quad \Downarrow K \ll N, M \\
 x \in X(\Omega) &= \{0, 1, \dots, K\} \\
 \mathbb{E}[X] &= \frac{KM}{N} \\
 \mathbb{V}[X] &= \frac{KM}{N} \frac{(N-M)(N-K)}{N(N-1)}
 \end{aligned}$$

15.1.2.8.1.3 Bernoulli distribution

$$\begin{aligned}
 X &\sim \mathcal{B}(p), p = \mathbb{P}(X = 1) \\
 f_X(x|p) &= (1-p)^{1-x} p^x \\
 x \in X(\Omega) &= \{0, 1\} \\
 \mathbb{E}[X] &= p \\
 \mathbb{V}[X] &= p(1-p) \\
 M_x(\xi) &= (1-p) + pe^\xi
 \end{aligned}$$

15.1.2.8.1.4 binomial distribution independent and identical Bernoulli trials

$$\begin{aligned}
 X &\sim \mathcal{B}(n, p), p = \mathbb{P}(X = 1) \\
 f_X(x|n, p) &= \binom{n}{x} (1-p)^{n-x} p^x \\
 x \in X(\Omega) &= \{0, 1, \dots, n\} \\
 \mathbb{E}[X] &= np \\
 \mathbb{V}[X] &= np(1-p) \\
 M_x(\xi) &= [(1-p) + pe^\xi]^n
 \end{aligned}$$

reparameterization technique

$$\begin{aligned}
M_X(\xi) &= \text{E} [e^{\xi X}] = \sum_{x \in X(\Omega)} e^{\xi x} f_X(x|n,p) \\
&= \sum_{x=1}^n e^{\xi x} \binom{n}{x} (1-p)^{n-x} p^x = \sum_{x=1}^n \binom{n}{x} (1-p)^{n-x} (pe^\xi)^x \\
&= \sum_{x=1}^n \binom{n}{x} \left[\frac{1-p}{(1-p)+pe^\xi} \right]^{n-x} \left[\frac{pe^\xi}{(1-p)+pe^\xi} \right]^x [(1-p)+pe^\xi]^{n-x} [(1-p)+pe^\xi]^x \\
&= \sum_{x=1}^n \binom{n}{x} \left[\frac{1-p}{(1-p)+pe^\xi} \right]^{n-x} \left[\frac{pe^\xi}{(1-p)+pe^\xi} \right]^x [(1-p)+pe^\xi]^n \\
&= [(1-p)+pe^\xi]^n \sum_{x=1}^n \binom{n}{x} \left[\frac{1-p}{(1-p)+pe^\xi} \right]^{n-x} \left[\frac{pe^\xi}{(1-p)+pe^\xi} \right]^x \\
&= [(1-p)+pe^\xi]^n \sum_{x=1}^n f_X(x|n,p^*) , X \sim b(n,p^*) \\
&= [(1-p)+pe^\xi]^n \cdot 1 = [(1-p)+pe^\xi]^n \\
M_X(\xi) &= [(1-p)+pe^\xi]^n
\end{aligned}$$

15.1.2.8.1.5 Poisson distribution count = number of events

an unbounded discrete distribution we first see or met

$$\begin{aligned}
X &\sim \mathcal{P}(\lambda) \\
\Updownarrow \\
\begin{cases} f_X(x|\lambda) = \frac{e^{-\lambda} \lambda^x}{x!} \\ x \in X(\Omega) = \{0, 1, \dots\} \end{cases} \\
\Downarrow \\
\begin{cases} \text{E}[X] = \lambda \\ \text{V}[X] = \lambda = \text{E}[X] \\ M_X(\xi) = \exp[\lambda(e^\xi - 1)] = e^{\lambda(e^\xi - 1)} \end{cases}
\end{aligned}$$

the Poisson postulates

$$\begin{cases} N_t \\ N_0 = N_{t=0} = 0 \\ \forall s < t [N_s \perp N_t - N_s] \\ N_s = N_{t+s} - N_t \\ \lim_{t \rightarrow 0} \frac{P(N_t = 1)}{t} = \lambda \\ \lim_{t \rightarrow 0} \frac{P(N_t > 1)}{t} = 0 \end{cases}
\begin{aligned}
&\text{a r.v. denoting the of events in } [0, t] \\
&\text{reset the count at the initial point} \\
&\text{disjoint intervals independent} \\
&\text{depends on length instead of initial point} \\
&\Rightarrow \forall t \approx 0 [P(N_t = 1) \approx \lambda t] \\
&\text{no coincidence for small } t \\
&\text{solve the differential equations } \Downarrow \text{ with probability axioms} \\
f_X(x|\lambda t) &= P(N_t = x) = \frac{e^{-\lambda t} (\lambda t)^x}{x!}
\end{aligned}$$

15.1.2.8.1.6 negative binomial distribution

also an unbounded discrete distribution

Count the number of independent and identical Bernoulli trials until r a fixed number of success.

$$\begin{aligned} X &\sim \mathcal{NB}(r, p) \\ &\Updownarrow \\ \begin{cases} f_x(x|r, p) = \binom{x-1}{r-1} (1-p)^{x-r} p^r \\ x \in X(\Omega) = \{r, r+1, \dots\} \end{cases} \\ &\Downarrow \\ \begin{cases} E[X] = \\ V[X] = \\ M_x(\xi) = \end{cases} \end{aligned}$$

$$\begin{aligned} Y = X - r, X \sim \mathcal{NB}(r, p) \Rightarrow X = Y + r \\ &\Updownarrow \\ \begin{cases} f_Y(y|r, p) = \binom{r+y-1}{r-1} (1-p)^y p^r \\ y \in Y(\Omega) = \{0, 1, \dots\} \end{cases} \\ &\Downarrow \\ \begin{cases} E[Y] = r \frac{1-p}{p} = r \left(\frac{1}{p} - 1 \right) \\ V[Y] = r \frac{1-p}{p^2} = r \left(\frac{1}{p^2} - \frac{1}{p} \right) \\ M_Y(\xi) = \left[\frac{p}{1 - (1-p)e^\xi} \right]^r \end{cases} \end{aligned}$$

Note:

$$\begin{aligned} Y = X - r \Rightarrow f_Y(y|r, p) &= P(Y = y) \\ &= P(X - r = y) \\ &= P(X = r + y) \end{aligned}$$

reparameterization technique

$$\begin{aligned} M_Y(\xi) &= E[e^{\xi Y}] = \sum_{y \in Y(\Omega)} e^{\xi y} f_Y(y|r, p) \\ &= \sum_{y=0}^{\infty} e^{\xi y} \binom{r+y-1}{r-1} (1-p)^y p^r \\ &= p^r \sum_{y=0}^{\infty} \binom{r+y-1}{r-1} [(1-p)e^\xi]^y \\ &= p^r \sum_{y=0}^{\infty} \binom{r+y-1}{r-1} [1-p^*]^y [p^*]^r \frac{1}{[p^*]^r}, 1-p^* = (1-p)e^\xi \\ &= \left[\frac{p}{p^*} \right]^r \sum_{y=0}^{\infty} f_Y(y|r, p^*), Y \sim \mathcal{NB}(r, p^*), p^* = 1 - (1-p)e^\xi \\ &= \left[\frac{p}{p^*} \right]^r \cdot 1 = \left[\frac{p}{p^*} \right]^r = \left[\frac{p}{1 - (1-p)e^\xi} \right]^r \end{aligned}$$

Note:

For sufficiently small t such that

$$0 \leq p^* = (1 - p) e^\xi \leq 1$$

or else $t \gg 1$

$$p^* = (1 - p) e^\xi > 1$$

15.1.2.8.1.7 geometric distribution

$$\begin{aligned} X &\sim \mathcal{NB}(r, p) \\ &\Downarrow \\ \begin{cases} f_x(x|r, p) = \binom{x-1}{r-1} (1-p)^{x-r} p^r \\ x \in X(\Omega) = \{r, r+1, \dots\} \end{cases} \\ &\Downarrow \\ \begin{cases} E[X] = \\ V[X] = \\ M_x(\xi) = \end{cases} \end{aligned}$$

$$r = 1,$$

$$\begin{aligned} X &\sim \mathcal{NB}(r=1, p) = \mathcal{G}(p) \\ &\Downarrow \\ \begin{cases} f_x(x|r=1, p) = \left[\binom{x-1}{r-1} (1-p)^{x-r} p^r \right]_{r=1} = \binom{x-1}{1-1} (1-p)^{x-1} p^1 = (1-p)^{x-1} p \\ x \in X(\Omega) = \{r, r+1, \dots\}_{r=1} = \{1, 2, \dots\} \end{cases} \\ &\Downarrow \\ \begin{cases} E[X] = \\ V[X] = \\ M_x(\xi) = \end{cases} \end{aligned}$$

the only “memoryless” discrete distribution, and there is also a “memoryless” continuous distribution.
memoryless property

$$\forall s > t [P(X > s | X > t) = P(X > s - t)]$$

Survival depends on length instead of initial point; it might be proper assumption for stuff survival, but might not be proper for human survival.

15.1.2.8.2 continuous distribution

15.1.2.8.2.1 uniform distribution = continuous uniform distribution

$$\begin{aligned}
 X &\sim \mathcal{U}(a, b) \\
 \Updownarrow \\
 \begin{cases} f_x(x|a, b) = \frac{1(a \leq x \leq b)}{b-a} = \frac{1(x \in [a, b])}{b-a} \\ x \in X(\Omega) = [a, b] \end{cases} \\
 \Downarrow \\
 \begin{cases} E[X] = \frac{a+b}{2} \\ V[X] = \frac{(b-a)^2}{12} \\ M_x(\xi) = \frac{e^{b\xi} - e^{a\xi}}{(b-a)\xi} \end{cases}
 \end{aligned}$$

$$a = 0, b = 1$$

$$\begin{aligned}
 X &\sim \mathcal{U}(a=0, b=1) = \mathcal{U}(0, 1) \\
 \Updownarrow \\
 \begin{cases} f_x(x|a=0, b=1) = \left[\frac{1(a \leq x \leq b)}{b-a} \right]_{a=0, b=1} = 1(0 \leq x \leq 1) = 1(x \in [0, 1]) \\ x \in X(\Omega) = [a, b]|_{a=0, b=1} = [0, 1] \end{cases} \\
 \Downarrow \\
 \begin{cases} E[X] = \frac{1}{2} \\ V[X] = \frac{1}{12} \\ M_x(\xi) = \frac{e^\xi - 1}{\xi} \end{cases}
 \end{aligned}$$

15.1.2.8.2.2 gamma distribution

15.1.2.8.2.3 exponential distribution

15.1.2.8.2.4 Chi-square distribution

15.1.2.8.2.5 Weibull distribution

15.1.2.8.2.6 normal distribution

$$\begin{aligned}
 X &\sim \mathcal{N}(\mu, \sigma^2) \\
 \Updownarrow \\
 \begin{cases} f_x(x|\mu, \sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} = \frac{e^{\frac{-1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}}{\sigma\sqrt{2\pi}} = \frac{e^{-(x-\mu)^2/(2\sigma^2)}}{\sigma\sqrt{2\pi}} = \frac{\exp\left\{\frac{-1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right\}}{\sigma\sqrt{2\pi}} \\ x \in X(\Omega) = \mathbb{R} \end{cases} \\
 \Downarrow \\
 \begin{cases} E[X] = \mu \\ V[X] = \sigma^2 \\ M_x(\xi) = e^{(\mu\xi + \frac{\sigma^2}{2}\xi^2)} = e^{\mu\xi + \frac{\sigma^2}{2}\xi^2} \end{cases}
 \end{aligned}$$

15.1.2.8.2.7 beta distribution random success probability

15.1.2.8.2.8 Cauchy distribution <https://www.youtube.com/watch?v=oJZb6nZWdvI&t=33m34s>

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

$$\begin{aligned}
 X &\sim \mathcal{C}(\theta, \sigma) \\
 &\Updownarrow \\
 \left\{ \begin{array}{l} f_x(x|\theta, \sigma) = \frac{1}{\pi\sigma} \left[1 + \left(\frac{x-\theta}{\sigma} \right)^2 \right]^{-1} = \frac{1}{\pi\sigma \left[1 + \left(\frac{x-\theta}{\sigma} \right)^2 \right]} = \frac{1}{\pi} \left[\frac{\sigma}{(x-\theta)^2 + \sigma^2} \right] \\ x \in X(\Omega) = \mathbb{R} \end{array} \right. \\
 &\Downarrow \\
 \left\{ \begin{array}{ll} E[X] & \text{diverges} \\ V[X] & \text{diverges} \\ M_X(\xi) & \text{diverges} \end{array} \right. \\
 &\boxed{202402170031-statistics_files/figure-latex/unnamed-chunk-14-1}
 \end{aligned}$$

Figure 15.1: not completed: Cauchy distribution vs. normal distribution

heavy tail

t distribution is also heavy tail

box plot

15.1.2.8.2.9 log-normal distribution

15.1.2.9 exponential family

Definition 15.18. exponential family: A family of PDF/PMF is called exponential family if

$$f(x|\boldsymbol{\theta}) = h(x) c(\boldsymbol{\theta}) e^{\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x)} = h(x) c(\boldsymbol{\theta}) \exp \left(\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x) \right)$$

with $\boldsymbol{\theta} = \boldsymbol{\theta}(\theta_1, \dots, \theta_k) = (\theta_1, \dots, \theta_k)$ for some $h(x), c(\boldsymbol{\theta}), w_j(\boldsymbol{\theta}), t_j(x)$, where

$$h(x) c(\boldsymbol{\theta}) \geq 0 \Rightarrow f(x|\boldsymbol{\theta}) \geq 0$$

and parameters $\boldsymbol{\theta}$ and statistic or real number x can be separated.

$$\mathcal{E}^f = \left\{ f \left| f = f(x|\boldsymbol{\theta}) = h(x) c(\boldsymbol{\theta}) e^{\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x)} = h(x) c(\boldsymbol{\theta}) \exp \left(\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x) \right) \right. \right\}$$

- exponential family
 - normal distribution^[15.1.2.8.2.6]
 - gamma distribution^[15.1.2.8.2.2]
 - log-normal distribution^[15.1.2.8.2.9]
- non-exponential family
 - Cauchy distribution^[15.1.2.8.2.8] <https://www.youtube.com/watch?v=oJZb6nZWdvI&t=1h7m43s>

15.1.2.9.1 binomial distribution with known n

$$f(x|p) = \binom{n}{x} (1-p)^{n-x} p^x$$

or

$$f(x|p) = \binom{n}{x} (1-p)^{n-x} p^x = f(x|n=n, p)$$

not

$$f(x|n, p) = \binom{n}{x} (1-p)^{n-x} p^x$$

$$\begin{aligned} f(x|p) &= \binom{n}{x} (1-p)^{n-x} p^x \\ &= \binom{n}{x} (1-p)^n \left(\frac{p}{1-p}\right)^x \\ &= \binom{n}{x} (1-p)^n e^{(\ln \frac{p}{1-p})x} \end{aligned}$$

$$= h(x) c(\boldsymbol{\theta}) e^{\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x)}, \quad \begin{cases} h(x) = \binom{n}{x} \\ c(\boldsymbol{\theta}) = c(\theta_1) = c(p) = (1-p)^n \\ w_1(\boldsymbol{\theta}) = w(\theta_1) = w(p) = \ln \frac{p}{1-p} \\ t_1(x) = x \\ k = 1 \end{cases}$$

⇓

$$f(x|p) = \binom{n}{x} (1-p)^{n-x} p^x \in \mathcal{E}^f = \left\{ f \mid f = f(x|\boldsymbol{\theta}) = h(x) c(\boldsymbol{\theta}) \exp \left(\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x) \right) \right\}$$

why known n ?

known n

$$\binom{n}{x} = h(x)$$

unknown n

$$\binom{n}{x} = h(x, n) \neq h_1(n) h_2(x)$$

15.1.2.9.2 continuous uniform distribution not in exponential family

$$X \sim \mathcal{U}(a, b)$$

$$\begin{aligned} f_X(x|a, b) &= \frac{1(x \in [a, b])}{b - a} \\ &= \frac{1}{b - a}, x \in [a, b] \end{aligned}$$

$$\frac{1}{b - a} = h(x) c(\boldsymbol{\theta}) e^{\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x)}, \begin{cases} h(x) = & 1 \\ c(\boldsymbol{\theta}) = c(\theta_1, \theta_2) = c(a, b) = & \frac{1}{b - a} \\ w_1(\theta_1) = w_2(\theta_2) = & 0 \\ t_1(x) = t_2(x) = & x \\ k = & 2 \end{cases}$$

however,

$$1(x \in [a, b]) \neq h(x) c(\boldsymbol{\theta}) = h(x) c(a, b)$$

thus

$$f_X(x|a, b) = \frac{1(x \in [a, b])}{b - a} \notin \mathcal{E}^f = \left\{ f \middle| f = f(x|\boldsymbol{\theta}) = h(x) c(\boldsymbol{\theta}) \exp \left(\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x) \right) \right\}$$

15.1.2.9.3 normal distribution is in exponential family

$$\begin{aligned} X &\sim \mathcal{N}(\mu, \sigma^2) \\ f_X(x|\mu, \sigma^2) &= \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-1}{2} \left(\frac{x-\mu}{\sigma} \right)^2} = \frac{e^{\frac{-1}{2} \left(\frac{x-\mu}{\sigma} \right)^2}}{\sigma\sqrt{2\pi}} = \frac{e^{-(x-\mu)^2/(2\sigma^2)}}{\sigma\sqrt{2\pi}} = \frac{\exp \left\{ \frac{-1}{2} \left(\frac{x-\mu}{\sigma} \right)^2 \right\}}{\sigma\sqrt{2\pi}} \\ x \in X(\Omega) &= \mathbb{R} \\ M_X(\xi) &= e^{(\mu\xi + \frac{\sigma^2}{2}\xi^2)} = e^{\mu\xi + \frac{\sigma^2}{2}\xi^2} \end{aligned}$$

$$\begin{aligned}
f_x(x|\mu, \sigma^2) &= f_x(x|\mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-1}{2}(\frac{x-\mu}{\sigma})^2} \\
&= \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-1}{2\sigma^2}(x^2 - 2x\mu + \mu^2)} = \frac{e^{\frac{-1}{2}(\frac{\mu}{\sigma})^2}}{\sigma\sqrt{2\pi}} e^{\frac{-1}{2\sigma^2}x^2 + \frac{\mu}{\sigma^2}x} = \frac{e^{\frac{-1}{2}(\frac{\mu}{\sigma})^2}}{\sigma\sqrt{2\pi}} e^{\frac{\mu}{\sigma^2}x - \frac{1}{2\sigma^2}x^2} \\
&= h(x) c(\boldsymbol{\theta}) e^{\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x)}, \quad \begin{cases} h(x) = & 1 \\ c(\boldsymbol{\theta}) = c(\theta_1, \theta_2) = c(\mu, \sigma) = & \frac{e^{\frac{-1}{2}(\frac{\mu}{\sigma})^2}}{\sigma\sqrt{2\pi}} \\ w_1(\theta_1, \theta_2) = w_1(\mu, \sigma) = & \frac{\mu}{\sigma^2} \\ w_2(\theta_2) = w_2(\sigma) = & \frac{-1}{2\sigma^2} \\ t_1(x) = & x \\ t_2(x) = & x^2 \\ k = & 2 \end{cases} \\
&\Downarrow \\
f_x(x|\mu, \sigma) &= \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-1}{2}(\frac{x-\mu}{\sigma})^2} \in \mathcal{E}^f = \left\{ f \middle| f = f(x|\boldsymbol{\theta}) = h(x) c(\boldsymbol{\theta}) \exp \left(\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x) \right) \right\}
\end{aligned}$$

15.1.2.9.4 normal distribution with unknown equal mean and standard deviation in curved exponential family

$$\begin{aligned}
X &\sim \mathcal{N}(\mu, \sigma^2 = \mu^2) = \mathcal{N}(\mu, \mu^2) \\
&\Updownarrow \\
\begin{cases} f_x(x|\mu, \mu^2) = f_x(x|\mu) = \left[\frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-1}{2}(\frac{x-\mu}{\sigma})^2} \right]_{\sigma=\mu} = \frac{1}{\mu\sqrt{2\pi}} e^{\frac{-1}{2}(\frac{x-\mu}{\mu})^2} \\ x \in X(\Omega) = \mathbb{R} \end{cases} \\
&\Downarrow \\
\begin{cases} E[X] = \mu \\ V[X] = \mu^2 \\ M_X(\xi) = e^{\left(\mu\xi + \frac{\mu^2}{2}\xi^2 \right)} = e^{\mu\xi + \frac{\mu^2}{2}\xi^2} \end{cases}
\end{aligned}$$

$$\begin{aligned}
f_x(x|\mu, \mu^2) &= f_x(x|\mu) = \frac{1}{\mu\sqrt{2\pi}} e^{\frac{-1}{2}\left(\frac{x-\mu}{\mu}\right)^2} \\
&= \frac{1}{\mu\sqrt{2\pi}} e^{\frac{-1}{2\mu^2}(x^2 - 2x\mu + \mu^2)} = \frac{e^{-\frac{1}{2}}}{\mu\sqrt{2\pi}} e^{\frac{-1}{2\mu^2}x^2 + \frac{\mu}{\mu^2}x} = \frac{e^{-\frac{1}{2}}}{\mu\sqrt{2\pi}} e^{\frac{1}{\mu}x - \frac{1}{2\mu^2}x^2} \\
&= h(x) c(\boldsymbol{\theta}) e^{\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x)}, \quad \begin{cases} h(x) = 1 \\ c(\boldsymbol{\theta}) = c(\theta_1) = c(\mu) = \frac{e^{-\frac{1}{2}}}{\mu\sqrt{2\pi}} \\ w_1(\theta_1) = w_1(\mu) = \frac{1}{\mu} \\ w_2(\theta_1) = w_2(\mu) = \frac{-1}{2\mu^2} \\ t_1(x) = x \\ t_2(x) = x^2 \\ k = 2 > 1 = p \end{cases} \\
&\Downarrow \begin{cases} p = \dim \boldsymbol{\theta} \\ k = \dim \mathbf{w} \end{cases} \\
f_x(x|\mu, \sigma) &= \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \in \mathcal{C}^f = \left\{ f \middle| f = f(x|\boldsymbol{\theta}) = h(x) c(\boldsymbol{\theta}) \exp \left(\sum_{j=1}^{k>p} w_j(\boldsymbol{\theta}) t_j(x) \right) \right\} \\
&\subset \mathcal{E}^f = \left\{ f \middle| f = f(x|\boldsymbol{\theta}) = h(x) c(\boldsymbol{\theta}) \exp \left(\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x) \right) \right\}
\end{aligned}$$

curved exponential family

$$\mathcal{C}^f = \left\{ f \middle| f = f(x|\boldsymbol{\theta}) = h(x) c(\boldsymbol{\theta}) \exp \left(\sum_{j=1}^{k>p} w_j(\boldsymbol{\theta}) t_j(x) \right) \right\}$$

exponential family

$$\mathcal{E}^f = \left\{ f \middle| f = f(x|\boldsymbol{\theta}) = h(x) c(\boldsymbol{\theta}) \exp \left(\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x) \right) \right\}$$

<https://tex.stackexchange.com/questions/145969/filling-specified-area-by-random-dots-in-tikz>

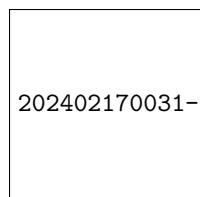


Figure 15.2: curved exponential family vs. exponential family

15.1.2.9.5.5 properties of exponential family

15.1.2.9.5.1 fundamentals of statistical inference

Lemma 15.1. *Leibnitz rule*

$$\frac{d}{d\theta} \int_{a(\theta)}^{b(\theta)} g(x, \theta) dx = \frac{d \int_{a(\theta)}^{b(\theta)} g(x, \theta) dx}{d\theta}$$

$$= g(x, b(\theta)) \frac{db(\theta)}{d\theta} - g(x, a(\theta)) \frac{da(\theta)}{d\theta} + \int_{a(\theta)}^{b(\theta)} \frac{d}{d\theta} g(x, \theta) dx$$

$$= g(x, b(\theta)) \frac{db(\theta)}{d\theta} - g(x, a(\theta)) \frac{da(\theta)}{d\theta} + \int_{a(\theta)}^{b(\theta)} \frac{dg(x, \theta)}{d\theta} dx$$

$$\frac{d}{d\theta} \int_{a(\theta)}^{b(\theta)} g(x, \theta) dx = g(x, b(\theta)) \frac{db(\theta)}{d\theta} - g(x, a(\theta)) \frac{da(\theta)}{d\theta} + \int_{a(\theta)}^{b(\theta)} \frac{dg(x, \theta)}{d\theta} dx$$

$$\begin{aligned} \frac{d}{d\theta} \int_{a(\theta)=a}^{b(\theta)=b} g(x, \theta) dx &= g(x, b(\theta)) \frac{db(\theta)}{d\theta} - g(x, a(\theta)) \frac{da(\theta)}{d\theta} + \int_{a(\theta)}^{b(\theta)} \frac{dg(x, \theta)}{d\theta} dx \\ &= g(x, b) \frac{db}{d\theta} - g(x, a) \frac{da}{d\theta} + \int_a^b \frac{dg(x, \theta)}{d\theta} dx \\ &= g(x, b) 0 - g(x, a) 0 + \int_a^b \frac{dg(x, \theta)}{d\theta} dx = 0 + 0 + \int_a^b \frac{dg(x, \theta)}{d\theta} dx \\ &= \int_a^b \frac{dg(x, \theta)}{d\theta} dx \end{aligned}$$

$$\frac{d}{d\theta} \int_{X(\Omega) \perp \theta}^{b(\theta)=b} g(x, \theta) dx = \frac{d}{d\theta} \int_{a(\theta)=a}^{b(\theta)=b} g(x, \theta) dx = \int_a^b \frac{dg(x, \theta)}{d\theta} dx = \int_{X(\Omega) \perp \theta} \frac{dg(x, \theta)}{d\theta} dx$$

$$\frac{d}{d\theta} \int_{X(\Omega) \perp \theta} g(x, \theta) dx = \int_{X(\Omega) \perp \theta} \frac{dg(x, \theta)}{d\theta} dx$$

$$\frac{d}{d\theta} \int_{X(\Omega) \perp \theta} g(x, \theta) dx = \int_{X(\Omega) \perp \theta} \frac{dg(x, \theta)}{d\theta} dx$$

point estimation

Lemma 15.2. *parameter-independent expectation:*

Assume the domain of X independent of θ , then

$$E \left[\frac{\partial \ln f(X|\theta)}{\partial \theta_i} \right] = 0, \forall i = 1, \dots, p$$

Proof:

$$\begin{aligned}
E \left[\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i} \right] &= \int \frac{\partial \ln f(x|\boldsymbol{\theta})}{\partial \theta_i} f(x|\boldsymbol{\theta}) dx \\
&= \int \left[\frac{\partial \ln f(x|\boldsymbol{\theta})}{\partial \theta_i} \right] f(x|\boldsymbol{\theta}) dx \\
&= \int \left[\frac{1}{f(x|\boldsymbol{\theta})} \frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i} \right] f(x|\boldsymbol{\theta}) dx = \int \frac{1}{f(x|\boldsymbol{\theta})} \frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i} f(x|\boldsymbol{\theta}) dx \\
&= \int \frac{f(x|\boldsymbol{\theta})}{f(x|\boldsymbol{\theta})} \frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i} dx = \int 1 \frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i} dx = \int \frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i} dx
\end{aligned}$$

{ Leibnitz rule
 $x \perp \boldsymbol{\theta}$
 $= \frac{\partial}{\partial \theta_i} \int f(x|\boldsymbol{\theta}) dx$

□

Note:

$$\begin{aligned}
E \left[\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i} \right] &= \int \frac{\partial \ln f(x|\boldsymbol{\theta})}{\partial \theta_i} f(x|\boldsymbol{\theta}) dx = \int \left(\frac{\frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i}}{f(x|\boldsymbol{\theta})} \right) f(x|\boldsymbol{\theta}) dx \\
X \sim f_x(x|\boldsymbol{\theta}) \Rightarrow E \left[\frac{\partial \ln f_x(X|\boldsymbol{\theta})}{\partial \theta_i} \right] &= \int \frac{\partial \ln f_x(x|\boldsymbol{\theta})}{\partial \theta_i} f_x(x|\boldsymbol{\theta}) dx = \int \left(\frac{\frac{\partial f_x(x|\boldsymbol{\theta})}{\partial \theta_i}}{f_x(x|\boldsymbol{\theta})} \right) f_x(x|\boldsymbol{\theta}) dx \\
&= \int \frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i} dx \\
X \sim f_x(x|\boldsymbol{\theta}) \Rightarrow E \left[\frac{\partial \ln f_x(X|\boldsymbol{\theta}^*)}{\partial \theta_i} \right] &= \int \frac{\partial \ln f_x(x|\boldsymbol{\theta}^*)}{\partial \theta_i} f_x(x|\boldsymbol{\theta}) dx = \int \left(\frac{\frac{\partial f_x(x|\boldsymbol{\theta}^*)}{\partial \theta_i}}{f_x(x|\boldsymbol{\theta}^*)} \right) f(x|\boldsymbol{\theta}) dx \\
&= \int \frac{\partial f_x(x|\boldsymbol{\theta}^*)}{\partial \theta_i} \left(\frac{f_x(x|\boldsymbol{\theta})}{f_x(x|\boldsymbol{\theta}^*)} \right) dx
\end{aligned}$$

$$E \left[\frac{\partial \ln f_x(X|\boldsymbol{\theta}^*)}{\partial \theta_i} \right] = E_{\boldsymbol{\theta}^*} \left[\frac{\partial \ln f_x(X|\boldsymbol{\theta}^*)}{\partial \theta_i} \right] = \int \frac{\partial \ln f_x(x|\boldsymbol{\theta}^*)}{\partial \theta_i} f_x(x|\boldsymbol{\theta}^*) dx$$

$$E \left[\frac{\partial \ln f_x(X|\boldsymbol{\theta}^*)}{\partial \theta_i} \right] = E_{\boldsymbol{\theta}} \left[\frac{\partial \ln f_x(X|\boldsymbol{\theta}^*)}{\partial \theta_i} \right] = \int \frac{\partial \ln f_x(x|\boldsymbol{\theta}^*)}{\partial \theta_i} f_x(x|\boldsymbol{\theta}) dx$$

$$E_{\boldsymbol{\theta}} \left[\frac{\partial \ln f_x(X|\boldsymbol{\theta}^*)}{\partial \theta_i} \right] = \int \frac{\partial \ln f_x(x|\boldsymbol{\theta}^*)}{\partial \theta_i} f_x(x|\boldsymbol{\theta}) dx$$

$$E_{\boldsymbol{\theta}} \left[\frac{\partial \ln f_x(X|\boldsymbol{\theta}^*)}{\partial \theta_i} \right] \not\equiv 0$$

$$\mathbb{E}_{\boldsymbol{\theta}} \left[\frac{\partial \ln f_X(X|\boldsymbol{\theta}^*)}{\partial \theta_i} \right] \underset{\boldsymbol{\theta}^* = \boldsymbol{\theta}}{=} 0$$

as the fundamental to estimate parameters.

interval estimation

Lemma 15.3. *parameter-independent variance:*

Assume the domain of X independent of θ , then

$$\mathbb{E} \left[\frac{\partial^2 \ln f(X|\boldsymbol{\theta})}{\partial \theta_i^2} \right] = -\mathbb{E} \left[\left(\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i} \right)^2 \right], \forall i = 1, \dots, p$$

Proof:

$$\begin{aligned} \mathbb{E} \left[\frac{\partial^2 \ln f(X|\boldsymbol{\theta})}{\partial \theta_i^2} \right] &= \int \frac{\partial^2 \ln f(X|\boldsymbol{\theta})}{\partial \theta_i^2} f(x|\boldsymbol{\theta}) dx = \int \frac{\partial}{\partial \theta_i} \frac{\partial \ln f(x|\boldsymbol{\theta})}{\partial \theta_i} f(x|\boldsymbol{\theta}) dx \\ &= \int \left\{ \frac{\partial}{\partial \theta_i} \left(\frac{1}{f(x|\boldsymbol{\theta})} \frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i} \right) \right\} f(x|\boldsymbol{\theta}) dx = \int \left\{ \frac{\partial}{\partial \theta_i} \left(\frac{\frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i}}{f(x|\boldsymbol{\theta})} \right) \right\} f(x|\boldsymbol{\theta}) dx \\ &= \int \frac{\frac{\partial^2 f(x|\boldsymbol{\theta})}{\partial \theta_i^2} f(x|\boldsymbol{\theta}) - \frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i} \frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i}}{[f(x|\boldsymbol{\theta})]^2} f(x|\boldsymbol{\theta}) dx = \int \frac{\frac{\partial^2 f(x|\boldsymbol{\theta})}{\partial \theta_i^2} [f(x|\boldsymbol{\theta})]^2 - \left[\frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i} \right]^2 [f(x|\boldsymbol{\theta})]}{[f(x|\boldsymbol{\theta})]^2} dx \\ &= \int \frac{\partial^2 f(x|\boldsymbol{\theta})}{\partial \theta_i^2} dx - \int \left(\frac{\frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i}}{f(x|\boldsymbol{\theta})} \right)^2 f(x|\boldsymbol{\theta}) dx \quad \begin{cases} \text{Leibnitz rule} \\ X(\Omega) \perp \boldsymbol{\theta} \end{cases} \quad \frac{\partial^2}{\partial \theta_i^2} \int f(x|\boldsymbol{\theta}) dx - \int \left(\frac{\frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i}}{f(x|\boldsymbol{\theta})} \right)^2 f(x|\boldsymbol{\theta}) dx \\ &= \frac{\partial^2}{\partial \theta_i^2} 1 - \int \left(\frac{\frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i}}{f(x|\boldsymbol{\theta})} \right)^2 f(x|\boldsymbol{\theta}) dx = 0 - \int \left(\frac{\frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i}}{f(x|\boldsymbol{\theta})} \right)^2 f(x|\boldsymbol{\theta}) dx = - \int \left(\frac{\frac{\partial f(x|\boldsymbol{\theta})}{\partial \theta_i}}{f(x|\boldsymbol{\theta})} \right)^2 f(x|\boldsymbol{\theta}) dx \\ &= - \int \left(\frac{\partial \ln f(x|\boldsymbol{\theta})}{\partial \theta_i} \right)^2 f(x|\boldsymbol{\theta}) dx = -\mathbb{E} \left[\left(\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i} \right)^2 \right] \end{aligned}$$

□

$$\begin{cases} \mathbb{E} \left[\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i} \right] = 0 \\ \mathbb{E} \left[\frac{\partial^2 \ln f(X|\boldsymbol{\theta})}{\partial \theta_i^2} \right] = -\mathbb{E} \left[\left(\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i} \right)^2 \right], \forall i = 1, \dots, p \end{cases}$$

exponential family expectation and variance

Theorem 15.15. *exponential family expectation*

$$X \in \mathcal{E}^f = \left\{ f \middle| f = h(x) c(\boldsymbol{\theta}) \exp \left(\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x) \right) \right\}$$

$\Downarrow \forall i = 1, \dots, p$

$$\mathbb{E} \left[\sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X) \right] = \frac{-\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i}$$

Proof:

$$\begin{aligned} f(x|\boldsymbol{\theta}) &= h(x) c(\boldsymbol{\theta}) e^{\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x)} = h(x) c(\boldsymbol{\theta}) \exp \left(\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x) \right) \\ \ln f(x|\boldsymbol{\theta}) &= \ln h(x) c(\boldsymbol{\theta}) e^{\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x)} \\ &= \ln h(x) + \ln c(\boldsymbol{\theta}) + \ln e^{\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x)} \\ &= \ln h(x) + \ln c(\boldsymbol{\theta}) + \sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x) \\ \ln f(x|\boldsymbol{\theta}) &= \ln h(x) + \ln c(\boldsymbol{\theta}) + \sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x) \\ \ln f(X|\boldsymbol{\theta}) &= \ln h(X) + \ln c(\boldsymbol{\theta}) + \sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(X) \\ \frac{\partial}{\partial \theta_i} \ln f(X|\boldsymbol{\theta}) &= \frac{\partial}{\partial \theta_i} \left[\ln h(X) + \ln c(\boldsymbol{\theta}) + \sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(X) \right] \\ &= \frac{\partial}{\partial \theta_i} \ln h(X) + \frac{\partial}{\partial \theta_i} \ln c(\boldsymbol{\theta}) + \frac{\partial}{\partial \theta_i} \sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(X) \\ &= 0 + \frac{\partial}{\partial \theta_i} \ln c(\boldsymbol{\theta}) + \sum_{j=1}^k \frac{\partial}{\partial \theta_i} \{w_j(\boldsymbol{\theta}) t_j(X)\} \\ &= \frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + \sum_{j=1}^k \left\{ \left(\frac{\partial}{\partial \theta_i} w_j(\boldsymbol{\theta}) \right) t_j(X) + w_j(\boldsymbol{\theta}) \left(\frac{\partial}{\partial \theta_i} t_j(X) \right) \right\} \\ &= \frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + \sum_{j=1}^k \left\{ \left(\frac{\partial}{\partial \theta_i} w_j(\boldsymbol{\theta}) \right) t_j(X) + w_j(\boldsymbol{\theta}) 0 \right\} \\ &= \frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + \sum_{j=1}^k \left\{ \left(\frac{\partial}{\partial \theta_i} w_j(\boldsymbol{\theta}) \right) t_j(X) \right\} \\ \frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i} &= \frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + \sum_{j=1}^k \left\{ \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X) \right\} \end{aligned}$$

$$\begin{aligned}
\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i} &= \frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + \sum_{j=1}^k \left\{ \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X) \right\} \\
0 &\stackrel{\text{lemma: } E\left[\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i}\right]=0}{=} E\left[\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i}\right] = E\left[\frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + \sum_{j=1}^k \left\{ \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X) \right\}\right] \\
&= E\left[\frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i}\right] + E\left[\sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X)\right] \\
&\stackrel{E[c]=c}{=} \frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + E\left[\sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X)\right] \\
&= \frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + \sum_{j=1}^k E\left[\frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X)\right] \\
&= \frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + \sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} E[t_j(X)] \\
0 &= \frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + E\left[\sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X)\right] \\
E\left[\sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X)\right] &= \frac{-\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i}
\end{aligned}$$

□

Theorem 15.16. exponential family variance

$$\begin{aligned}
X \in \mathcal{E}^f &= \left\{ f \middle| f = h(x) c(\boldsymbol{\theta}) \exp \left(\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x) \right) \right\} \\
&\Downarrow \forall i = 1, \dots, p \\
V\left[\sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X)\right] &= \frac{-\partial^2 \ln c(\boldsymbol{\theta})}{\partial \theta_i^2} - E\left[\sum_{j=1}^k \frac{\partial^2 w_j(\boldsymbol{\theta})}{\partial \theta_i^2} t_j(X)\right]
\end{aligned}$$

Proof:

same as the above

$$\begin{aligned}
f(x|\boldsymbol{\theta}) &= h(x) c(\boldsymbol{\theta}) e^{\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x)} = h(x) c(\boldsymbol{\theta}) \exp \left(\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x) \right) \\
\ln f(x|\boldsymbol{\theta}) &= \ln h(x) c(\boldsymbol{\theta}) e^{\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x)} \\
&= \ln h(x) + \ln c(\boldsymbol{\theta}) + \ln e^{\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x)} \\
&= \ln h(x) + \ln c(\boldsymbol{\theta}) + \sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x) \\
\ln f(x|\boldsymbol{\theta}) &= \ln h(x) + \ln c(\boldsymbol{\theta}) + \sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x) \\
\ln f(X|\boldsymbol{\theta}) &= \ln h(X) + \ln c(\boldsymbol{\theta}) + \sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(X) \\
\frac{\partial}{\partial \theta_i} \ln f(X|\boldsymbol{\theta}) &= \frac{\partial}{\partial \theta_i} \left[\ln h(X) + \ln c(\boldsymbol{\theta}) + \sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(X) \right] \\
&= \frac{\partial}{\partial \theta_i} \ln h(X) + \frac{\partial}{\partial \theta_i} \ln c(\boldsymbol{\theta}) + \frac{\partial}{\partial \theta_i} \sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(X) \\
&= 0 + \frac{\partial}{\partial \theta_i} \ln c(\boldsymbol{\theta}) + \sum_{j=1}^k \frac{\partial}{\partial \theta_i} \{w_j(\boldsymbol{\theta}) t_j(X)\} \\
&= \frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + \sum_{j=1}^k \left\{ \left(\frac{\partial}{\partial \theta_i} w_j(\boldsymbol{\theta}) \right) t_j(X) + w_j(\boldsymbol{\theta}) \left(\frac{\partial}{\partial \theta_i} t_j(X) \right) \right\} \\
&= \frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + \sum_{j=1}^k \left\{ \left(\frac{\partial}{\partial \theta_i} w_j(\boldsymbol{\theta}) \right) t_j(X) + w_j(\boldsymbol{\theta}) 0 \right\} \\
&= \frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + \sum_{j=1}^k \left\{ \left(\frac{\partial}{\partial \theta_i} w_j(\boldsymbol{\theta}) \right) t_j(X) \right\} \\
\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i} &= \frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + \sum_{j=1}^k \left\{ \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X) \right\}
\end{aligned}$$

$$\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i} = \frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + \sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X)$$

$$V\left[\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i}\right] = V\left[\frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + \sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X)\right]$$

$$V[aX+b] = a^2 V[X] V\left[\sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X)\right]$$

$$V\left[\sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X)\right] = V\left[\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i}\right]$$

$$V\left[\sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X)\right] = V\left[\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i}\right] = E\left[\left(\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i} - E\left[\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i}\right]\right)^2\right]$$

$$\text{lemma: } E\left[\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i}\right] = E\left[\left(\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i} - 0\right)^2\right] = E\left[\left(\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i}\right)^2\right]$$

$$\text{lemma: } E\left[\frac{\partial^2 \ln f(X|\boldsymbol{\theta})}{\partial \theta_i^2}\right] = -E\left[\left(\frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i}\right)^2\right] - E\left[\frac{\partial^2 \ln f(X|\boldsymbol{\theta})}{\partial \theta_i^2}\right] = -E\left[\frac{\partial}{\partial \theta_i} \frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i}\right]$$

$$\begin{aligned} \frac{\partial \ln f(X|\boldsymbol{\theta})}{\partial \theta_i} &= \frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + \sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X) \\ &= -E\left[\frac{\partial}{\partial \theta_i} \left\{ \frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} + \sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X) \right\}\right] \\ &= -E\left[\frac{\partial^2 \ln c(\boldsymbol{\theta})}{\partial \theta_i^2} + \frac{\partial}{\partial \theta_i} \sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X)\right] \end{aligned}$$

$$= -\frac{\partial^2 \ln c(\boldsymbol{\theta})}{\partial \theta_i^2} - E\left[\sum_{j=1}^k \frac{\partial}{\partial \theta_i} \left\{ \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X) \right\}\right]$$

$$= -\frac{\partial^2 \ln c(\boldsymbol{\theta})}{\partial \theta_i^2} - E\left[\sum_{j=1}^k \left\{ \left(\frac{\partial}{\partial \theta_i} \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} \right) t_j(X) + \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} 0 \right\}\right]$$

$$= -\frac{\partial^2 \ln c(\boldsymbol{\theta})}{\partial \theta_i^2} - E\left[\sum_{j=1}^k \left\{ \frac{\partial^2 w_j(\boldsymbol{\theta})}{\partial \theta_i^2} t_j(X) + \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} 0 \right\}\right]$$

$$= -\frac{\partial^2 \ln c(\boldsymbol{\theta})}{\partial \theta_i^2} - E\left[\sum_{j=1}^k \frac{\partial^2 w_j(\boldsymbol{\theta})}{\partial \theta_i^2} t_j(X)\right]$$

$$V\left[\sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X)\right] = -\frac{\partial^2 \ln c(\boldsymbol{\theta})}{\partial \theta_i^2} - E\left[\sum_{j=1}^k \frac{\partial^2 w_j(\boldsymbol{\theta})}{\partial \theta_i^2} t_j(X)\right]$$

□

exponential family expectation and variance

sense of downgrading by differentiation instead of integration

$$X \in \mathcal{E}^f = \left\{ f \middle| f = h(x) c(\boldsymbol{\theta}) \exp \left(\sum_{j=1}^k w_j(\boldsymbol{\theta}) t_j(x) \right) \right\}$$

$$\Rightarrow \begin{cases} E \left[\sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X) \right] = -\frac{\partial \ln c(\boldsymbol{\theta})}{\partial \theta_i} \\ V \left[\sum_{j=1}^k \frac{\partial w_j(\boldsymbol{\theta})}{\partial \theta_i} t_j(X) \right] = -\frac{\partial^2 \ln c(\boldsymbol{\theta})}{\partial \theta_i^2} - E \left[\sum_{j=1}^k \frac{\partial^2 w_j(\boldsymbol{\theta})}{\partial \theta_i^2} t_j(X) \right], \forall i = 1, \dots, p \end{cases}$$

15.1.3 multivariable distribution

15.2 Chen, Lin-An

<https://www.youtube.com/playlist?list=PLTpF-A8hKVUPXtNAX9lro-leGgEK0OSEW>

https://en.wikipedia.org/wiki/Inverse_distance_weighting Shepard interpolation

Chapter 16

covariance matrix

16.1 covariance matrix

8

16.1.1 calculation

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

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

16.1.2 $V[\mathbf{X} + \mathbf{b}] = V[\mathbf{X}]$

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

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

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

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

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

Chapter 17

Gosper algorithm

Chapter 18

Lorentz transformation

18.1 Einstein

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

18.2 Bondi k -calculus

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

18.3 wordline in Minkowski space

18.3.1 Wick rotation

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

18.3.1.1 Osterwalder-Schrader reconstruction theorem

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

Chapter 19

R

19.1 TonyKuoYJ

郭耀仁 認識 R 的美好

<https://bookdown.org/tonykuoyj/eloquentr/getting-started.html>

<https://bookdown.org/tonykuoyj/eloquentr/easy-installation.html#about-packages>

```
install.packages()
```

```
library()
```

<https://bookdown.org/tonykuoyj/eloquentr/getting-started.html>

19.1.1 quick intro

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

Ctrl + Enter to run the current line

Ctrl + Shift + Enter to run the current chunk

```
R.version
```

```
##           -
## platform      x86_64-w64-mingw32
## arch         x86_64
## os            mingw32
## crt          ucrt
## system       x86_64, mingw32
## status
## major        4
## minor        2.1
## year         2022
## month        06
## day          23
## svn rev      82513
## language     R
## version.string R version 4.2.1 (2022-06-23 ucrt)
```

```

## nickname      Funny-Looking Kid
a <- 23 # prime
a

## [1] 23

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

## [1] 11 13

# ?c
# help(c)

```

Ctrl + L to clean R console

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

19.1.1.1 function

```

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

add(11, 13)

```

[1] 24

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

```

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

get_bmi(70, 170)

```

[1] 24.22145

19.1.2 R style

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

snake_case rather than camelCase

19.1.3 data workflow or forward pipe

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

19.1.3.1 %>% operator

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

```
## [1] 5 4 3 2 1 0 1 2 3 4 5
# install.packages("magrittr")

library(magrittr)

##
## Attaching package: 'magrittr'
## The following object is masked _by_ '.GlobalEnv':
##       add
-5:5 %>% abs()

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

# with readability but too many lines
sys_date <- Sys.Date()
sys_date_yr <- format(sys_date, format = "%Y")
sys_date_num <- as.numeric(sys_date_yr)
sys_date_num

## [1] 2024

# less line but also less readability
sys_date_num <- as.numeric(format(Sys.Date(), format = "%Y"))
sys_date_num

## [1] 2024

# use %>% operator to demonstrate data workflow or forward pipe
sys_date_num <- Sys.Date() %>%
  format(format = "%Y") %>%
  as.numeric()
sys_date_num

## [1] 2024
```

19.1.4 data processing with dplyr

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

some functions functioning like those in **SQL**

```
library(dplyr)

## Warning: package 'dplyr' was built under R version 4.2.3
##
## Attaching package: 'dplyr'
## The following objects are masked from 'package:stats':
##       filter, lag
## The following objects are masked from 'package:base':
```

```

##  

##      intersect, setdiff, setequal, union  

# install.packages("gapminder")  

library(gapminder)  
  

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

head(gapminder)  
  

## # A tibble: 6 x 6  

##   country   continent   year lifeExp     pop gdpPercap  

##   <fct>     <fct>     <int>   <dbl>   <int>     <dbl>  

## 1 Afghanistan Asia     1952    28.8  8425333    779.  

## 2 Afghanistan Asia     1957    30.3  9240934    821.  

## 3 Afghanistan Asia     1962    32.0  10267083   853.  

## 4 Afghanistan Asia     1967    34.0  11537966   836.  

## 5 Afghanistan Asia     1972    36.1  13079460   740.  

## 6 Afghanistan Asia     1977    38.4  14880372   786.  
  

library(gapminder)  

library(dplyr)  

library(magrittr)  
  

gapminder %>%  

  filter(year == 2007)  
  

## # A tibble: 142 x 6  

##   country   continent   year lifeExp     pop gdpPercap  

##   <fct>     <fct>     <int>   <dbl>   <int>     <dbl>  

## 1 Afghanistan Asia     2007    43.8  31889923    975.  

## 2 Albania     Europe    2007    76.4  3600523    5937.  

## 3 Algeria     Africa    2007    72.3  33333216   6223.  

## 4 Angola      Africa    2007    42.7  12420476   4797.  

## 5 Argentina   Americas  2007    75.3  40301927  12779.  

## 6 Australia   Oceania   2007    81.2  20434176  34435.  

## 7 Austria     Europe    2007    79.8  8199783  36126.  

## 8 Bahrain     Asia      2007    75.6  708573   29796.  

## 9 Bangladesh  Asia      2007    64.1  150448339  1391.  

## 10 Belgium    Europe   2007    79.4  10392226  33693.  

## # i 132 more rows  
  

library(gapminder)  

library(dplyr)  

library(magrittr)  
  

gapminder %>%  

  filter(year == 2007) %>%  

  select(country)  
  

## # A tibble: 142 x 1  

##   country  

##   <fct>

```

```

## 1 Afghanistan
## 2 Albania
## 3 Algeria
## 4 Angola
## 5 Argentina
## 6 Australia
## 7 Austria
## 8 Bahrain
## 9 Bangladesh
## 10 Belgium
## # i 132 more rows

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

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

## # A tibble: 1,704 x 7
##   country   continent year lifeExp      pop gdpPercap pop_in_thousands
##   <fct>     <fct>    <int>  <dbl>    <int>    <dbl>          <dbl>
## 1 Afghanistan Asia      1952    28.8  8425333    779.        8425.
## 2 Afghanistan Asia      1957    30.3  9240934    821.        9241.
## 3 Afghanistan Asia      1962    32.0 10267083    853.       10267.
## 4 Afghanistan Asia      1967    34.0 11537966    836.       11538.
## 5 Afghanistan Asia      1972    36.1 13079460    740.       13079.
## 6 Afghanistan Asia      1977    38.4 14880372    786.       14880.
## 7 Afghanistan Asia      1982    39.9 12881816    978.       12882.
## 8 Afghanistan Asia      1987    40.8 13867957    852.       13868.
## 9 Afghanistan Asia      1992    41.7 16317921    649.       16318.
## 10 Afghanistan Asia     1997    41.8 22227415    635.       22227.
## # i 1,694 more rows

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

gapminder %>%
  arrange(year)

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

```

```
## 10 Belgium      Europe      1952     68     8730405     8343.
## # i 1,694 more rows
```

total population in the world in 2007

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

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

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

total population group by the continents in 2007

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

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

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

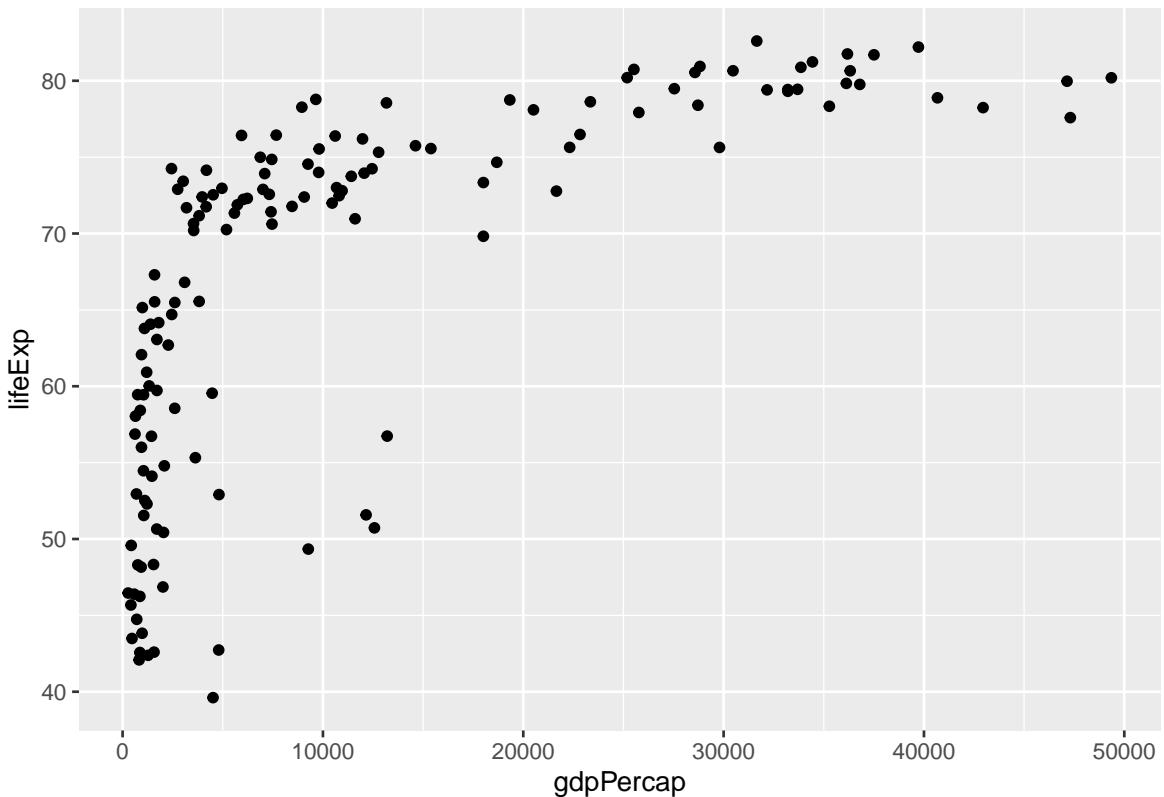
19.1.5 visualization statically with ggplot2

```
library(ggplot2)

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

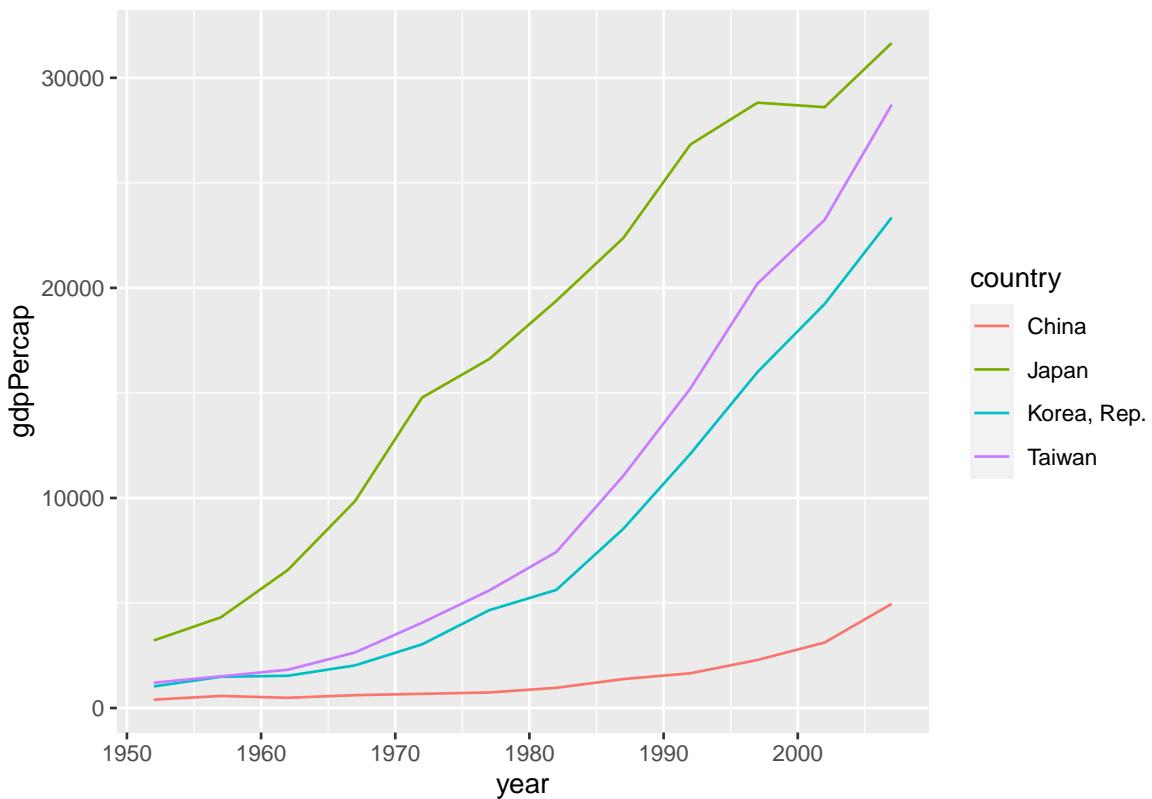
library(gapminder)

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



```
library(ggplot2)
library(gapminder)

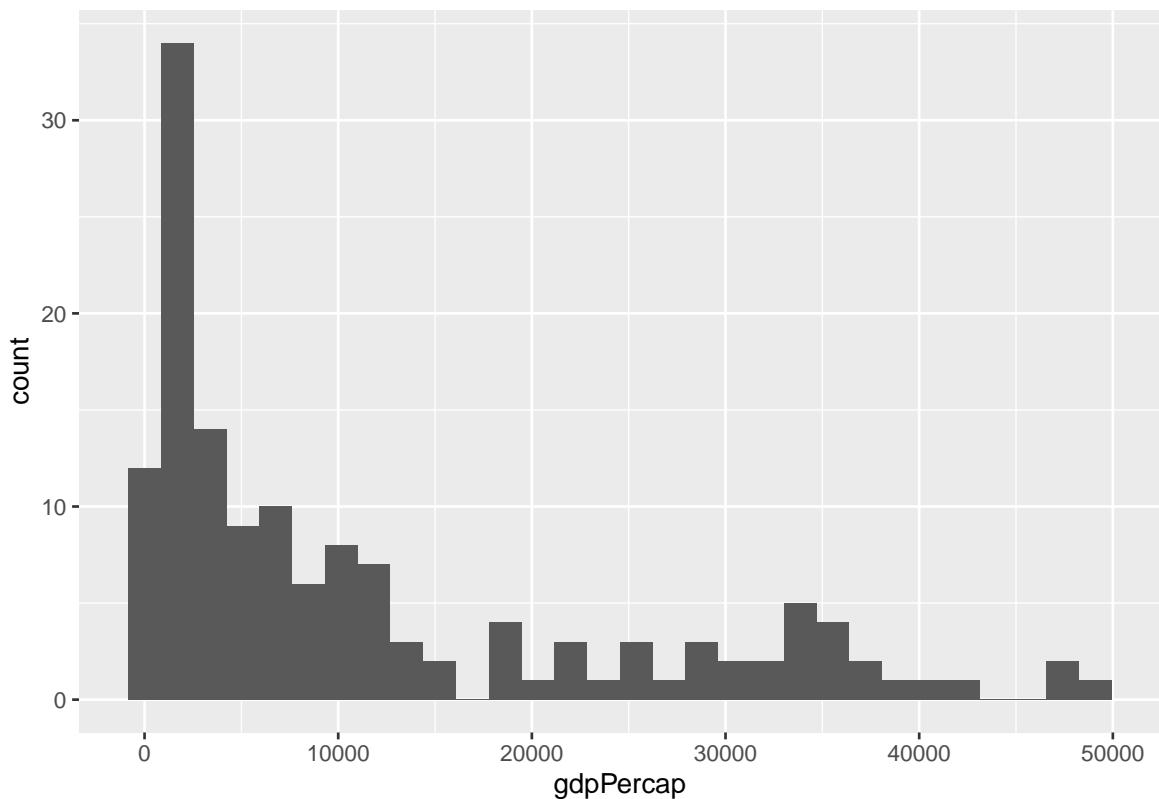
north_asia <- gapminder %>%
  filter(country %in% c("China", "Japan", "Taiwan", "Korea, Rep."))
line_plot <- ggplot(north_asia, aes(x = year, y = gdpPercap, colour = country)) +
  geom_line()
line_plot
```



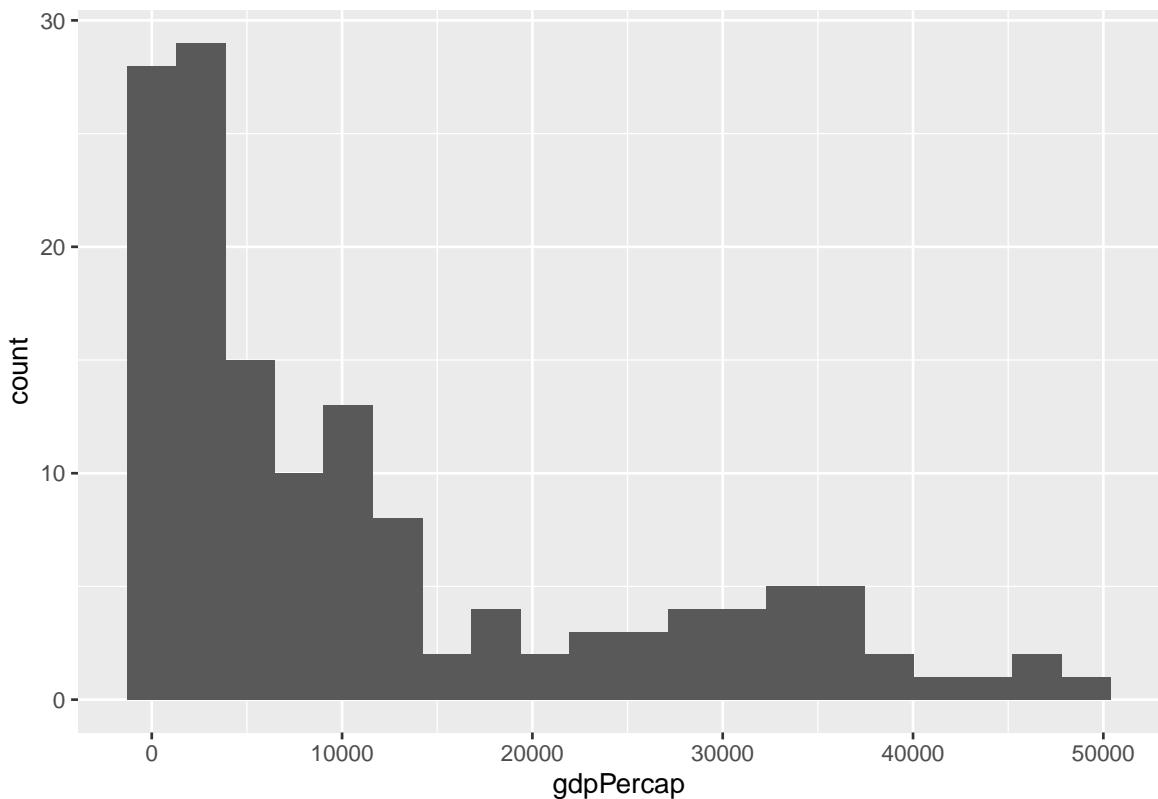
```
library(ggplot2)
library(gapminder)

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

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

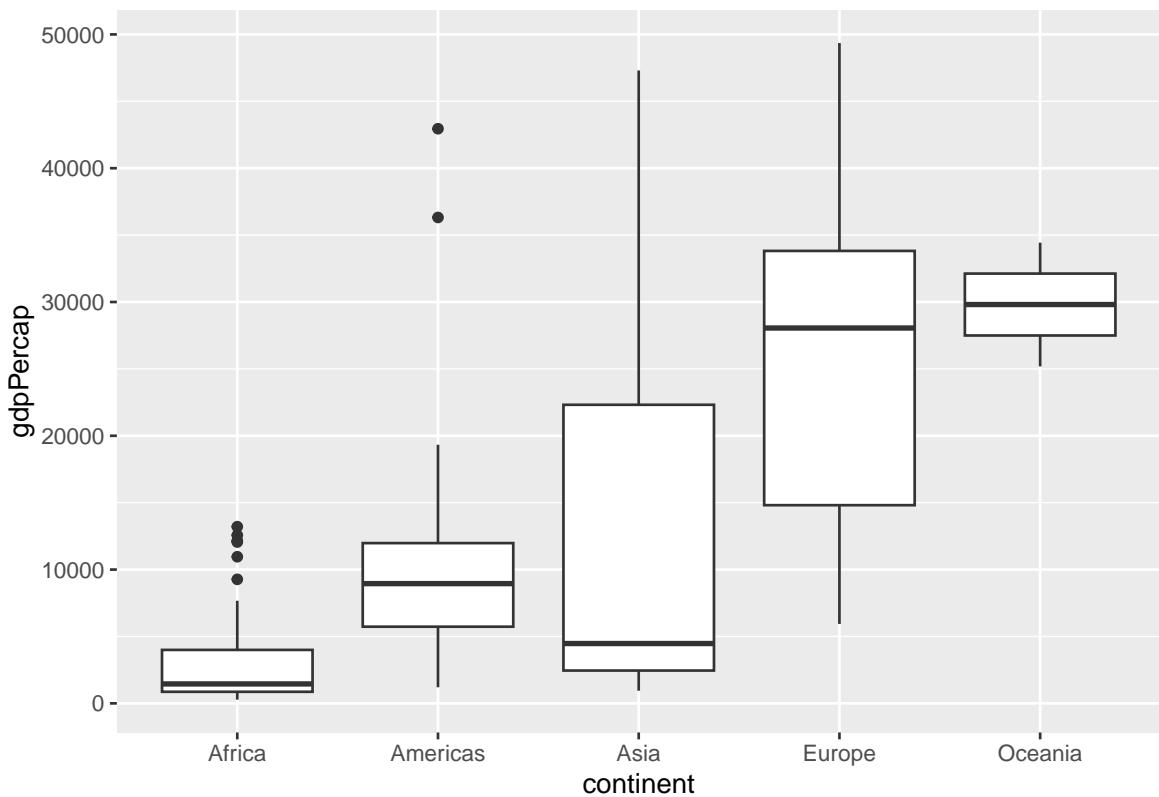


```
hist_plot <- ggplot(gapminder_2007, aes(x = gdpPercap)) +  
  geom_histogram(bins = 20)  
hist_plot
```



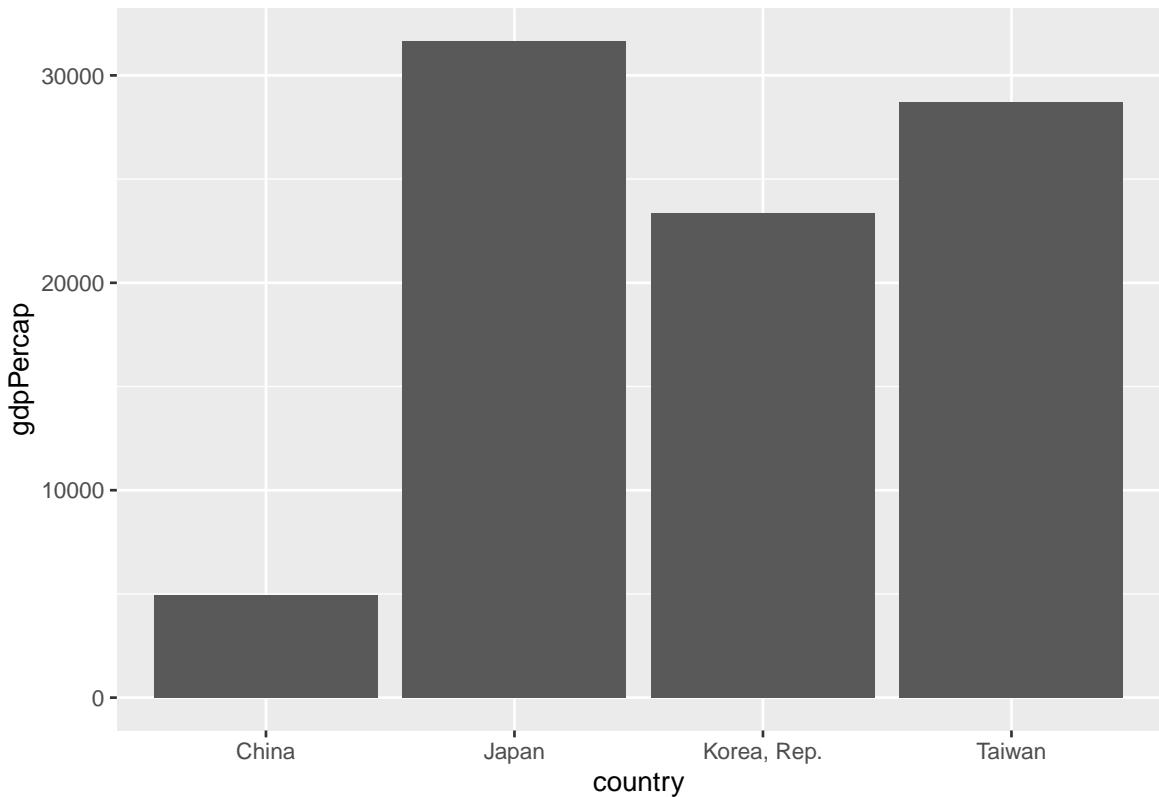
```
library(ggplot2)
library(gapminder)

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



```
library(ggplot2)
library(gapminder)

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



19.1.6 loop

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

```
month.name
```

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

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

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

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

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

```
## [1] "November"
## [1] "December"
```

19.1.7 variable type

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

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

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

```
class(2L)
```

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

```
class(2.0L)
```

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

```
class(2.3L)
```

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

time: POSIXct POSIXt

```
class(Sys.time())
```

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

```
0 %in% -5:5
```

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

19.1.7.1 date

1970-01-01 = 0L

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

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

check if type of x is Date

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

convert character to Date

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

19.1.7.2 time

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

tz = time zone

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

```
## [1] 0
check if type of x is time
inherits(x, what = "POSIXct")
convert character to time
as.POSIXct("1970-01-01 00:00:00", tz = "GMT")
```

19.1.7.3 quotient %/% operator

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

```
7 %/% 3
```

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

19.1.8 data type

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

- 1D
 - `vector`^[19.1.8.1]
 - `factor`^[19.1.8.2]
- 2D
 - `matrix`^[19.1.8.3]
 - `data frame`^[19.1.8.4]
- n D
 - `array`^[19.2.6.1]
 - `list`^[19.2.6.2]

19.1.8.1 vector

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

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

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

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

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

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

only one variable type for a vector

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

```

## [1] "numeric"
lucky_numbers <- c(7L, FALSE)
lucky_numbers

## [1] 7 0

class(lucky_numbers[2])

## [1] "integer"
mixed_vars <- c(TRUE, 7L, 24, "spring")
mixed_vars

## [1] "TRUE"    "7"       "24"      "spring"
class(mixed_vars[1])

## [1] "character"
class(mixed_vars[2])

## [1] "character"
class(mixed_vars[3])

## [1] "character"

four_seasons <- c("spring", "summer", "autumn", "winter")
my_favorite_seasons <- four_seasons == "spring" | four_seasons == "autumn"
four_seasons[my_favorite_seasons]

```

19.1.8.1.1 logic

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

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

19.1.8.1.2 rep repeat

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

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

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

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

19.1.8.1.3 seq sequence

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

```
11:20
```

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

19.1.8.2 factor

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

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

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

four_seasons_factor <- factor(four_seasons)
four_seasons_factor

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

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

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

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

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

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

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

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

19.1.8.3 matrix

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

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

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

class(my_mat)

## [1] "matrix" "array"

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

```

##      [,1] [,2] [,3]
## [1,]    1    2    3
## [2,]    4    5    6
my_mat2[2, 3]

## [1] 6
my_mat2[2, ]

## [1] 4 5 6
my_mat2[, 3]

## [1] 3 6
filter <- my_mat2 < 6 & my_mat2 > 1
my_mat2[filter]

## [1] 4 2 5 3

```

boolean will become value in a matrix, like vector

```

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

##      [,1] [,2] [,3]
## [1,]    1    1    3
## [2,]    2    0    4
class(my_mat3[, 2])

## [1] "numeric"

```

19.1.8.4 data frame

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

```

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

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

##              team_name wins losses is_champion   season
## 1          Chicago Bulls    72     10        TRUE 1995-96
## 2 Golden State Warriors    73      9       FALSE 2015-16
great_nba_teams[1, 1]

## [1] "Chicago Bulls"

```

```

great_nba_teams[1, ]

##      team_name wins losses is_champion season
## 1 Chicago Bulls    72     10      TRUE 1995-96
great_nba_teams[, 1]

## [1] "Chicago Bulls"      "Golden State Warriors"
stringsAsFactors = TRUE

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

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

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

stringsAsFactors = FALSE

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

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

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

great_nba_teams$team_name

```

19.1.8.4.1 selecting variable or column

```

## [1] "Chicago Bulls"      "Golden State Warriors"
great_nba_teams[, "team_name"]

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

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

```

19.1.8.4.2 filtering observation or row

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

str(great_nba_teams)
```

19.1.8.4.3 check mixed data type

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

19.2 W3School

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

19.2.1 same multiple variable

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

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

# Print variable values
var1

## [1] "Orange"

var2

## [1] "Orange"

var3

## [1] "Orange"
```

19.2.2 legal variable name

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

```
# Legal variable names:
myvar <- "John"
my_var <- "John"
myVar <- "John"
MYVAR <- "John"
myvar2 <- "John"
.myvar <- "John"

## Illegal variable names:
# 2myvar <- "John"
# my-var <- "John"
```

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

19.2.3 complex number

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

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

19.2.4 escape character

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

19.2.5 global assignment <<-

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

```
my_function()
```

```
## [1] "R is fantastic"
```

```
print(txt)
```

```
## [1] "fantastic"
```

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

```
my_function()
```

```
## [1] "R is fantastic"
```

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

```
## [1] "R is fantastic"
```

19.2.6 data type

19.2.6.1 array

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

```
# An array with one dimension with values ranging from 1 to 24
thisarray <- c(1:24)
thisarray
```

```

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

# An array with more than one dimension
multiarray <- array(thisarray, dim = c(4, 3, 2))
multiarray

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

## [1] 22

```

19.2.6.2 list

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

19.3 Apan Liao

R 演習室

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

19.3.1 data input

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

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

19.3.2 descriptive statistics

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

Chapter 20

Laplace transform

Chapter 21

conic section

conic section 圓錐曲線 / 圓錐截痕

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

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

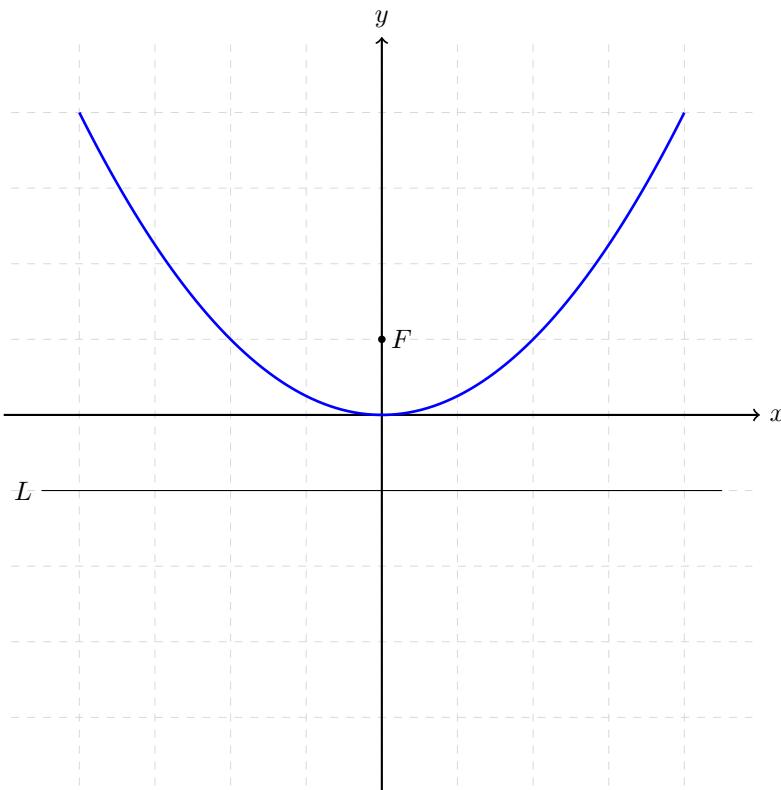


Figure 21.1: parabola defined by focus, directrix, eccentricity

21.1 Cartesian coordinate: focus, directrix, eccentricity

focus, directrix, eccentricity 焦點, 準線, 離心率

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\epsilon = 1$$

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

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

$$\epsilon \neq 1$$

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

$$\epsilon = 1$$

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

or by definition of eccentricity (21.1)

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

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

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

actually,

$$y_F = -\epsilon y_L$$

21.2 two-definition equivalence for ellipse and hyperbola

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

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

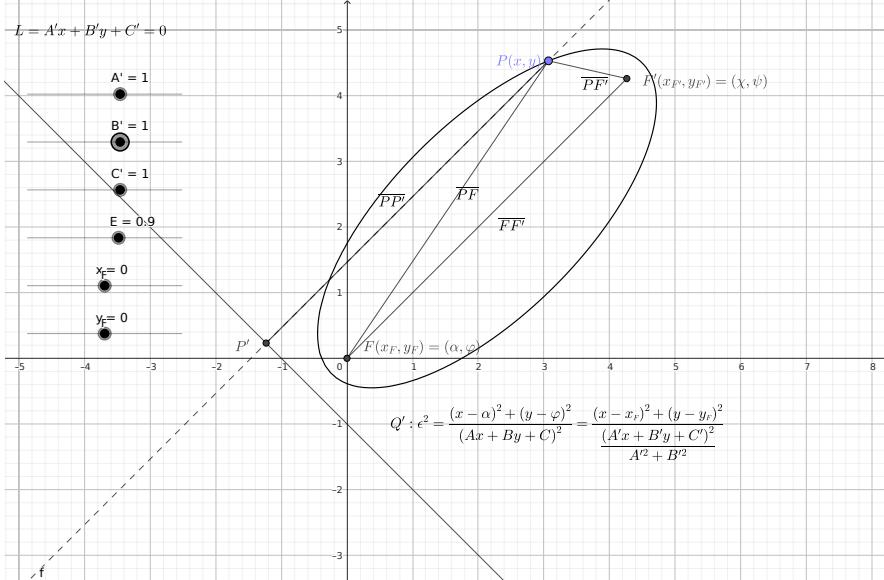


Figure 21.2: conic sections

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

21.2.1 first definition for conic sections including ellipses and hyperbolas

distance from a point to a line^[^22^]

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

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

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

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

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

21.2.2 second definition for ellipses and hyperbolas

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

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

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

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

$D \neq 0$

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

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

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

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

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

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

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

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

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

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

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

actually, only one of two solutions is true

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

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

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

Can the above be more simplified?

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

21.2.3 eccentricity and its equivalent representation

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

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

21.3 Cartesian coordinate: standard form / standard equation

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

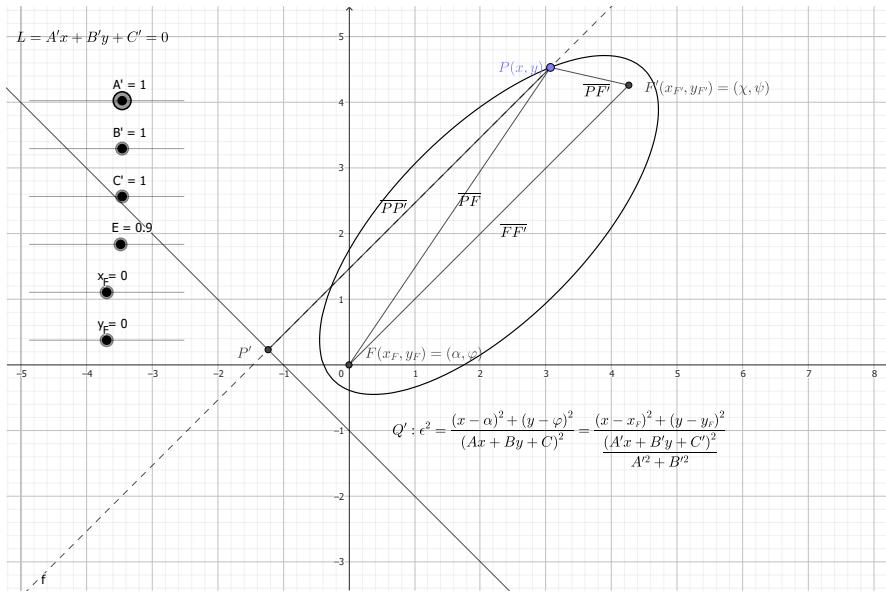


Figure 21.3: conic sections: ellipse

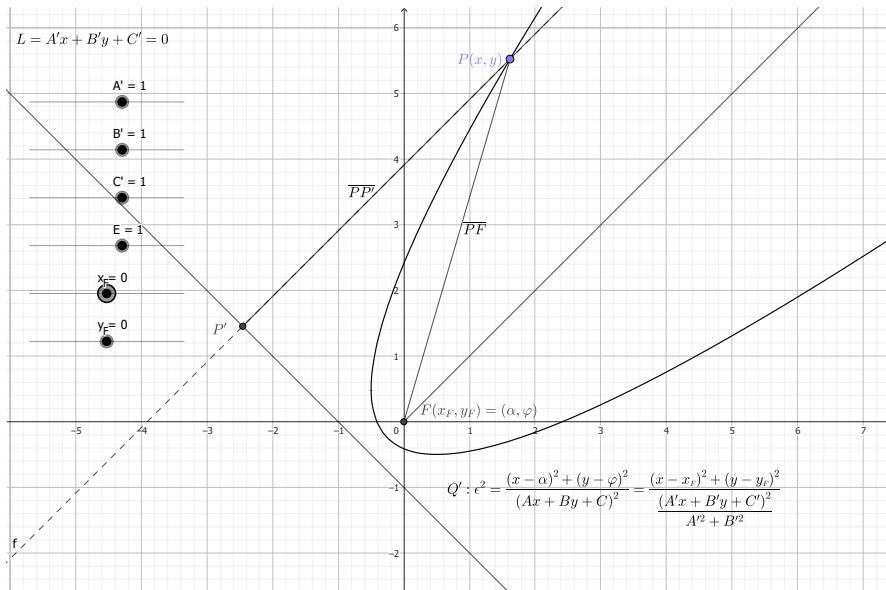


Figure 21.4: conic sections: parabola

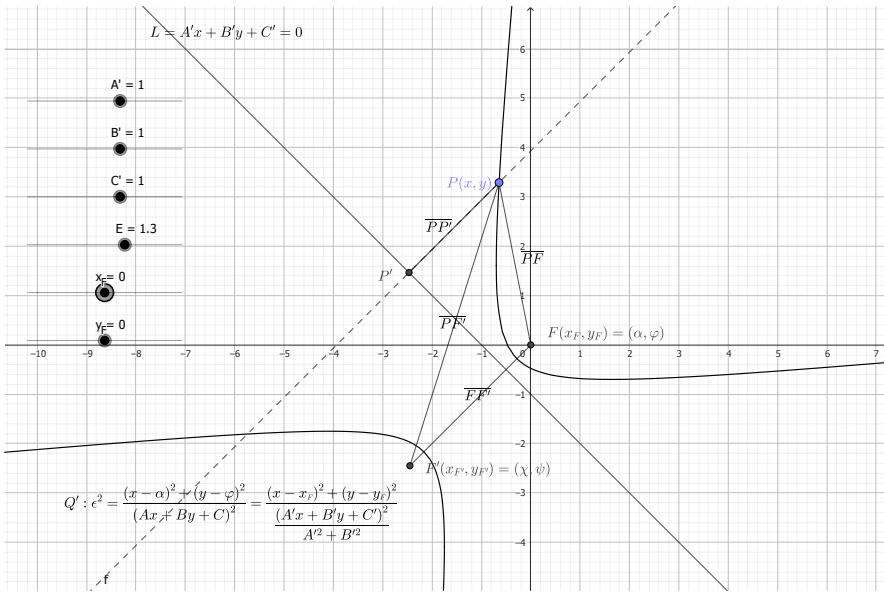


Figure 21.5: conic sections: hyperbola

21.4 parametric equation

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

tangent half-angle formula^[24]

21.5 polar coordinate

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

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

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

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

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

$$r^2 =$$

$$r = \pm \epsilon (r \cos \theta + p)$$

$$= \pm (r \epsilon \cos \theta + \epsilon p)$$

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

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

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

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

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

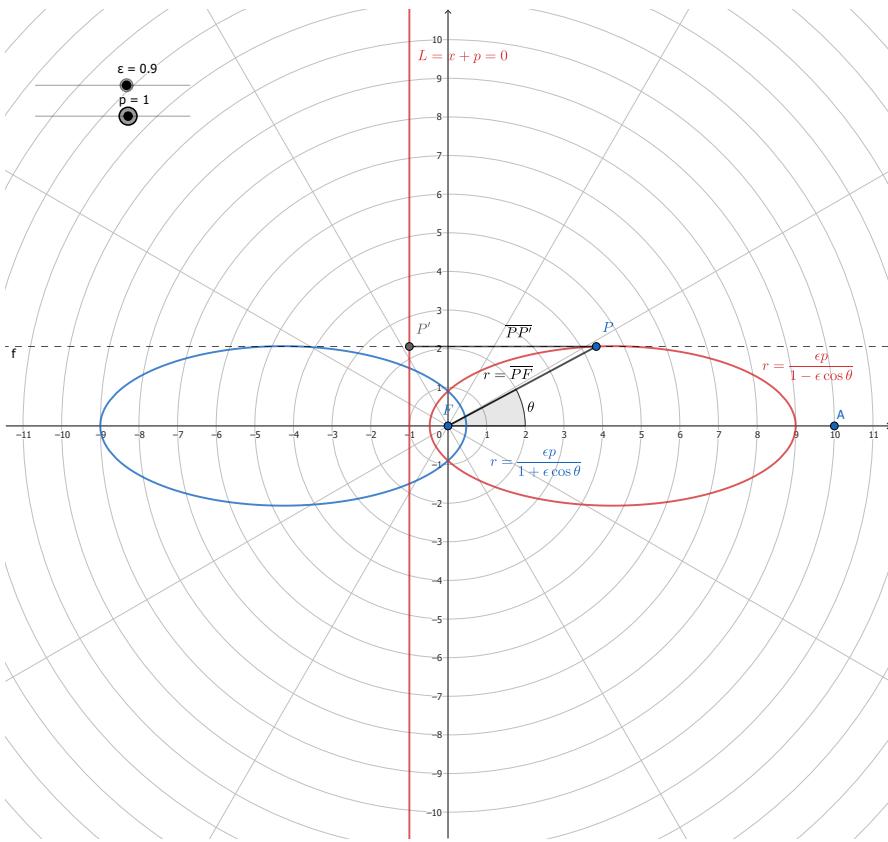


Figure 21.6: polar conic sections: ellipse

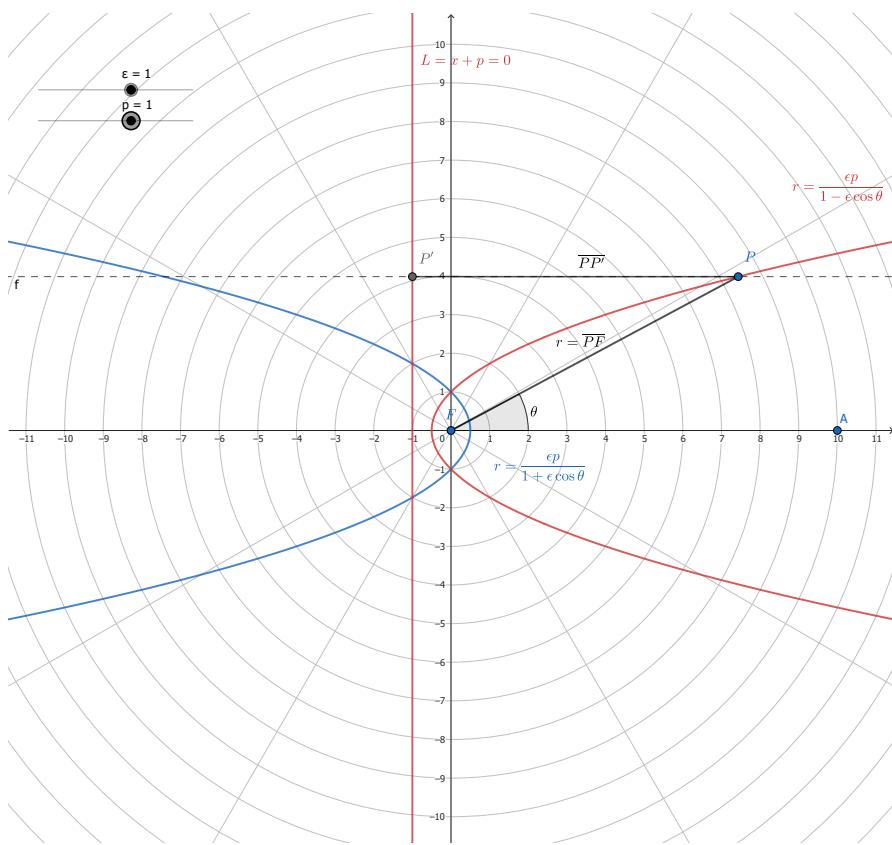


Figure 21.7: polar conic sections: parabola

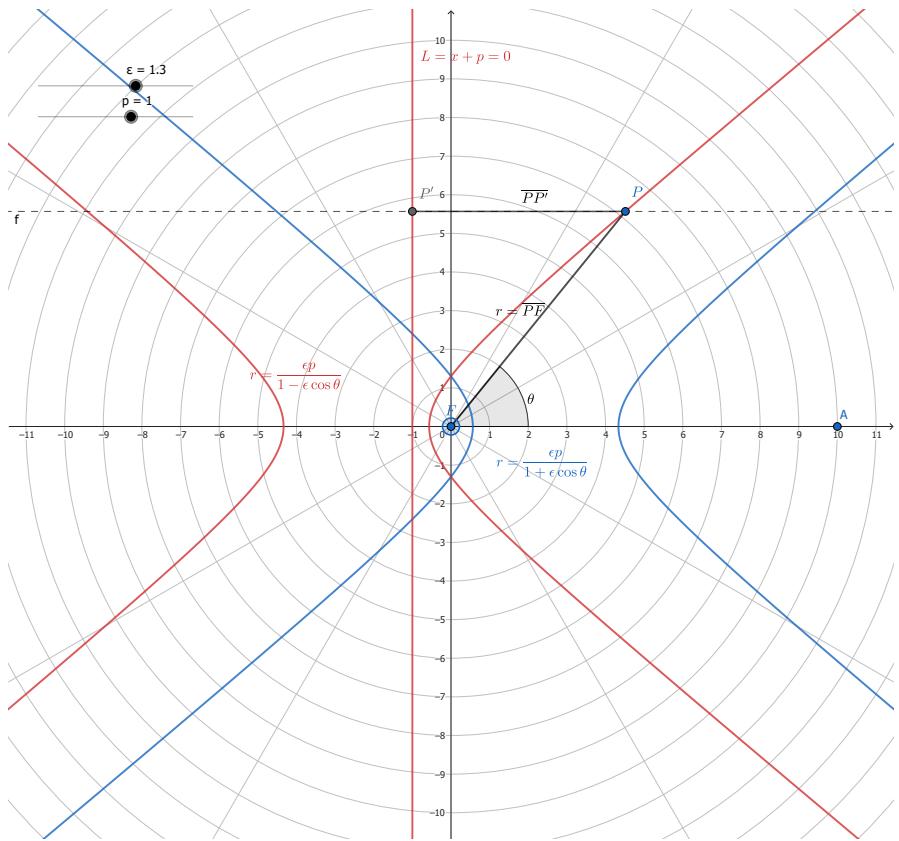


Figure 21.8: polar conic sections: hyperbola

21.6 Cartesian coordinate: general form / quadratic equation

<https://ccjou.wordpress.com/2013/05/24/%E5%9C%A8%E9%9D%A2/>

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

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

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

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

real symmetric matrix diagonalizable^[23]

21.7 homogeneous coordinate

X homogeneous coordinate

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

O homogeneous coordinate^[25]

X homogeneous coordinate

X homogeneous coordinate^[21.7]

<https://ccjou.wordpress.com/2013/05/24/%E5%9C%A8%E9%9D%A2/>

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

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

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

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

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

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

Chapter 22

distance from a point to a line

點到直線距離

Theorem 22.1.

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

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

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

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

Proofs:

22.1 by shortest $\overline{PP'}$

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

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

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

or by completing the square to find x .

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

22.2 by perpendicular foot

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

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

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

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

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

perpendicular foot = foot of the perpendicular P'

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

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

22.3 by normal vector

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

P 到 L 的距離 $d(P, L)$ 即為 L 線上一點 P' 對應之 $\vec{PP'}$ 在 L 法向量 \vec{n} 方向上的投影長

$$\begin{aligned}
\vec{PP'} \cdot \vec{n} &= \left\| \vec{PP'} \right\| \left\| \vec{n} \right\| \cos \theta \\
\left| \vec{PP'} \cdot \vec{n} \right| &= \left\| \vec{PP'} \right\| \left\| \vec{n} \right\| |\cos \theta| \\
\left\| \vec{PP'} \right\| |\cos \theta| &= \left| \vec{PP'} \cdot \hat{n} \right| = \frac{\left| \vec{PP'} \cdot \vec{n} \right|}{\left\| \vec{n} \right\|} = \frac{|(x - x_0, y - y_0) \cdot (A, B)|}{\|(A, B)\|} \\
&= \frac{|A(x - x_0) + B(y - y_0)|}{\sqrt{A^2 + B^2}} = \frac{|-Ax_0 - By_0 + Ax + By|}{\sqrt{A^2 + B^2}} \\
\frac{Ax + By + C = 0}{Ax + By = -C} &= \frac{|-Ax_0 - By_0 - C|}{\sqrt{A^2 + B^2}} = \frac{|Ax_0 + By_0 + C|}{\sqrt{A^2 + B^2}}
\end{aligned}$$

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

```

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

```

22.4 by Cauchy inequality

$$\begin{aligned}
Ax + By + C &= 0 \\
Ax + By &= -C \\
(Ax + By) - (Ax_0 + By_0) &= -C - (Ax_0 + By_0) \\
A(x - x_0) + B(y - y_0) &= -(Ax_0 + By_0 + C) \\
\overline{PP'}^2 &= (x_0 - x)^2 + (y_0 - y)^2 \\
[A^2 + B^2] \overline{PP'}^2 &= [A^2 + B^2] \left[(x_0 - x)^2 + (y_0 - y)^2 \right] \\
&\geq [A(x - x_0) + B(y - y_0)]^2 \\
&= [- (Ax_0 + By_0 + C)]^2 = (Ax_0 + By_0 + C)^2 \\
\overline{PP'}^2 &\geq \frac{(Ax_0 + By_0 + C)^2}{A^2 + B^2} \\
\overline{PP'} &\geq \frac{|Ax_0 + By_0 + C|}{\sqrt{A^2 + B^2}}
\end{aligned}$$

Chapter 23

real symmetric matrix diagonalizable

<https://ccjou.wordpress.com/2011/02/09/%E5%80%BC%E5%AE%9A%E7%9F%A5%E6%9C%8D%E6%9E%9A%E7%9F%A5%E5%80%BC/>

<https://tex.stackexchange.com/questions/30619/what-is-the-best-symbol-for-vector-matrix-transpose>

Theorem 23.1.

實對稱矩陣的特徵值皆是實數，且對應特徵向量是實向量。

$$\begin{aligned}
 & \left\{ \begin{array}{l} A \in \mathcal{M}_{n \times n}(\mathbb{R}) \\ A^\top = A \end{array} \right. \quad \begin{array}{l} \text{real matrix} \\ \text{symmetric matrix} \end{array} \quad \left. \begin{array}{l} \text{real symmetric matrix} \\ \lambda \in \mathbb{C} \\ \mathbf{0} \neq \mathbf{x} \in \mathbb{C}^n \end{array} \right. \quad \begin{array}{l} \text{complex eigenvalue} \\ \text{complex eigenvector} \end{array} \\
 & \left\{ \begin{array}{l} Ax = \lambda x \end{array} \right. \quad \Downarrow \quad \left\{ \begin{array}{l} \lambda \in \mathbb{R} \\ \mathbf{x} \in \mathbb{R}^n \end{array} \right. \quad \begin{array}{l} \text{real eigenvalue (1)} \\ \text{real eigenvector (2)} \end{array}
 \end{aligned}$$

Proof. (1)

$$\begin{aligned}
 Ax &= \lambda x \\
 \bar{A}\bar{x} &= \overline{Ax} = \overline{\lambda x} = \bar{\lambda}\bar{x} \\
 \bar{x}^\top \bar{A}^\top &= (\bar{A}\bar{x})^\top = (\bar{\lambda}\bar{x})^\top = \bar{\lambda}\bar{x}^\top \\
 \bar{x}^\top A &\stackrel{\text{symmetric}}{=} \bar{x}^\top A^\top \stackrel{\text{real}}{=} \\
 \bar{x}^\top A &= \bar{\lambda}\bar{x}^\top \\
 \lambda\bar{x}^\top x &= \bar{x}^\top (\lambda x) \stackrel{Ax=\lambda x}{=} \bar{x}^\top Ax = \bar{\lambda}\bar{x}^\top x \\
 \lambda\bar{x}^\top x &= \bar{\lambda}\bar{x}^\top x \\
 (\lambda - \bar{\lambda})\bar{x}^\top x &= 0 \wedge \begin{cases} \bar{x}^\top x = \sum_{i=1}^n |x_i|^2 \\ x \neq 0 \end{cases} \Rightarrow \bar{x}^\top x \neq 0 \\
 \lambda - \bar{\lambda} &= 0 \\
 \lambda = \bar{\lambda} &\Leftrightarrow \lambda \in \mathbb{R}
 \end{aligned}$$

□

Proof. (1) fast concept

$$\begin{aligned}
 (\bar{A}\bar{x})^\top \mathbf{x} &= (\bar{x}^\top \bar{A}^\top) \mathbf{x} \stackrel{\text{symmetric}}{=} (\bar{x}^\top \bar{A}) \mathbf{x} = \bar{x}^\top (\bar{A}\mathbf{x}) \\
 (L) &= (\bar{A}\bar{x})^\top \mathbf{x} = \bar{x}^\top (\bar{A}\mathbf{x}) = (R) \\
 (L) &= (\bar{A}\bar{x})^\top \mathbf{x} \stackrel{Ax=\lambda x}{=} (\bar{\lambda}\bar{x})^\top \mathbf{x} = \bar{\lambda}\bar{x}^\top \mathbf{x} \\
 (R) &= \bar{x}^\top (\bar{A}\mathbf{x}) \stackrel{\text{real}}{=} \bar{x}^\top (Ax) \stackrel{Ax=\lambda x}{=} \bar{x}^\top (\lambda\mathbf{x}) = \lambda\bar{x}^\top \mathbf{x} \\
 \bar{\lambda}\bar{x}^\top \mathbf{x} &= (\bar{A}\bar{x})^\top \mathbf{x} = \bar{x}^\top (\bar{A}\mathbf{x}) = \lambda\bar{x}^\top \mathbf{x} \\
 \bar{\lambda}\bar{x}^\top \mathbf{x} &= \lambda\bar{x}^\top \mathbf{x}
 \end{aligned}$$

□

Proof. (2)

???

推論特徵空間 $N(A - \lambda I)$ ($A - \lambda I$ 的零空間) 為 \mathbb{R}^n 的子空間，故 $\mathbf{x} \in N(A - \lambda I)$ 是一個非零實向量。

□

Theorem 23.2.

實對稱矩陣對應相異特徵值的特徵向量互為正交。

$$\left\{
 \begin{array}{ll}
 \begin{cases} A \in \mathcal{M}_{n \times n}(\mathbb{R}) & \text{real matrix} \\ A^\top = A & \text{symmetric matrix} \end{cases} & \text{real symmetric matrix} \\
 Ax = \lambda x & \\
 \begin{cases} Ax_1 = \lambda_1 x_1 & (e_1) \\ Ax_2 = \lambda_2 x_2 & (e_2) \end{cases} & \begin{array}{ll} \lambda \in \mathbb{R} & \text{real eigenvalue} \\ x \in \mathbb{R}^n & \text{real eigenvector} \end{array} \\
 \lambda_1 \neq \lambda_2 & \\
 \Downarrow & \\
 x_1^\top x_2 = 0 \Leftrightarrow x_1 \perp x_2 &
 \end{array}
 \right.$$

Proof. (1)

$$\begin{aligned}
A\mathbf{x}_2 &= \lambda_2 \mathbf{x}_2 \\
\mathbf{x}_1^\top A \mathbf{x}_2 &\stackrel{\mathbf{x}_1^\top}{=} \mathbf{x}_1^\top \lambda_2 \mathbf{x}_2 = \lambda_2 \mathbf{x}_1^\top \mathbf{x}_2 = (1) \\
A\mathbf{x}_1 &= \lambda_1 \mathbf{x}_1 \\
\mathbf{x}_1^\top A^\top &= (A\mathbf{x}_1)^\top = (\lambda_1 \mathbf{x}_1)^\top = \lambda_1 \mathbf{x}_1^\top \\
\mathbf{x}_1^\top A^\top &= \lambda_1 \mathbf{x}_1^\top \\
\mathbf{x}_1^\top A \mathbf{x}_2 &\stackrel{\text{symmetric}}{=} \mathbf{x}_1^\top A^\top \mathbf{x}_2 \stackrel{\mathbf{x}_2}{=} \lambda_1 \mathbf{x}_1^\top \mathbf{x}_2 = (2) \\
\lambda_2 \mathbf{x}_1^\top \mathbf{x}_2 &\stackrel{(1)}{=} \mathbf{x}_1^\top A \mathbf{x}_2 \stackrel{(2)}{=} \lambda_1 \mathbf{x}_1^\top \mathbf{x}_2 \\
\lambda_2 \mathbf{x}_1^\top \mathbf{x}_2 &= \lambda_1 \mathbf{x}_1^\top \mathbf{x}_2 \\
(\lambda_2 - \lambda_1) \mathbf{x}_1^\top \mathbf{x}_2 &= 0 \wedge \lambda_1 \neq \lambda_2 \\
\mathbf{x}_1^\top \mathbf{x}_2 &= 0
\end{aligned}$$

□

Proof. (1) fast concept

$$\begin{aligned}
(A\mathbf{x}_1)^\top \mathbf{x}_2 &= (\mathbf{x}_1^\top A^\top) \mathbf{x}_2 \stackrel{\text{symmetric}}{=} (\mathbf{x}_1^\top A) \mathbf{x}_2 = \mathbf{x}_1^\top (A\mathbf{x}_2) \\
(L) &= (A\mathbf{x}_1)^\top \mathbf{x}_2 = \mathbf{x}_1^\top (A\mathbf{x}_2) = (R) \\
(L) &= (A\mathbf{x}_1)^\top \mathbf{x}_2 \stackrel{(e_1)}{=} (\lambda_1 \mathbf{x}_1)^\top \mathbf{x}_2 = \lambda_1 \mathbf{x}_1^\top \mathbf{x}_2 \\
(R) &= \mathbf{x}_1^\top (A\mathbf{x}_2) \stackrel{(e_2)}{=} \mathbf{x}_1^\top (\lambda_2 \mathbf{x}_2) = \lambda_2 \mathbf{x}_1^\top \mathbf{x}_2 \\
\lambda_1 \mathbf{x}_1^\top \mathbf{x}_2 &= (A\mathbf{x}_1)^\top \mathbf{x}_2 = \mathbf{x}_1^\top (A\mathbf{x}_2) = \lambda_2 \mathbf{x}_1^\top \mathbf{x}_2 \\
\lambda_1 \mathbf{x}_1^\top \mathbf{x}_2 &= \lambda_2 \mathbf{x}_1^\top \mathbf{x}_2
\end{aligned}$$

□

Theorem 23.3.

$$\left\{
\begin{array}{ll}
\begin{cases} A \in \mathcal{M}_{n \times n}(\mathbb{R}) & \text{real matrix} \\ A^\top = A & \text{symmetric matrix} \end{cases} & \text{real symmetric matrix} \\
\begin{cases} A\mathbf{x}_1 = \lambda \mathbf{x}_1 \\ \mathbf{x}_2^\top \mathbf{x}_1 = 0 \Leftrightarrow \mathbf{x}_2 \perp \mathbf{x}_1 \end{cases} & \begin{array}{l} (e) \\ (o) \end{array} \\
\Downarrow \\
A\mathbf{x}_2 \perp \mathbf{x}_1 \Leftrightarrow (A\mathbf{x}_2)^\top \mathbf{x}_1 = 0
\end{array}
\right.$$

Proof.

$$\begin{aligned}
(A\mathbf{x}_2)^\top \mathbf{x}_1 &= (\mathbf{x}_2^\top A^\top) \mathbf{x}_1 \stackrel{\text{symmetric}}{=} (\mathbf{x}_2^\top A) \mathbf{x}_1 \\
&= \mathbf{x}_2^\top (A\mathbf{x}_1) \stackrel{(e)}{=} \mathbf{x}_2^\top (\lambda \mathbf{x}_1) \\
&= \lambda \mathbf{x}_2^\top \mathbf{x}_1 \stackrel{(o)}{=} \lambda \cdot 0 = 0 \\
(A\mathbf{x}_2)^\top \mathbf{x}_1 &= 0 \Leftrightarrow A\mathbf{x}_2 \perp \mathbf{x}_1
\end{aligned}$$

□

Chapter 24

tangent half-angle formula

https://en.wikipedia.org/wiki/Tangent_half-angle_formula

<https://zh.wikipedia.org/zh-tw/正切半角公式>

正切半形公式又稱萬能公式

以切表弦公式，簡稱以切表弦

Chapter 25

homogeneous coordinate

<https://youtu.be/EKN7dTJ4ep8?si=8woajZxbqPfEXhdK&t=2263>

<https://youtu.be/1z1S2kQKXD8?si=71o339yBtIQYhWtj&t=3082>

Chapter 26

Archimedean property

26.1 integer Archimedean property

26.2 rational Archimedean property

<https://math.stackexchange.com/questions/3699023/proof-the-the-field-of-rational-numbers-has-the-archimedean-property>

<https://math.stackexchange.com/questions/1919829/proving-the-archimedean-properties-of-rational-numbers>

26.3 real Archimedean property

Chapter 27

Matplotlib / matplotlib

- tikzplotlib^[13.5]: Python^[12] matplotlib^[27] export to TikZ^[13] .tex

27.1 Timothy H. Wu

巫孟叡

- API = application programming interface
 - functional^[27.1.1]
 - object-oriented^[27.1.2]
 - * figure
 - * axes
 - * subplot

https://matplotlib.org/stable/tutorials/introductory/quick_start.html

<https://pbpython.com/effective-matplotlib.html>

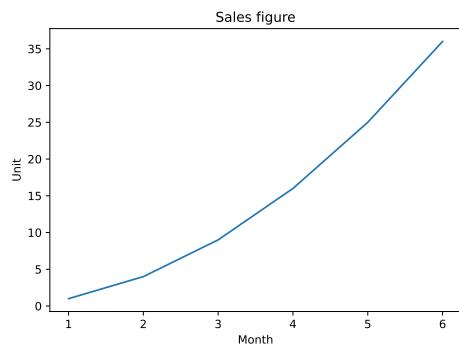
<https://tex.stackexchange.com/questions/84847/can-i-use-webp-images-in-latex>

You probably need to convert the image to png.

27.1.1 funcitonal API

```
import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
↪ 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
plt.title('Sales figure')
plt.xlabel('Month')
plt.ylabel('Unit')
plt.plot(a1, a2) # this doesn't
↪ actually show the plot.
# plt.show() This is automatically
↪ called for Jupyter notebook.
```



To plot a scatterplot, call `scatter()` instead of `plot()`.

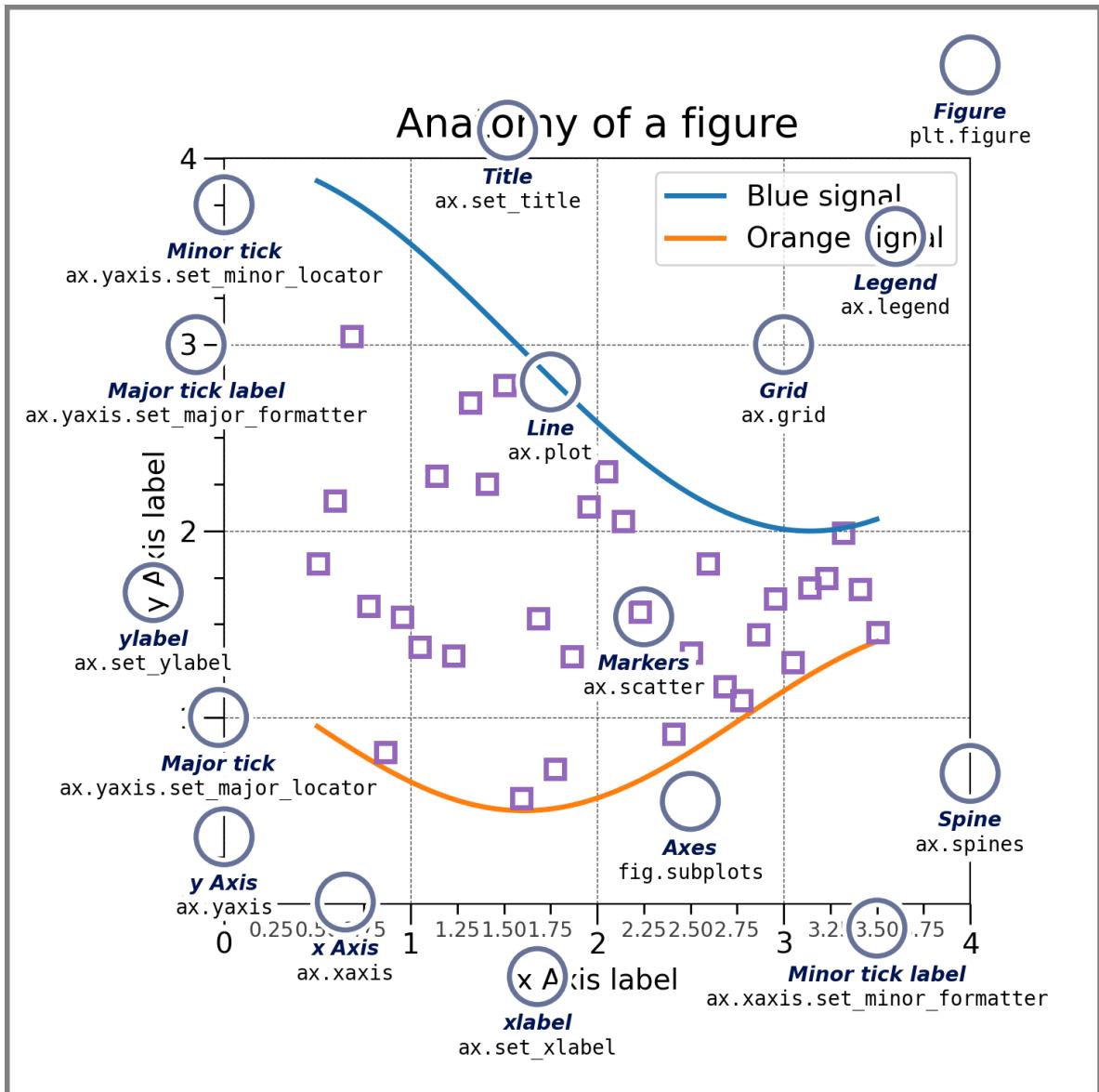


Figure 27.1: matplotlib figure anatomy

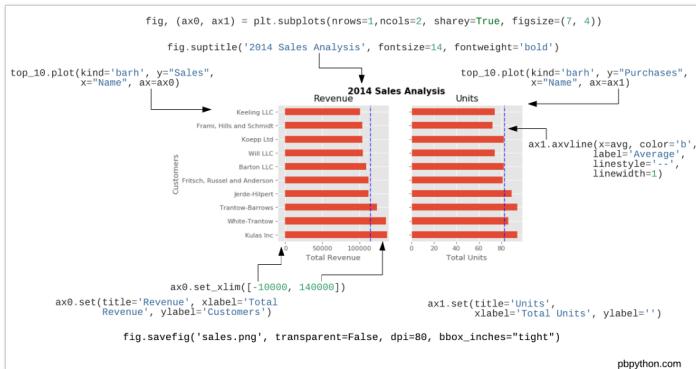


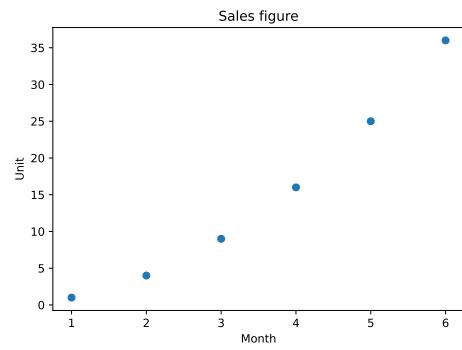
Figure 27.2: matplotlib subplot anatomy

```

import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
↪ 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
plt.title('Sales figure')
plt.xlabel('Month')
plt.ylabel('Unit')
plt.scatter(a1, a2) # instead of
↪ plot.plot(), use scatter() to show
↪ scatter plot

```

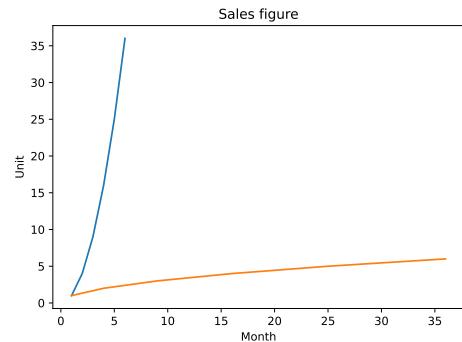


```

import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
↪ 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
plt.title('Sales figure')
plt.xlabel('Month')
plt.ylabel('Unit')
plt.plot(a1, a2)
plt.plot(a2, a1)

```



The behavior of the functional API is stateful. What's stateful? An example is when you read a text file. When you `open()` a text file to read, the library read the next line every time you call `readline()`. It remembers where you left off, despite the fact that you do not give it the position to read from. This behavior of the library is called **stateful**. The way we've used Matplotlib is also **stateful**. And everytime, `plot.show()` is called (and it automatically gets called on cell ends), some state about plots is reset. We can see that here:

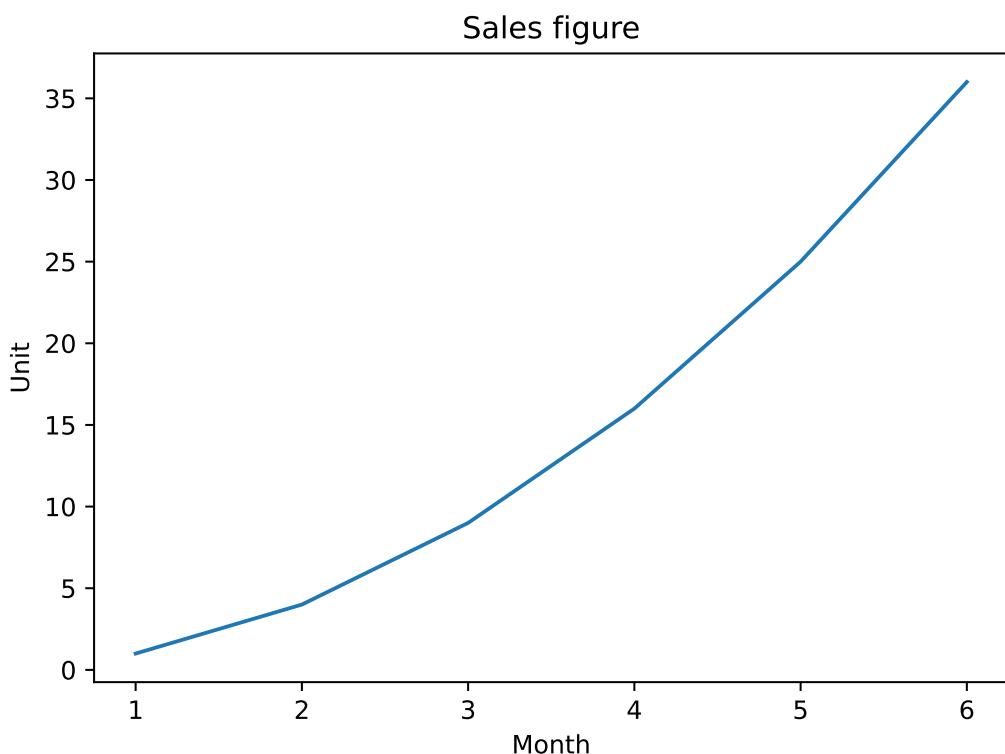
```

import matplotlib.pyplot as plt

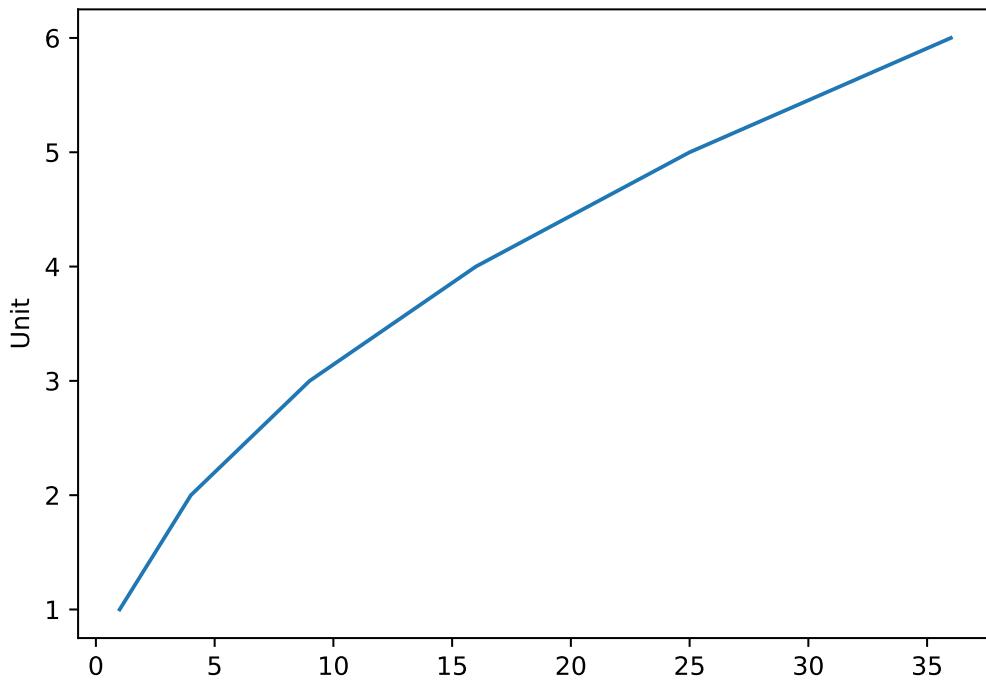
a1 = list(range(1, 7)) # [1, 2, 3, 4, 5, 6]

```

```
a2 = [1, 4, 9, 16, 25, 36]
plt.title('Sales figure')
plt.xlabel('Month')
plt.ylabel('Unit')
plt.plot(a1, a2)
```



```
plt.plot(a2, a1)
plt.ylabel('Unit')
```



It makes two graphs instead of one. Also note that `ylabel()` was called after `plot()`, and it is still shown before `plot.show()` but `Sales` Figure plot title and other labels don't show up on this graph. Because every time `plot.show()` is called, things are reset. This is a **stateful API** we're using. The functional APIs are used when you plot Matplotlib by calling on `pyplot` module level API (module level functions).

27.1.2 object-oriented API

In object-oriented API, we're getting two type of objects. One is `Figure`, the other one is `Axes`. `Figure` is the *canvas* of the plot. In English, `axes` is the plural form of `axis`. We're talking about the axis in x axis and y axis. Since one `plot` consists of both axis, in Matplotlib the object that represents one plot is called `Axes`. Since it's an object. We'll call it "a" axes.

```
import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4, 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure()
print("fig is of type:", type(fig))

## fig is of type: <class 'matplotlib.figure.Figure'>

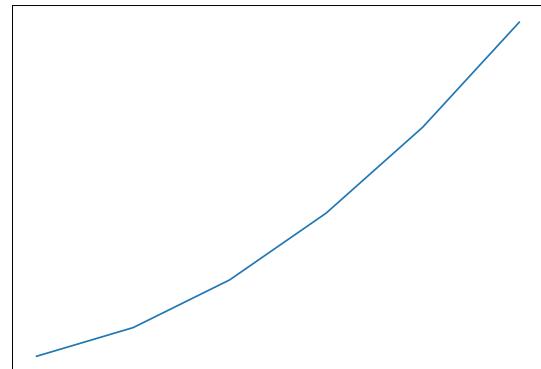
ax1 = fig.add_axes([0, 0, 1, 1]) # [left, bottom, width, height]
print("ax1 is of type:", type(ax1))
# ax1.plot(a1, a2)
```

```
## ax1 is of type: <class 'matplotlib.axes._axes.Axes'>
```

1. Call `figure()` to get a Figure type
2. Call `add_axes()` to get a `ax1` type `ax1 = fig.add_axes([0, 0, 1, 1]) # [left, bottom, width, height]`
- The list given to `add_axes()` is the rectangular region of where to show the plot:
 - Bottom left corner at $x=0, y=0$, width and height of both 1, 1

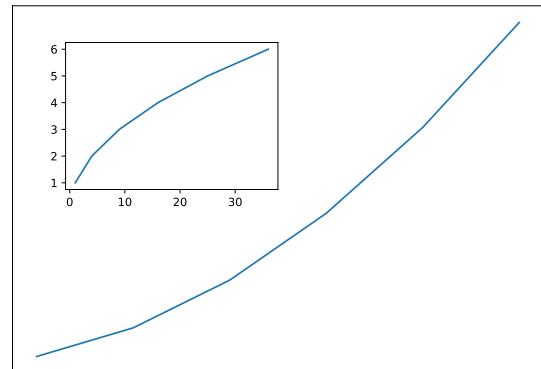
```
import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
↪ 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure()
# print("fig is of type:", type(fig))
ax1 = fig.add_axes([0, 0, 1, 1]) #
↪ [left, bottom, width, height]
# print("ax1 is of type:", type(ax1))
ax1.plot(a1, a2)
```



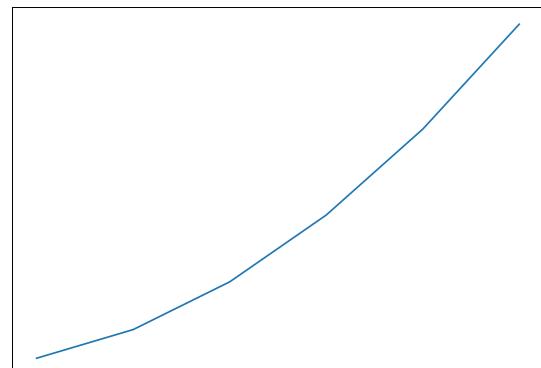
```
import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
↪ 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure()
ax1 = fig.add_axes([0, 0, 1, 1])
ax1.plot(a1, a2)
ax2 = fig.add_axes([0.1, 0.5, .4, .4])
ax2.plot(a2, a1)
```



```
import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
↪ 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure()
ax = fig.add_axes([0, 0, 1, 1])
ax.plot(a1, a2)
ax.set_xlabel('Time')
ax.set_ylabel('Unit')
ax.set_title('Sales figure')
# alternatively:
# ax.set(xlabel='Time', ylabel='Unit',
↪ title='Sales figure')
```

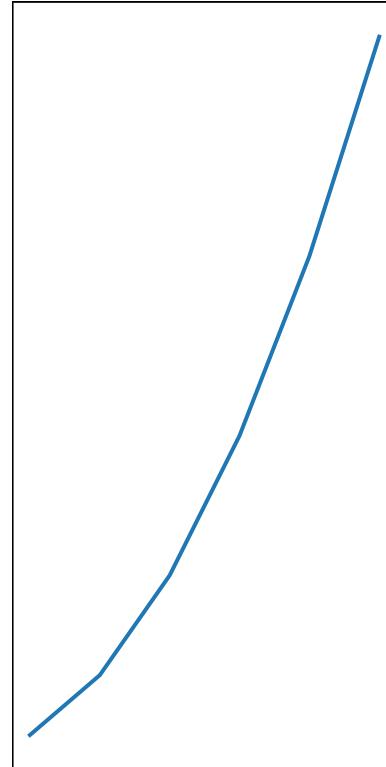


27.1.2.1 Configure the figure size and DPI

Get image size for the figure object. 6 by 4 is the default.

```
fig.get_size_inches()  
import matplotlib.pyplot as plt  
  
fig = plt.figure()  
fig.get_size_inches()  
  
## array([6.5, 4.5])
```

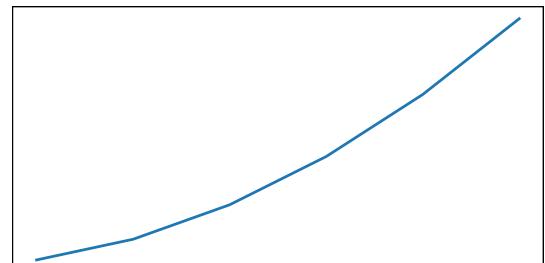
```
fig = plt.figure(figsize=(2, 4))
```



```
import matplotlib.pyplot as plt  
  
a1 = list(range(1, 7)) # [1, 2, 3, 4,  
↪ 5, 6]  
a2 = [1, 4, 9, 16, 25, 36]  
fig = plt.figure(figsize=(2, 4))  
# you can also set after getting the  
↪ figure  
# fig.set_size_inches((12, 2))  
ax = fig.add_axes([0, 0, 1, 1])  
ax.plot(a1, a2)
```

```
fig.set_size_inches((4, 2))
```

```
import matplotlib.pyplot as plt  
  
a1 = list(range(1, 7)) # [1, 2, 3, 4,  
↪ 5, 6]  
a2 = [1, 4, 9, 16, 25, 36]  
fig = plt.figure()  
# you can also set after getting the  
↪ figure  
fig.set_size_inches((4, 2))  
ax = fig.add_axes([0, 0, 1, 1])  
ax.plot(a1, a2)
```



DPI = dots per inch

Get image DPI for the figure object. 100 is the default here.

```
fig.get_dpi()  
import matplotlib.pyplot as plt  
  
fig = plt.figure()  
fig.get_dpi()  
  
## 100.0
```

```
import matplotlib.pyplot as plt  
  
a1 = list(range(1, 7)) # [1, 2, 3, 4, 5, 6]  
a2 = [1, 4, 9, 16, 25, 36]  
fig = plt.figure()  
# you can also set after getting the figure  
fig.set_size_inches((12, 2))  
ax = fig.add_axes([0, 0, 1, 1])  
ax.plot(a1, a2)  
plt.title('Sales figure')  
fig.get_dpi()
```

```
## 100.0
```

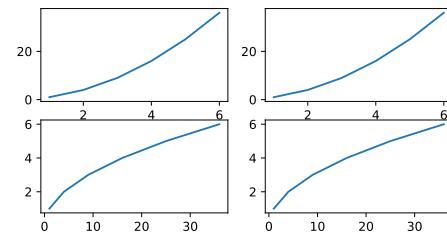
```
import matplotlib.pyplot as plt  
  
# Subplots handles add_axes for you according to the number of rows and columns  
fig, axes = plt.subplots(nrows=2, ncols=2, figsize=(6, 3))  
# axes is a numpy array, you can use it like using a list.  
print(axes)  
  
## [[<Axes: > <Axes: >]  
##   [<Axes: > <Axes: >]]
```

```

import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
↪ 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
# Subplots handles add_axes for you
↪ according to the number of rows
↪ and columns
fig, axes = plt.subplots(nrows=2,
↪ ncols=2, figsize=(6, 3))
# axes is a numpy array, you can use
↪ it like using a list.
# print(axes)
axes[0][0].plot(a1, a2)
axes[0][1].plot(a1, a2)
axes[1][0].plot(a2, a1)
axes[1][1].plot(a2, a1)

```



27.1.2.3 color and linestyle

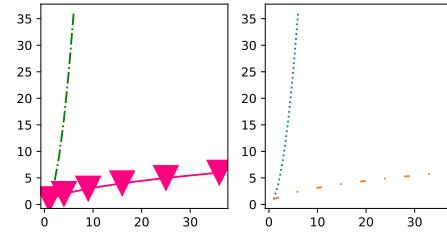
- Color
 - <https://matplotlib.org/stable/tutorials/colors/colors.html>
- line-style (ls)
 - https://matplotlib.org/stable/gallery/lines_bars_and_markers/linestyles.html
- marker
- linewidth (lw)

```

import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
↪ 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
# Subplots handles add_axes for you
↪ according to the number of rows
↪ and columns
fig, axes = plt.subplots(nrows=1,
↪ ncols=2, figsize=(6, 3))
# axes is a numpy array
axes[0].plot(a1, a2, color='green',
↪ linestyle='-.')
axes[0].plot(a2, a1, color=(1, 0,
↪ 0.5), marker='v', markersize=20)
axes[1].plot(a1, a2,
↪ linestyle='dotted')
axes[1].plot(a2, a1, linestyle=(0, (3,
↪ 10, 1, 10)))

```



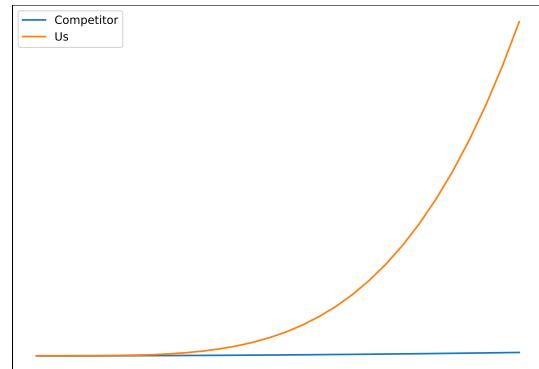
27.1.2.4 other inputs

- NumPy array
- Pandas series

27.1.2.5 legend

```
import matplotlib.pyplot as plt
import numpy as np

x = np.linspace(0, 10, 30)
y = x * x
fig = plt.figure()
ax = fig.add_axes([0, 0, 1, 1])
line1 = ax.plot(x, y,
                 label="Competitor")
line2 = ax.plot(x, y**2, label="Us")
ax.legend()
```



27.1.2.6 customize style

predefined styles

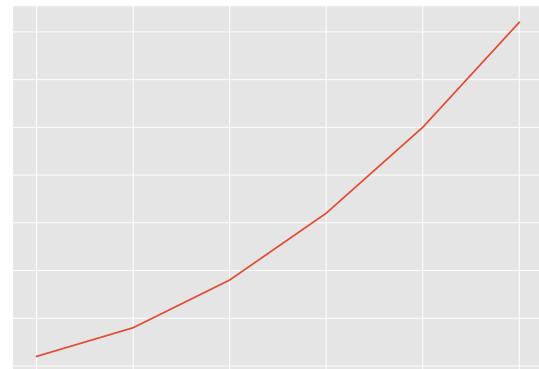
```
import matplotlib.pyplot as plt

print(plt.style.available)

## ['Solarize_Light2', '_classic_test_patch', '_mpl-gallery', '_mpl-gallery-nogrid', 'bmh'
```

```
import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4,
                     # 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure()
plt.style.use('ggplot')
ax = fig.add_axes([0, 0, 1, 1])
ax.plot(a1, a2)
```



restore default style

```
import matplotlib.pyplot as plt

plt.style.use('default') # But strangely enough figure size gets changed still

import matplotlib.pyplot as plt

plt.rcParams["figure.figsize"] = (6, 4)
plt.rcParams["figure.dpi"] = 100
```

27.1.2.7 save to file

`savefig` saves image to file. We also set the `bbox_inches` parameter to `tight` to make sure the image doesn't get out of the image bound.

save to .png

```

import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4, 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure()
ax = fig.add_axes([0, 0, 1, 1])
ax.plot(a1, a2)
fig.savefig('out.png', bbox_inches = 'tight')

```

save to .pdf

```

import matplotlib.pyplot as plt

a1 = list(range(1, 7)) # [1, 2, 3, 4, 5, 6]
a2 = [1, 4, 9, 16, 25, 36]
fig = plt.figure()
ax = fig.add_axes([0, 0, 1, 1])
ax.plot(a1, a2)
fig.savefig('out.pdf', bbox_inches = 'tight')

```

27.1.3 Seaborn

- Kimberly Fessel

- visually explained
- Seaborn
- Matplotlib
- Pandas
- iPyWidgets

- Seaborn

- figure-level plot
- axes-level plot

R or RStudio run Python with installing packages or modules by using `reticulate`, R package and directly using Anaconda `conda` environment for convenience, instead of `virtualenv`

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

```

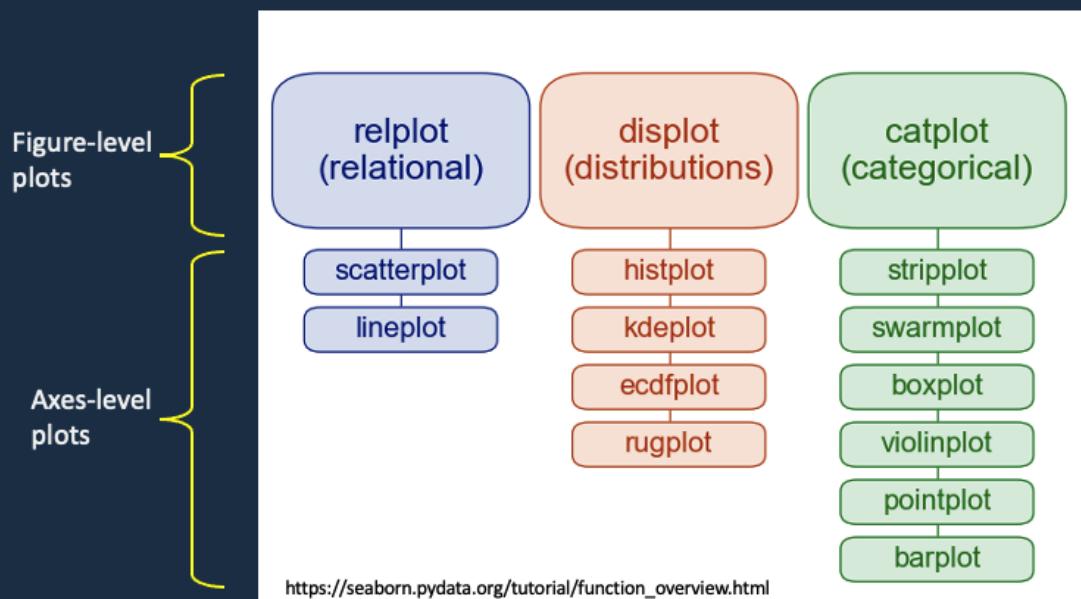
library(reticulate)

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

```

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

Three main type of Seaborn plots



Yes, that correspond to Matplotlib's concept of figure and axes

Figure 27.3: seaborn plot type

```
## 10      sandbox-3.9      D:\\Anaconda3\\envs\\sandbox-3.9/python.exe
use_condaenv(condaenv = 'sandbox-3.9')

## install Seaborn
# conda_install("r-reticulate", "seaborn")

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

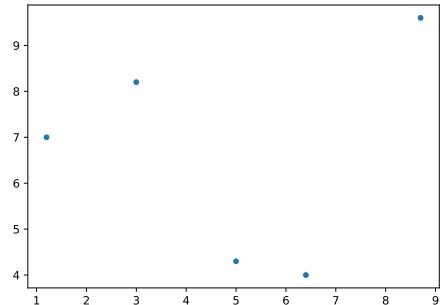
27.1.3.1 basic

```
import matplotlib.pyplot as plt # need it sometimes
import seaborn as sns

sns.set_theme() # set the default theme
```

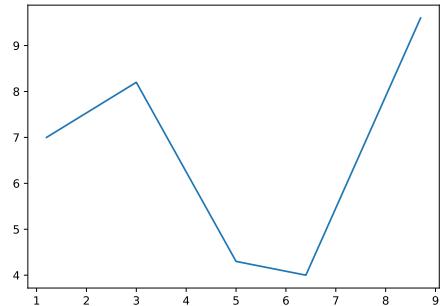
```
import seaborn as sns

x = [3, 5, 1.2, 8.7, 6.4]
y = [8.2, 4.3, 7, 9.6, 4]
sns.scatterplot(x=x, y=y)
```



```
import seaborn as sns

x = [3, 5, 1.2, 8.7, 6.4]
y = [8.2, 4.3, 7, 9.6, 4]
sns.lineplot(x=x, y=y)
```



27.1.3.2 data frame

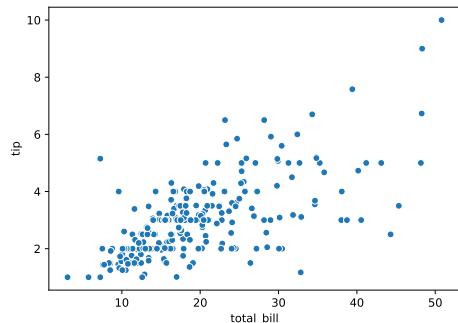
```
sns.load_dataset
```

```
import seaborn as sns
tips = sns.load_dataset("tips")
tips
```

	##	total_bill	tip	sex	smoker	day
## 0	## 0	16.99	1.01	Female	No	Su
## 1	## 1	10.34	1.66	Male	No	Su
## 2	## 2	21.01	3.50	Male	No	Su
## 3	## 3	23.68	3.31	Male	No	Su
## 4	## 4	24.59	3.61	Female	No	Su
## ..	##
## 239	## 239	29.03	5.92	Male	No	Sa
## 240	## 240	27.18	2.00	Female	Yes	Sa
## 241	## 241	22.67	2.00	Male	Yes	Sa
## 242	## 242	17.82	1.75	Male	No	Sa
## 243	## 243	18.78	3.00	Female	No	Thu
##	##	## [244 rows x 7 columns]	##	##	##	##

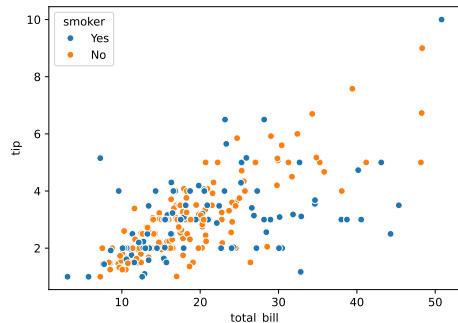
data

```
import seaborn as sns
tips = sns.load_dataset("tips")
sns.scatterplot(data=tips,
                 x='total_bill',
                 y='tip')
```



hue

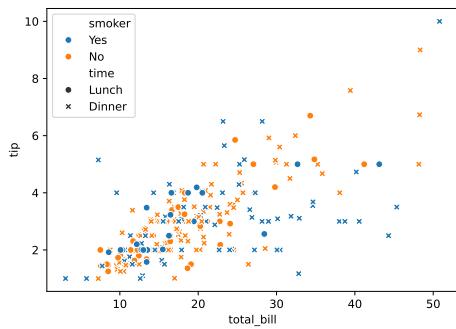
```
import seaborn as sns
tips = sns.load_dataset("tips")
sns.scatterplot(data=tips,
                 x='total_bill',
                 y='tip',
                 hue='smoker')
```



style

```
import seaborn as sns

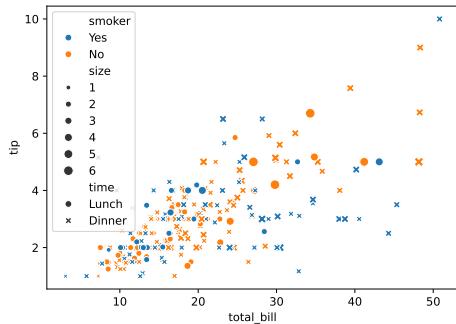
tips = sns.load_dataset("tips")
sns.scatterplot(data=tips,
                 x='total_bill',
                 y='tip',
                 hue='smoker',
                 style='time')
```



size

```
import seaborn as sns

tips = sns.load_dataset("tips")
sns.scatterplot(data=tips,
                 x='total_bill',
                 y='tip',
                 hue='smoker',
                 style='time',
                 size='size')
```



- Legend is covering up the graph, it's getting out of hand. Let's tune the range of x
- `sns.scatterplot()` actually returns something that resembles Matplotlib axis. So we use a Matplotlib axis function:

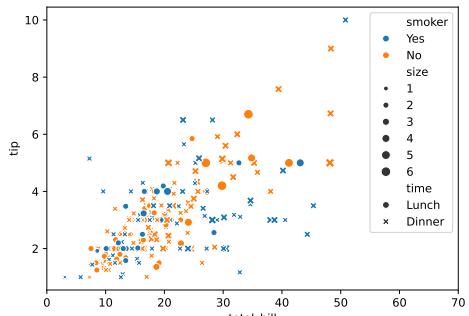
```
ax = sns.scatterplot(...)
```

<https://stackoverflow.com/questions/26597116/seaborn-plots-not-showing-up>

```
import matplotlib.pyplot as plt
import seaborn as sns

tips = sns.load_dataset("tips")
ax = sns.scatterplot(data=tips,
                      x='total_bill',
                      y='tip',
                      hue='smoker',
                      style='time',
                      size='size')
ax.set_xlim((0, 70))
# alternatively:
# ax.set(xlim=(0, 70))
plt.show()
```

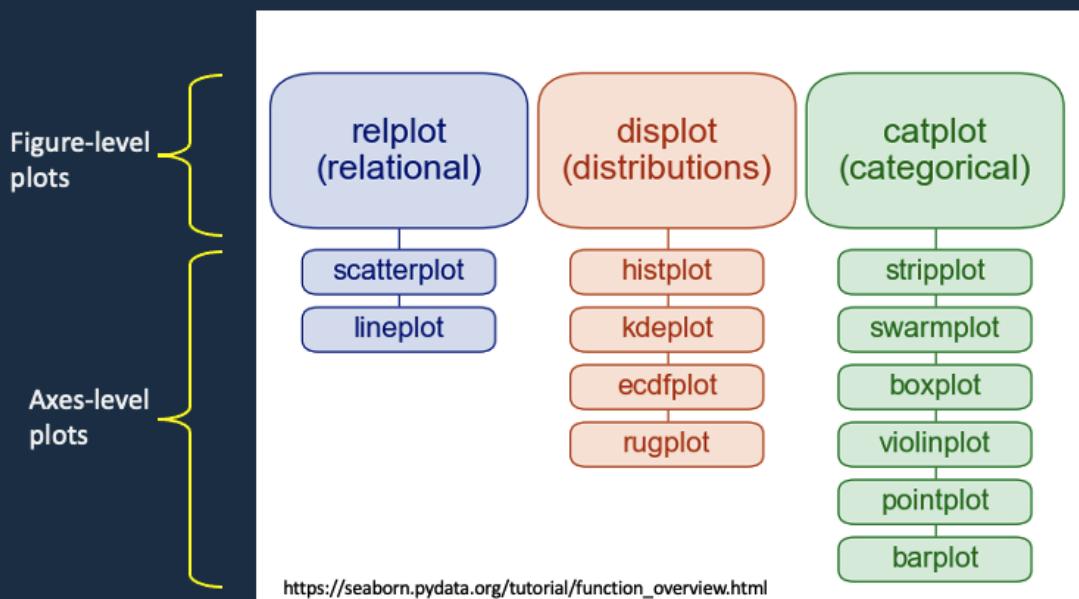
(0.0, 70.0)



27.1.3.3 axis-level plot and figure-level plot

`sns.relpplot`

Three main type of Seaborn plots

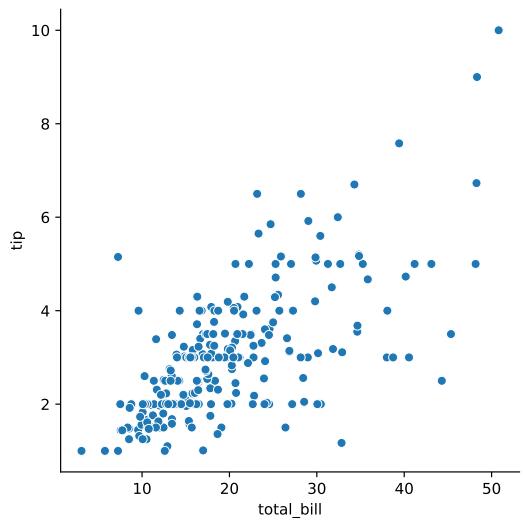


Yes, that correspond to Matplotlib's concept of figure and axes

Figure 27.4: seaborn plot type

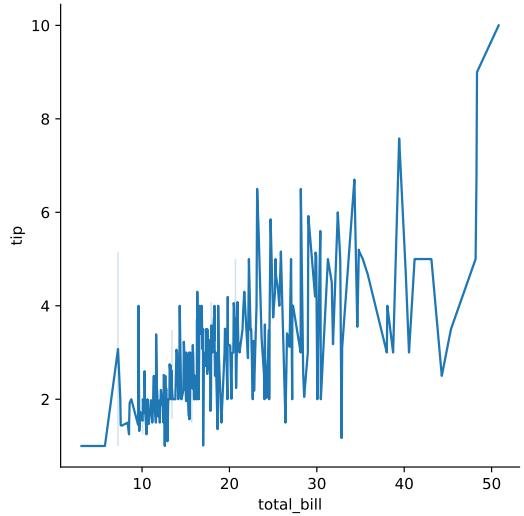
```
import seaborn as sns

tips = sns.load_dataset("tips")
sns.relplot(kind='scatter',
            data=tips,
            x='total_bill',
            y='tip')
```



```
import seaborn as sns

tips = sns.load_dataset("tips")
sns.relplot(kind='line',
            data=tips,
            x='total_bill',
            y='tip')
```



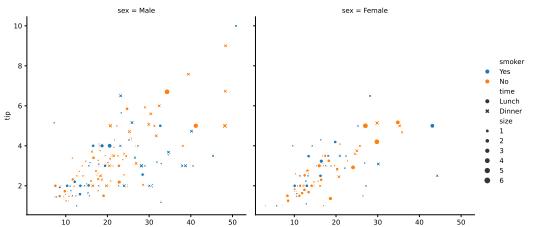
With figure-level plot, we can draw more than one plot (one `axes`).

Here we specify that different `sex` be on different column by specifying `col=sex`.

```
col=sex
```

```
import seaborn as sns

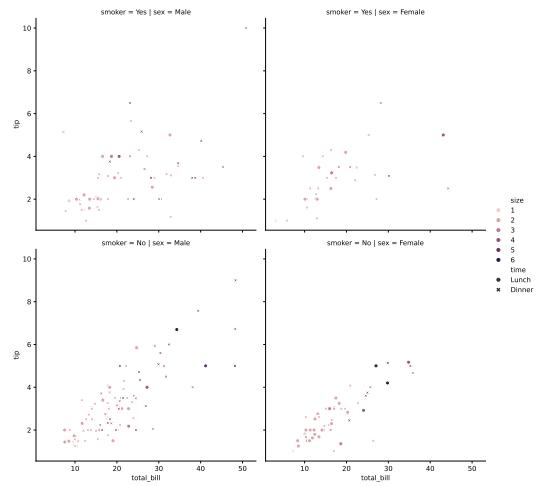
tips = sns.load_dataset("tips")
sns.relplot(kind='scatter',
            data=tips,
            x='total_bill',
            y='tip',
            hue='smoker',
            style='time',
            size='size',
            col='sex')
```



col=sex row=smoker

```
import seaborn as sns

tips = sns.load_dataset("tips")
sns.relplot(kind='scatter',
             data=tips,
             x='total_bill',
             y='tip',
             style='time',
             hue='size',
             row='smoker',
             col='sex')
```



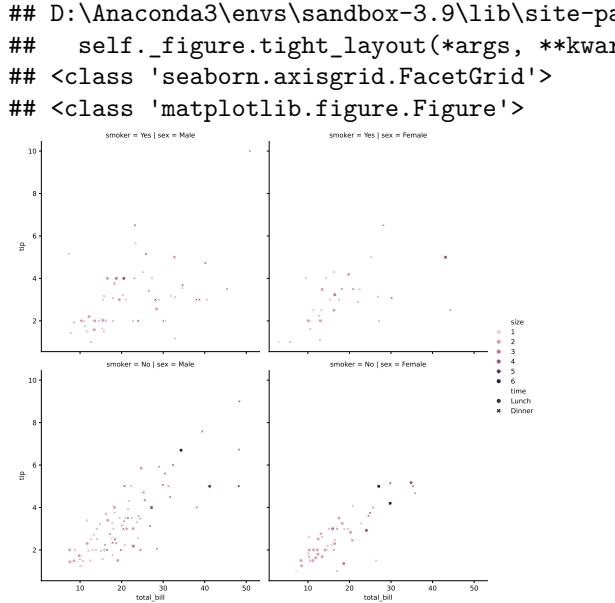
27.1.3.4 accessing figure and axes objects

Recall that Seaborn uses Matplotlib to draw the graphics. So underneath the Seaborn library, you can still access Matplotlib's figure object and axes objects if necessary. The call to figure-level plot returns an object.

```
import seaborn as sns

tips = sns.load_dataset("tips")
g = sns.relplot(kind='scatter',
                 data=tips,
                 x='total_bill',
                 y='tip',
                 style='time',
                 hue='size',
                 row='smoker',
                 col='sex')

print(type(g))
print(type(g.fig)) # g.fig gets you
                    ← the Figure
g.fig
```



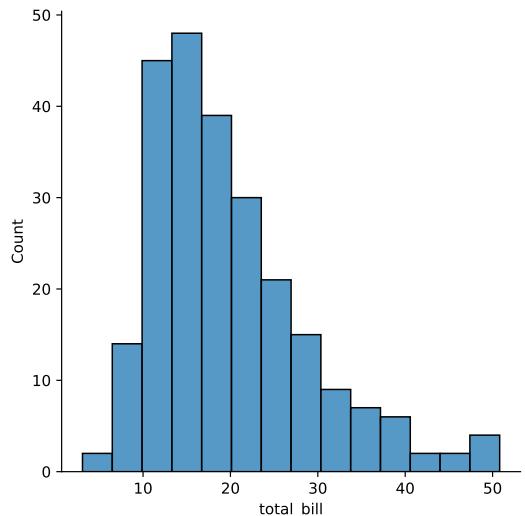
27.1.3.5 distribution plot

```
sns.displot
```

27.1.3.5.1 histogram

```
import seaborn as sns

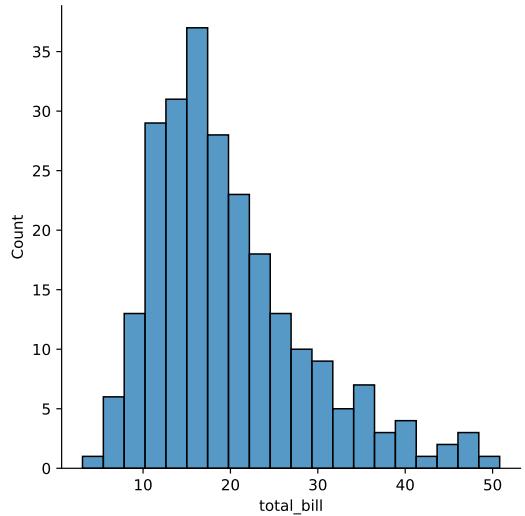
tips = sns.load_dataset("tips")
sns.displot(kind='hist',
            data=tips,
            x='total_bill')
```



bins

```
import seaborn as sns

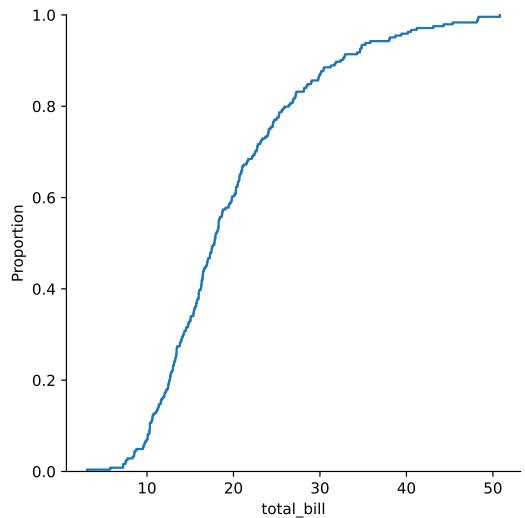
tips = sns.load_dataset("tips")
sns.displot(kind='hist', bins=20,
            data=tips,
            x='total_bill')
```



27.1.3.5.2 ECDF = empirical cumulative distrutive function

```
import seaborn as sns

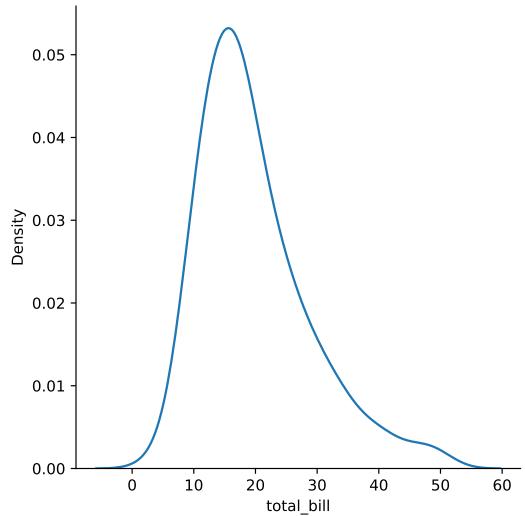
tips = sns.load_dataset("tips")
sns.displot(kind='ecdf',
            data=tips,
            x='total_bill')
```



27.1.3.5.3 KDE = kernel density estimation

```
import seaborn as sns

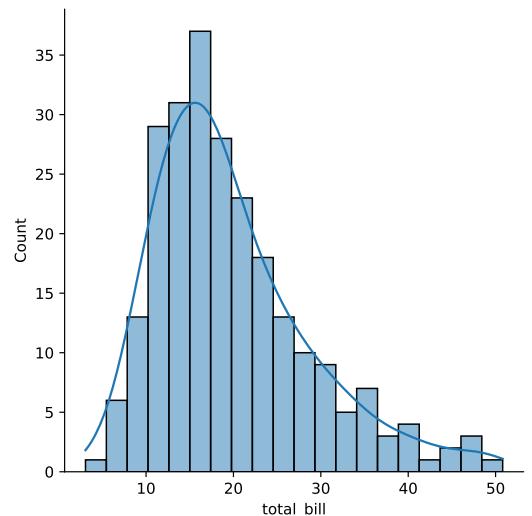
tips = sns.load_dataset("tips")
sns.displot(kind='kde',
            data=tips,
            x='total_bill')
```



histogram with KDE

```
import seaborn as sns

tips = sns.load_dataset("tips")
sns.displot(kind='hist', bins=20,
            kde=True,
            data=tips,
            x='total_bill')
```



```
## '% This file was created with tikzplotlib
```

TikZ / `tikzpicture` with PGFplots `axis` by transforming Matplotlib-based Seaborn plot to .tex via Python package `tikzplotlib`

`xlabel={total_bill}`, changed to `xlabel={total bill}`, without `_` in text

`X ylabel={Count}`, changed to `ylabel={Count}`,: not necessary to be changed, the problem is `_` in xlabel name

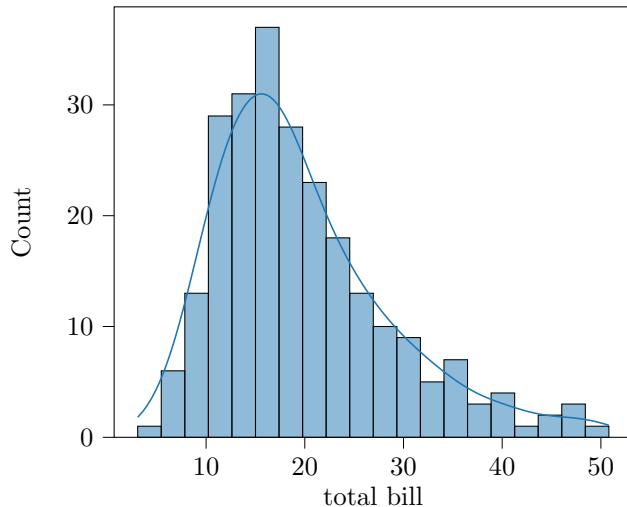
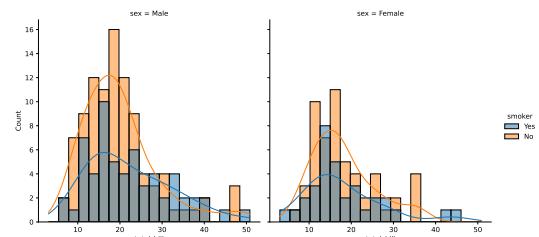


Figure 27.5: `tikzplotlib`

```
import seaborn as sns

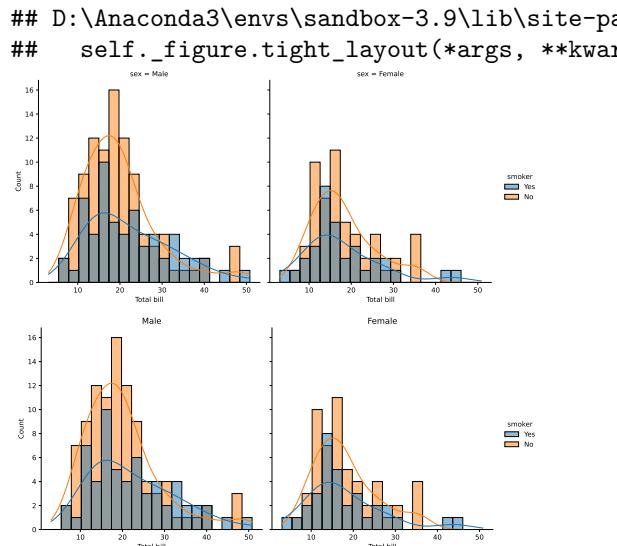
tips = sns.load_dataset("tips")
sns.displot(kind='hist', bins=20,
            kde='true',
            data=tips,
            x='total_bill',
            hue='smoker',
            col='sex'
            )
```



Let's customize the label and title.

```
import seaborn as sns

tips = sns.load_dataset("tips")
g = sns.displot(kind='hist', bins=20,
                 kde='true',
                 data=tips,
                 x='total_bill',
                 hue='smoker',
                 col='sex'
                 )
g.set(xlabel='Total bill')
g.axes[0][0].set(title='Male')
g.axes[0][1].set(title='Female')
g.fig
```

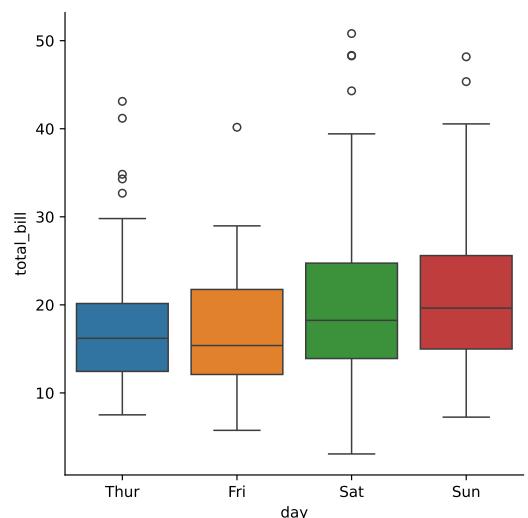


27.1.3.6 categorical plot

`sns.catplot`

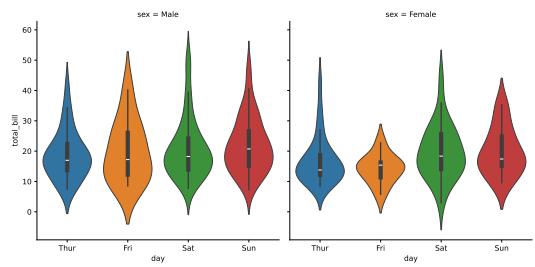
```
import seaborn as sns

tips = sns.load_dataset("tips")
sns.catplot(kind='box',
            data=tips,
            x="day", hue="day",
            y="total_bill"
            )
```



```
import seaborn as sns

tips = sns.load_dataset("tips")
sns.catplot(kind='violin',
            data=tips,
            x="day", hue="day",
            y="total_bill",
            col='sex'
            )
```



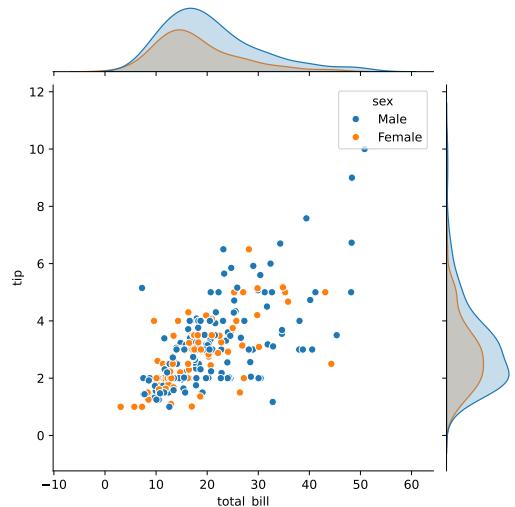
27.1.3.7 joint plot

```
sns.jointplot
```

```
## <seaborn.axisgrid.JointGrid object at 0x0000000000000000>
```

```
import matplotlib.pyplot as plt
import seaborn as sns

tips = sns.load_dataset("tips")
sns.jointplot(data=tips,
               x="total_bill",
               y="tip",
               hue='sex'
               )
plt.show()
```

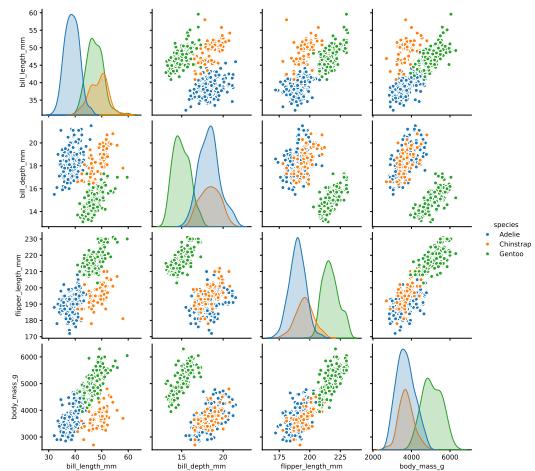


27.1.3.8 pair plot

```
sns.pairplot
```

```
import seaborn as sns

penguins =
    sns.load_dataset("penguins")
sns.pairplot(data=penguins,
             hue='species')
```



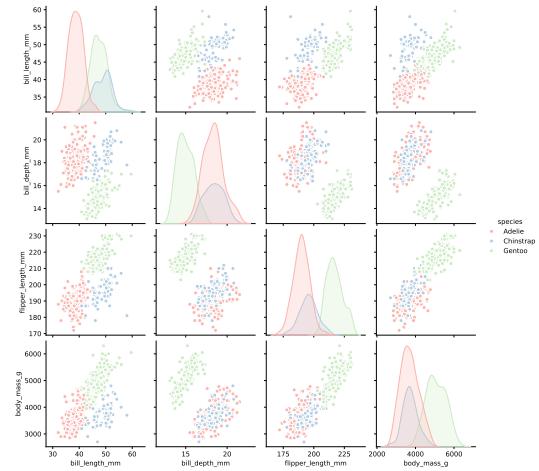
27.1.3.9 palette

Changing the color with Matplotlib's color

A list of color: <https://matplotlib.org/stable/tutorials/colors/colormaps.html>

```
import seaborn as sns

penguins =
    sns.load_dataset("penguins")
sns.pairplot(data=penguins,
             hue='species',
             palette='Pastel1')
```



27.1.3.10 volcano plot

27.1.3.11 heatmap

27.2 export

27.2.1 .svg

<https://stackoverflow.com/questions/24525111/how-can-i-get-the-output-of-a-matplotlib-plot-as-an-svg>

```
import matplotlib.pyplot as plt
import seaborn as sns

penguins = sns.load_dataset("penguins")
sns.pairplot(data=penguins,
             hue='species')

plt.savefig("test.svg")
# plt.savefig("test.svg", dpi=1200)
```

27.2.2 .eps

<https://stackoverflow.com/questions/16183462/saving-images-in-python-at-a-very-high-quality>

The PostScript backend does not support transparency; partially transparent artists will be rendered opaque.

```
import matplotlib.pyplot as plt
import seaborn as sns

penguins = sns.load_dataset("penguins")
sns.pairplot(data=penguins,
```

```
hue='species')

plt.savefig("test.eps")
# plt.savefig("test.eps", dpi=1200)
```


Chapter 28

survival analysis

28.1 Python package `tableone`

28.2 Python package `lifelines`

Chapter 29

Manim

29.1 VSCode extension: Manim Sideview

<https://marketplace.visualstudio.com/items?itemName=Rickaym.manim-sideview>

ffmpeg.exe placed in the same folder with .py

VSCode Ctrl + Shift + P: open Mobject gallery

29.2 installation

<https://docs.manim.community/en/stable/installation.html>

29.2.1 Conda

conda install -c conda-forge manim

29.3 quickstart

<https://docs.manim.community/en/stable/tutorials/quickstart.html>

https://www.w3schools.com/tags/att_video_autoplay.asp

https://www.w3schools.com/tags/att_video_loop.asp

```
from manim import *

class CreateCircle(Scene):
    def construct(self):
        circle = Circle() # create a
        ← circle
        circle.set_fill(PINK,
        ← opacity=0.5) # set the color and
        ← transparency
        self.play(Create(circle)) # 
        → show the circle on screen
```

manim -pql scene.py CreateCircle

Chapter 30

ggplot2

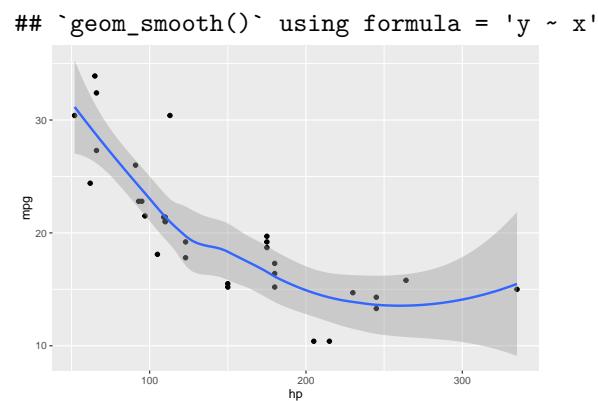
<https://bookdown.org/xiangyun/msg/system.html#chap:system>

Modern Statistical Graphics section 5.1

- <https://www.rdocumentation.org/> to search function
- ggplot2
 - <https://ggplot2.tidyverse.org/index.html> to search ggplot2 function
 - panel = layer
 - * geom = geometric objects / geometry = element
 - element
 - * statistic
 - * scale
 - * coordinate system
 - * facet

```
library(ggplot2)

p <- ggplot(aes(x = hp, y = mpg), data
  = mtcars) +
  geom_point() # layer of scatterplot
p + geom_smooth(method = "loess") #  
  add layer of smooth
```

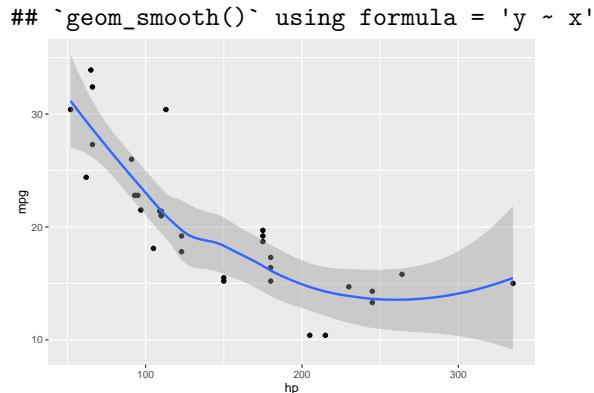


30.1 geom

<https://bookdown.org/xiangyun/msg/system.html#section-13>

```
library(ggplot2)

ggplot(aes(x = hp, y = mpg), data =
  mtcars) +
  geom_point() +
  geom_smooth(method = "loess")
```



points https://ggplot2.tidyverse.org/reference/geom_point.html?q=geom_point#null

geom_point

smoothed conditional means https://ggplot2.tidyverse.org/reference/geom_smooth.html?q=geom_sm#null

Aids the eye in seeing patterns in the presence of overplotting. **geom_smooth()** and **stat_smooth()** are effectively aliases: they both use the same arguments. Use **stat_smooth()** if you want to display the results with a non-standard geom.

geom_smooth

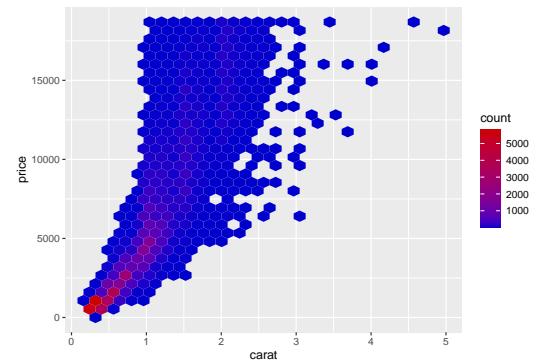
stat_smooth

method Smoothing method (function) to use, accepts either NULL or a character vector, e.g. "lm", "glm", "gam", "loess" or a function, e.g. MASS::rlm or mgcv::gam, **stats::lm**, or **stats::loess**. "auto" is also accepted for backwards compatibility. It is equivalent to NULL.

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

```
library(ggplot2)

ggplot(aes(x = carat, y = price), data
  = diamonds) +
  geom_hex() +
  scale_fill_gradient(low = "blue3",
  high = "red3")
```

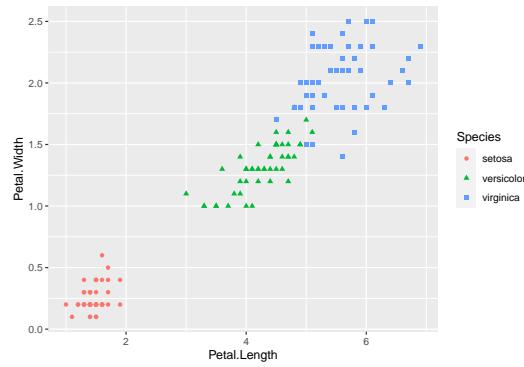


gradient color scales https://ggplot2.tidyverse.org/reference/scale_gradient.html?q=scale_fill_gradie#ref-usage

https://ggplot2.tidyverse.org/reference/scale_gradient.html?q=scale_fill_gradient#ref-examples

```
library(ggplot2)

ggplot(aes(x = Petal.Length, y =
  Petal.Width), data = iris) +
  geom_point(aes(color = Species,
    shape = Species))
```



basic plot system

<https://bookdown.org/xiangyun/msg/elements.html#sec:points>

```
# iris species converted to type
# integer 1, 2, 3 for further using
# vectors
idx <- as.integer(iris[["Species"]])
plot(iris[, 3:4],
  pch = c(24, 21, 25)[idx],
  col = c("black", "red",
    "blue")[idx], panel.first =
  grid())
)
legend("topleft",
  legend = levels(iris[["Species"]]),
  col = c("black", "red", "blue"), pch
  = c(24, 21, 25), bty = "n"
)
```

plot <https://www.rdocumentation.org/packages/graphics/versions/3.6.2/topics/plot.default>

pch a vector of **plotting characters** or symbols: see **points**.

col The **colors** for lines and points. Multiple colors can be specified so that each point can be given its own color. If there are fewer colors than points they are recycled in the standard fashion. Lines will all be plotted in the first colour specified.

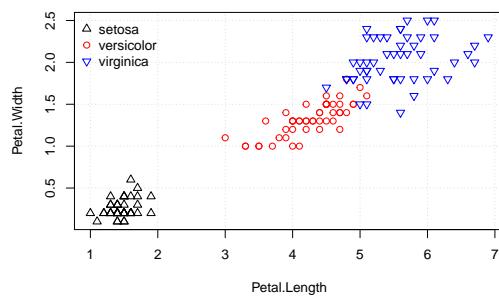
panel.first an ‘expression’ to be evaluated after the plot axes are set up but before any plotting takes place. This can be useful for drawing **background grids** or **scatterplot smooths**. Note that this works by lazy evaluation: passing this argument from other plot methods may well not work since it may be evaluated too early.

legend <https://www.rdocumentation.org/packages/graphics/versions/3.6.2/topics/legend>

bty the **type of box** to be drawn around the legend. The allowed values are “o” (the default) and “n”.

<https://stackoverflow.com/questions/10108073/plot-legends-without-border-and-with-white-background>

Use option **bty = "n"** in legend to remove the box around the legend.



legend a character or expression vector of length ≥ 1 to appear in the legend. Other objects will be coerced by [as.graphicsAnnot](#)

30.1.1 basic plot system decomposition

```
##      Sepal.Length Sepal.Width Petal.Length  
## 1          5.1       3.5      1.4  
## 2          4.9       3.0      1.4  
## 3          4.7       3.2      1.3  
## 4          4.6       3.1      1.5  
## 5          5.0       3.6      1.4  
## 6          5.4       3.9      1.7  
## 7          4.6       3.4      1.4  
## 8          5.0       3.4      1.5  
## 9          4.4       2.9      1.4  
## 10         4.9       3.1      1.5  
## 11         5.4       3.7      1.5  
## 12         4.8       3.4      1.6  
## 13         4.8       3.0      1.4  
## 14         4.3       3.0      1.1  
## 15         5.8       4.0      1.2  
## 16         5.7       4.4      1.5  
## 17         5.4       3.9      1.3  
## 18         5.1       3.5      1.4  
## 19         5.7       3.8      1.7  
## 20         5.1       3.8      1.5  
## 21         5.4       3.4      1.7  
## 22         5.1       3.7      1.5  
## 23         4.6       3.6      1.0  
## 24         5.1       3.3      1.7  
## 25         4.8       3.4      1.9  
## 26         5.0       3.0      1.6  
## 27         5.0       3.4      1.6  
## 28         5.2       3.5      1.5  
## 29         5.2       3.4      1.4  
## 30         4.7       3.2      1.6  
## 31         4.8       3.1      1.6  
## 32         5.4       3.4      1.5  
## 33         5.2       4.1      1.5  
## 34         5.5       4.2      1.4  
## 35         4.9       3.1      1.5  
## 36         5.0       3.2      1.2  
## 37         5.5       3.5      1.3  
## 38         4.9       3.6      1.4  
## 39         4.4       3.0      1.3  
## 40         5.1       3.4      1.5  
## 41         5.0       3.5      1.3  
## 42         4.5       2.3      1.3  
## 43         4.4       3.2      1.3  
## 44         5.0       3.5      1.6  
## 45         5.1       3.8      1.9  
## 46         4.8       3.0      1.4  
## 47         5.1       3.8      1.6  
## 48         4.6       3.2      1.4  
## 49         5.3       3.7      1.5  
## 50         5.0       3.3      1.4  
## 51         7.0       3.2      4.7  
## 52         6.4       3.2      4.5  
## 53         6.9       3.1      4.9  
## 54         5.5       3.0      4.6  
## 55         6.9       3.1      4.8  
## 56         5.4       3.4      4.5  
## 57         6.5       3.0      4.9  
## 58         5.7       3.5      4.2  
## 59         5.5       4.2      1.5  
## 60         4.9       3.0      1.4  
## 61         6.6       3.6      4.4  
## 62         5.0       3.4      4.0  
## 63         5.7       3.8      4.4  
## 64         5.4       3.9      4.5  
## 65         5.0       3.4      4.0  
## 66         5.4       3.9      4.5  
## 67         5.5       4.1      4.0  
## 68         4.9       3.1      1.3  
## 69         6.5       3.0      4.9  
## 70         5.0       3.3      4.3  
## 71         5.9       3.4      4.8  
## 72         5.2       3.5      4.7  
## 73         5.5       4.2      4.0  
## 74         4.9       3.0      1.4  
## 75         6.2       3.4      4.5  
## 76         5.1       3.7      4.3  
## 77         5.7       3.8      4.4  
## 78         5.4       4.3      4.5  
## 79         5.0       3.3      4.0  
## 80         5.5       4.2      4.9  
## 81         5.1       3.6      4.3  
## 82         5.9       3.9      4.8  
## 83         5.4       4.5      4.5  
## 84         4.9       3.0      1.4  
## 85         6.3       3.3      4.9  
## 86         5.0       3.4      4.4  
## 87         5.8       3.5      4.5  
## 88         5.4       3.9      4.5  
## 89         5.0       3.4      4.0  
## 90         5.5       4.2      4.9  
## 91         5.1       3.6      4.3  
## 92         5.9       3.9      4.8  
## 93         5.4       4.5      4.5  
## 94         4.9       3.0      1.4  
## 95         6.4       3.4      5.0  
## 96         5.0       3.4      4.5  
## 97         5.8       3.5      4.6  
## 98         5.4       3.9      4.6  
## 99         5.0       3.4      4.0  
## 100        5.5       4.2      4.9  
## 101        5.1       3.6      4.3  
## 102        5.9       3.9      4.8  
## 103        5.4       4.5      4.5  
## 104        4.9       3.0      1.4  
## 105        6.5       3.3      5.1  
## 106        5.0       3.4      4.6  
## 107        5.8       3.5      4.7  
## 108        5.4       3.9      4.7  
## 109        5.0       3.4      4.0  
## 110        5.5       4.2      4.9  
## 111        5.1       3.6      4.3  
## 112        5.9       3.9      4.8  
## 113        5.4       4.5      4.5  
## 114        4.9       3.0      1.4  
## 115        6.6       3.4      5.2  
## 116        5.0       3.4      4.7  
## 117        5.8       3.5      4.8  
## 118        5.4       3.9      4.8  
## 119        5.0       3.4      4.0  
## 120        5.5       4.2      4.9  
## 121        5.1       3.6      4.3  
## 122        5.9       3.9      4.8  
## 123        5.4       4.5      4.5  
## 124        4.9       3.0      1.4  
## 125        6.7       3.3      5.3  
## 126        5.0       3.4      4.8  
## 127        5.8       3.5      4.9  
## 128        5.4       3.9      4.9  
## 129        5.0       3.4      4.0  
## 130        5.5       4.2      4.9  
## 131        5.1       3.6      4.3  
## 132        5.9       3.9      4.8  
## 133        5.4       4.5      4.5  
## 134        4.9       3.0      1.4  
## 135        6.8       3.3      5.4  
## 136        5.0       3.4      4.9  
## 137        5.8       3.5      5.0  
## 138        5.4       3.9      4.9  
## 139        5.0       3.4      4.0  
## 140        5.5       4.2      4.9  
## 141        5.1       3.6      4.3  
## 142        5.9       3.9      4.8  
## 143        5.4       4.5      4.5  
## 144        4.9       3.0      1.4  
## 145        6.9       3.3      5.5  
## 146        5.0       3.4      5.0  
## 147        5.8       3.5      5.0  
## 148        5.4       3.9      5.0  
## 149        5.0       3.4      4.0  
## 150        5.5       4.2      4.9  
## 151        5.1       3.6      4.3  
## 152        5.9       3.9      4.8  
## 153        5.4       4.5      4.5  
## 154        4.9       3.0      1.4  
## 155        7.0       3.3      5.6  
## 156        5.0       3.4      5.1  
## 157        5.8       3.5      5.1  
## 158        5.4       3.9      5.1  
## 159        5.0       3.4      4.0  
## 160        5.5       4.2      4.9  
## 161        5.1       3.6      4.3  
## 162        5.9       3.9      4.8  
## 163        5.4       4.5      4.5  
## 164        4.9       3.0      1.4  
## 165        7.1       3.3      5.7  
## 166        5.0       3.4      5.2  
## 167        5.8       3.5      5.2  
## 168        5.4       3.9      5.2  
## 169        5.0       3.4      4.0  
## 170        5.5       4.2      4.9  
## 171        5.1       3.6      4.3  
## 172        5.9       3.9      4.8  
## 173        5.4       4.5      4.5  
## 174        4.9       3.0      1.4  
## 175        7.2       3.3      5.8  
## 176        5.0       3.4      5.3  
## 177        5.8       3.5      5.3  
## 178        5.4       3.9      5.3  
## 179        5.0       3.4      4.0  
## 180        5.5       4.2      4.9  
## 181        5.1       3.6      4.3  
## 182        5.9       3.9      4.8  
## 183        5.4       4.5      4.5  
## 184        4.9       3.0      1.4  
## 185        7.3       3.3      5.9  
## 186        5.0       3.4      5.4  
## 187        5.8       3.5      5.4  
## 188        5.4       3.9      5.4  
## 189        5.0       3.4      4.0  
## 190        5.5       4.2      4.9  
## 191        5.1       3.6      4.3  
## 192        5.9       3.9      4.8  
## 193        5.4       4.5      4.5  
## 194        4.9       3.0      1.4  
## 195        7.4       3.3      6.0  
## 196        5.0       3.4      5.5  
## 197        5.8       3.5      5.5  
## 198        5.4       3.9      5.5  
## 199        5.0       3.4      4.0  
## 200        5.5       4.2      4.9  
## 201        5.1       3.6      4.3  
## 202        5.9       3.9      4.8  
## 203        5.4       4.5      4.5  
## 204        4.9       3.0      1.4  
## 205        7.5       3.3      6.1  
## 206        5.0       3.4      5.6  
## 207        5.8       3.5      5.6  
## 208        5.4       3.9      5.6  
## 209        5.0       3.4      4.0  
## 210        5.5       4.2      4.9  
## 211        5.1       3.6      4.3  
## 212        5.9       3.9      4.8  
## 213        5.4       4.5      4.5  
## 214        4.9       3.0      1.4  
## 215        7.6       3.3      6.2  
## 216        5.0       3.4      5.7  
## 217        5.8       3.5      5.7  
## 218        5.4       3.9      5.7  
## 219        5.0       3.4      4.0  
## 220        5.5       4.2      4.9  
## 221        5.1       3.6      4.3  
## 222        5.9       3.9      4.8  
## 223        5.4       4.5      4.5  
## 224        4.9       3.0      1.4  
## 225        7.7       3.3      6.3  
## 226        5.0       3.4      5.8  
## 227        5.8       3.5      5.8  
## 228        5.4       3.9      5.8  
## 229        5.0       3.4      4.0  
## 230        5.5       4.2      4.9  
## 231        5.1       3.6      4.3  
## 232        5.9       3.9      4.8  
## 233        5.4       4.5      4.5  
## 234        4.9       3.0      1.4  
## 235        7.8       3.3      6.4  
## 236        5.0       3.4      5.9  
## 237        5.8       3.5      5.9  
## 238        5.4       3.9      5.9  
## 239        5.0       3.4      4.0  
## 240        5.5       4.2      4.9  
## 241        5.1       3.6      4.3  
## 242        5.9       3.9      4.8  
## 243        5.4       4.5      4.5  
## 244        4.9       3.0      1.4  
## 245        7.9       3.3      6.5  
## 246        5.0       3.4      6.0  
## 247        5.8       3.5      6.0  
## 248        5.4       3.9      6.0  
## 249        5.0       3.4      4.0  
## 250        5.5       4.2      4.9  
## 251        5.1       3.6      4.3  
## 252        5.9       3.9      4.8  
## 253        5.4       4.5      4.5  
## 254        4.9       3.0      1.4  
## 255        8.0       3.3      6.6  
## 256        5.0       3.4      6.1  
## 257        5.8       3.5      6.1  
## 258        5.4       3.9      6.1  
## 259        5.0       3.4      4.0  
## 260        5.5       4.2      4.9  
## 261        5.1       3.6      4.3  
## 262        5.9       3.9      4.8  
## 263        5.4       4.5      4.5  
## 264        4.9       3.0      1.4  
## 265        8.1       3.3      6.7  
## 266        5.0       3.4      6.2  
## 267        5.8       3.5      6.2  
## 268        5.4       3.9      6.2  
## 269        5.0       3.4      4.0  
## 270        5.5       4.2      4.9  
## 271        5.1       3.6      4.3  
## 272        5.9       3.9      4.8  
## 273        5.4       4.5      4.5  
## 274        4.9       3.0      1.4  
## 275        8.2       3.3      6.8  
## 276        5.0       3.4      6.3  
## 277        5.8       3.5      6.3  
## 278        5.4       3.9      6.3  
## 279        5.0       3.4      4.0  
## 280        5.5       4.2      4.9  
## 281        5.1       3.6      4.3  
## 282        5.9       3.9      4.8  
## 283        5.4       4.5      4.5  
## 284        4.9       3.0      1.4  
## 285        8.3       3.3      6.9  
## 286        5.0       3.4      6.4  
## 287        5.8       3.5      6.4  
## 288        5.4       3.9      6.4  
## 289        5.0       3.4      4.0  
## 290        5.5       4.2      4.9  
## 291        5.1       3.6      4.3  
## 292        5.9       3.9      4.8  
## 293        5.4       4.5      4.5  
## 294        4.9       3.0      1.4  
## 295        8.4       3.3      7.0  
## 296        5.0       3.4      6.5  
## 297        5.8       3.5      6.5  
## 298        5.4       3.9      6.5  
## 299        5.0       3.4      4.0  
## 300        5.5       4.2      4.9  
## 301        5.1       3.6      4.3  
## 302        5.9       3.9      4.8  
## 303        5.4       4.5      4.5  
## 304        4.9       3.0      1.4  
## 305        8.5       3.3      7.1  
## 306        5.0       3.4      6.6  
## 307        5.8       3.5      6.6  
## 308        5.4       3.9      6.6  
## 309        5.0       3.4      4.0  
## 310        5.5       4.2      4.9  
## 311        5.1       3.6      4.3  
## 312        5.9       3.9      4.8  
## 313        5.4       4.5      4.5  
## 314        4.9       3.0      1.4  
## 315        8.6       3.3      7.2  
## 316        5.0       3.4      6.7  
## 317        5.8       3.5      6.7  
## 318        5.4       3.9      6.7  
## 319        5.0       3.4      4.0  
## 320        5.5       4.2      4.9  
## 321        5.1       3.6      4.3  
## 322        5.9       3.9      4.8  
## 323        5.4       4.5      4.5  
## 324        4.9       3.0      1.4  
## 325        8.7       3.3      7.3  
## 326        5.0       3.4      6.8  
## 327        5.8       3.5      6.8  
## 328        5.4       3.9      6.8  
## 329        5.0       3.4      4.0  
## 330        5.5       4.2      4.9  
## 331        5.1       3.6      4.3  
## 332        5.9       3.9      4.8  
## 333        5.4       4.5      4.5  
## 334        4.9       3.0      1.4  
## 335        8.8       3.3      7.4  
## 336        5.0       3.4      6.9  
## 337        5.8       3.5      6.9  
## 338        5.4       3.9      6.9  
## 339        5.0       3.4      4.0  
## 340        5.5       4.2      4.9  
## 341        5.1       3.6      4.3  
## 342        5.9       3.9      4.8  
## 343        5.4       4.5      4.5  
## 344        4.9       3.0      1.4  
## 345        8.9       3.3      7.5  
## 346        5.0       3.4      7.0  
## 347        5.8       3.5      7.0  
## 348        5.4       3.9      7.0  
## 349        5.0       3.4      4.0  
## 350        5.5       4.2      4.9  
## 351        5.1       3.6      4.3  
## 352        5.9       3.9      4.8  
## 353        5.4       4.5      4.5  
## 354        4.9       3.0      1.4  
## 355        9.0       3.3      7.6  
## 356        5.0       3.4      7.1  
## 357        5.8       3.5      7.1  
## 358        5.4       3.9      7.1  
## 359        5.0       3.4      4.0  
## 360        5.5       4.2      4.9  
## 361        5.1       3.6      4.3  
## 362        5.9       3.9      4.8  
## 363        5.4       4.5      4.5  
## 364        4.9       3.0      1.4  
## 365        9.1       3.3      7.7  
## 366        5.0       3.4      7.2  
## 367        5.8       3.5      7.2  
## 368        5.4       3.9      7.2  
## 369        5.0       3.4      4.0  
## 370        5.5       4.2      4.9  
## 371        5.1       3.6      4.3  
## 372        5.9       3.9      4.8  
## 373        5.4       4.5      4.5  
## 374        4.9       3.0      1.4  
## 375        9.2       3.3      7.8  
## 376        5.0       3.4      7.3  
## 377        5.8       3.5      7.3  
## 378        5.4       3.9      7.3  
## 379        5.0       3.4      4.0  
## 380        5.5       4.2      4.9  
## 381        5.1       3.6      4.3  
## 382        5.9       3.9      4.8  
## 383        5.4       4.5      4.5  
## 384        4.9       3.0      1.4  
## 385        9.3       3.3      7.9  
## 386        5.0       3.4      7.4  
## 387        5.8       3.5      7.4  
## 388        5.4       3.9      7.4  
## 389        5.0       3.4      4.0  
## 390        5.5       4.2      4.9  
## 391        5.1       3.6      4.3  
## 392        5.9       3.9      4.8  
## 393        5.4       4.5      4.5  
## 394        4.9       3.0      1.4  
## 395        9.4       3.3      8.0  
## 396        5.0       3.4      7.5  
## 397        5.8       3.5      7.5  
## 398        5.4       3.9      7.5  
## 399        5.0       3.4      4.0  
## 400        5.5       4.2      4.9  
## 401        5.1       3.6      4.3  
## 402        5.9       3.9      4.8  
## 403        5.4       4.5      4.5  
## 404        4.9       3.0      1.4  
## 405        9.5       3.3      8.1  
## 406        5.0       3.4      7.6  
## 407        5.8       3.5      7.6  
## 408        5.4       3.9      7.6  
## 409        5.0       3.4      4.0  
## 410        5.5       4.2      4.9  
## 411        5.1       3.6      4.3  
## 412        5.9       3.9      4.8  
## 413        5.4       4.5      4.5  
## 414        4.9       3.0      1.4  
## 415        9.6       3.3      8.2  
## 416        5.0       3.4      7.7  
## 417        5.8       3.5      7.7  
## 418        5.4       3.9      7.7  
## 419        5.0       3.4      4.0  
## 420        5.5       4.2      4.9  
## 421        5.1       3.6      4.3  
## 422        5.9       3.9      4.8  
## 423        5.4       4.5      4.5  
## 424        4.9       3.0      1.4  
## 425        9.7       3.3      8.3  
## 426        5.0       3.4      7.8  
## 427        5.8       3.5      7.8  
## 428        5.4       3.9      7.8  
## 429        5.0       3.4      4.0  
## 430        5.5       4.2      4.9  
## 431        5.1       3.6      4.3  
## 432        5.9       3.9      4.8  
## 433        5.4       4.5      4.5  
## 434        4.9       3.0      1.4  
## 435        9.8       3.3      8.4  
## 436        5.0       3.4      7.9  
## 437        5.8       3.5      7.9  
## 438        5.4       3.9      7.9  
## 439        5.0       3.4      4.0  
## 440        5.5       4.2      4.9  
## 441        5.1       3.6      4.3  
## 442        5.9       3.9      4.8  
## 443        5.4       4.5      4.5  
## 444        4.9       3.0      1.4  
## 445        9.9       3.3      8.5  
## 446        5.0       3.4      8.0  
## 447        5.8       3.5      8.0  
## 448        5.4       3.9      8.0  
## 449        5.0       3.4      4.0  
## 450        5.5       4.2      4.9  
## 451        5.1       3.6      4.3  
## 452        5.9       3.9      4.8  
## 453        5.4       4.5      4.5  
## 454        4.9       3.0      1.4  
## 455        10.0       3.3      8.6  
## 456        5.0       3.4      8.1  
## 457        5.8       3.5      8.1  
## 458        5.4       3.9      8.1  
## 459        5.0       3.4      4.0  
## 460        5.5       4.2      4.9  
## 461        5.1       3.6      4.3  
## 462        5.9       3.9      4.8  
## 463        5.4       4.5      4.5  
## 464        4.9       3.0      1.4  
## 465        10.1       3.3      8.7  
## 466        5.0       3.4      8.2  
## 467        5.8       3.5      8.2  
## 468        5.4       3.9      8.2  
## 469        5.0       3.4      4.0  
## 470        5.5       4.2      4.9  
## 471        5.1       3.6      4.3  
## 472        5.9       3.9      4.8  
## 473        5.4       4.5      4.5  
## 474        4.9       3.0      1.4  
## 475        10.2       3.3      8.8  
## 476        5.0       3.4      8.3  
## 477        5.8       3.5      8.3  
## 478        5.4       3.9      8.3  
## 479        5.0       3.4      4.0  
## 480        5.5       4.2      4.9  
## 481        5.1       3.6      4.3  
## 482        5.9       3.9      4.8  
## 483        5.4       4.5      4.5  
## 484        4.9       3.0      1.4  
## 485        10.3       3.3      8.9  
## 486        5.0       3.4      8.4  
## 487        5.8       3.5      8.4  
## 488        5.4       3.9      8.4  
## 489        5.0       3.4      4.0  
## 490        5.5       4.2      4.9  
## 491        5.1       3.6      4.3  
## 492        5.9       3.9      4.8  
## 493        5.4       4.5      4.5  
## 494        4.9       3.0      1.4  
## 495        10.4       3.3      9.0  
## 496        5.0       3.4      8.5  
## 497        5.8       3.5      8.5  
## 498        5.4       3.9      8.5  
## 499        5.0       3.4      4.0  
## 500        5.5       4.2      4.9  
## 501        5.1       3.6      4.3  
## 502        5.9       3.9      4.8  
## 503        5.4       4.5      4.5  
## 504        4.9       3.0      1.4  
## 505        10.5       3.3      9.1  
## 506        5.0       3.4      8.6  
## 507        5.8       3.5      8.6  
## 508        5.4       3.9      8.6  
## 509        5.0       3.4      4.0  
## 510        5.5       4.2      4.9  
## 511        5.1       3.6      4.3  
## 512        5.9       3.9      4.8  
## 513        5.4       4.5      4.5  
## 514        4.9       3.0      1.4  
## 515        10.6       3.3      9.2  
## 516        5.0       3.4      8.7  
## 517        5.8       3.5      8.7  
## 518        5.4       3.9      8.7  
## 519        5.0       3.4      4.0  
## 520        5.5       4.2      4.9  
## 521        5.1       3.6      4.3  
## 522        5.9       3.9      4.8  
## 523        5.4       4.5      4.5  
## 524        4.9       3.0      1.4  
## 525        10.7       3.3      9.3  
## 526        5.0       3.4      8.8  
## 527        5.8       3.5      8.8  
## 528        5.4       3.9      8.8  
## 529        5.0       3.4      4.0  
## 530        5.5       4.2      4.9  
## 531        5.1       3.6      4.3  
## 532        5.9       3.9      4.8  
## 533        5.4       4.5      4.5  
## 534        4.9       3.0      1.4  
## 535        10.8       3.3      9.4  
## 536        5.0       3.4      8.9  
## 537        5.8       3.5      8.9  
## 538        5.4       3.9      8.9  
## 539        5.0       3.4      4.0  
## 540        5.5       4.2      4.9  
## 541        5.1       3.6      4.3  
## 542        5.9       3.9      4.8  
## 543        5.4       4.5      4.5  
## 544        4.9       3.0      1.4  
## 545        10.9       3.3      9.5  
## 546        5.0       3.4      9.0  
## 547        5.8       3.5      9.0  
## 548        5.4       3.9      9.0  
## 549        5.0       3.4      4.0  
## 550        5.5       4.2      4.9  
## 551        5.1       3.6      4.3  
## 552        5.9       3.9      4.8  
## 553        5.4       4.5      4.5  
## 554        4.9       3.0      1.4  
## 555        11.0       3.3      9.6  
## 556        5.0       3.4      9.1  
## 557        5.8       3.5      9.1  
## 558        5.4       3.9      9.1  
## 559        5.0       3.4      4.0  
## 560        5.5       4.2      4.9  
## 561        
```

```
iris$Species
```

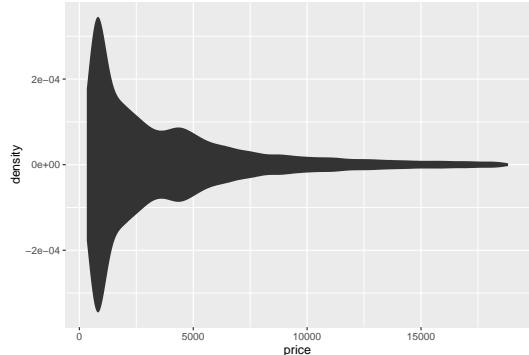
```
## [1] setosa      setosa      setosa      setosa      se
## [7] setosa      setosa      setosa      setosa      se
## [13] setosa     setosa      setosa      setosa      se
## [19] setosa     setosa      setosa      setosa      se
## [25] setosa     setosa      setosa      setosa      se
## [31] setosa     setosa      setosa      setosa      se
## [37] setosa     setosa      setosa      setosa      se
## [43] setosa     setosa      setosa      setosa      se
## [49] setosa     setosa      setosa      versicolor ve
## [55] versicolor versicolor versicolor versicolor ve
## [61] versicolor versicolor versicolor versicolor ve
## [67] versicolor versicolor versicolor versicolor ve
## [73] versicolor versicolor versicolor versicolor ve
## [79] versicolor versicolor versicolor versicolor ve
## [85] versicolor versicolor versicolor versicolor ve
## [91] versicolor versicolor versicolor versicolor ve
## [97] versicolor versicolor versicolor versicolor ve
## [103] virginica virginica virginica virginica vi
## [109] virginica virginica virginica virginica vi
## [115] virginica virginica virginica virginica vi
## [121] virginica virginica virginica virginica vi
## [127] virginica virginica virginica virginica vi
## [133] virginica virginica virginica virginica vi
## [139] virginica virginica virginica virginica vi
## [145] virginica virginica virginica virginica vi
## Levels: setosa versicolor virginica
```

30.2 statistic

```
library(ggplot2)

ggplot(diamonds, aes(x = price)) +
  stat_density(aes(ymax = ..density..,
    ymin = -..density..),
  geom = "ribbon", position =
  "identity"
)
```

Warning: The dot-dot notation (`..density..`)
 ## i Please use `after_stat(density)` instead.
 ## This warning is displayed once every 8 hours.
 ## Call `lifecycle::last_lifecycle_warnings()`
 ## generated.



smoothed density estimates https://ggplot2.tidyverse.org/reference/geom_density.html

Computes and draws kernel density estimate, which is a smoothed version of the histogram. This is a useful alternative to the histogram for continuous data that comes from an underlying smooth distribution.

`geom_density`

`stat_density`

https://ggplot2.tidyverse.org/reference/geom_density.html#ref-examples

30.3 scale

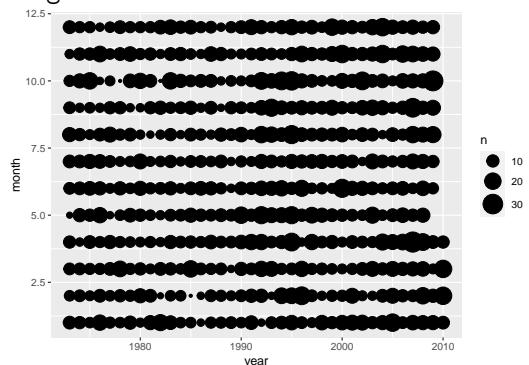
`ggplot2`

<https://bookdown.org/xiangyun/msg/system.html#section-15>

```
library(ggplot2)

data(quake6, package = "MSG")
ggplot(quake6, aes(x = year, y =
  month)) +
  stat_sum(aes(size = ..n..)) +
  scale_size(range = c(1, 8))
```

Warning: package 'ggplot2' was built under R 4.0.0
 ## Warning: The dot-dot notation (`..n..`) was deprecated
 ## i Please use `after_stat(n)` instead.
 ## This warning is displayed once every 8 hours.
 ## Call `lifecycle::last_lifecycle_warnings()`
 ## generated.



count overlapping points https://ggplot2.tidyverse.org/reference/geom_count.html?q=stat_sum#ref-usage

This is a variant `geom_point()` that counts the number of observations at each location, then maps the count to point area. It useful when you have discrete data and overplotting.

`geom_count`

`stat_sum`

https://ggplot2.tidyverse.org/reference/geom_count.html?q=stat_sum#ref-examples

scales for area or radius https://ggplot2.tidyverse.org/reference/scale_size.html?q=scale_size#null

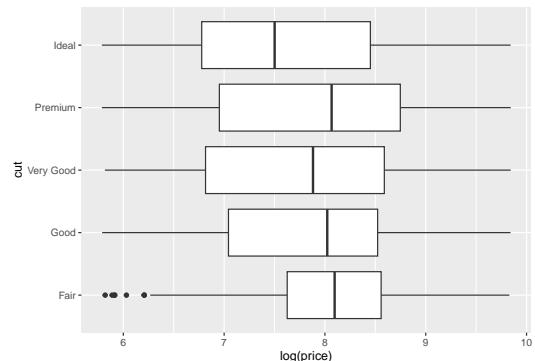
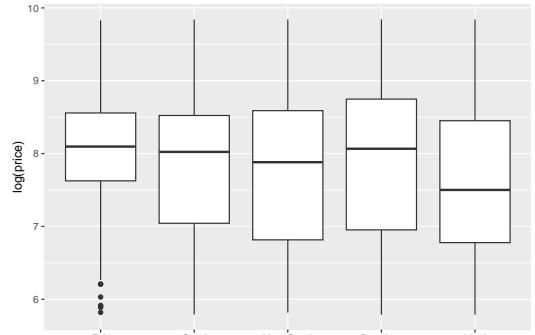
`scale_size`

30.4 coordinate system

<https://bookdown.org/xiangyun/msg/system.html#section-16>

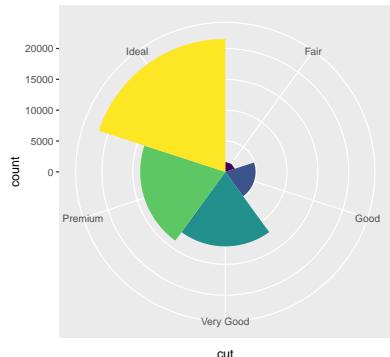
```
library(ggplot2)

p <- ggplot(aes(x = cut, y =
  log(price)), data = diamonds) +
  geom_boxplot()
p
p + coord_flip()
```



```
library(ggplot2)

ggplot(aes(x = cut, fill = cut), data
  = diamonds) +
  coord_polar() +
  geom_bar(width = 1, show.legend =
    FALSE)
```

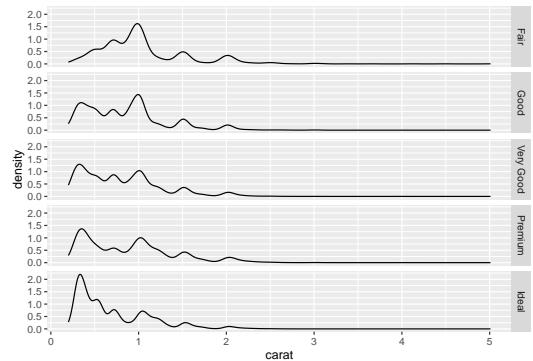


30.5 facet

<https://bookdown.org/xiangyun/msg/system.html#subsec:facet>

```
library(ggplot2)

ggplot(aes(x = carat), data =
  diamonds) +
  geom_density() +
  facet_grid(cut ~ .)
```

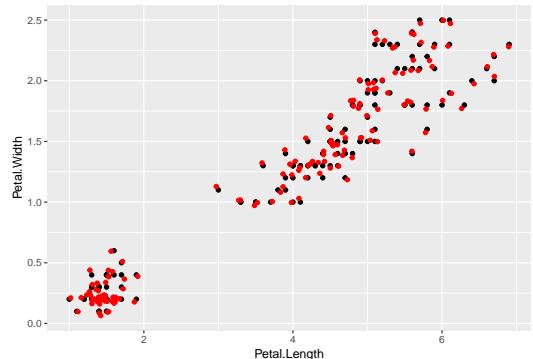


30.6 jitter

<https://bookdown.org/xiangyun/msg/system.html#section-17>

```
library(ggplot2)

ggplot(aes(x = Petal.Length, y =
  Petal.Width), data = iris) +
  geom_point() +
  geom_jitter(color = "red")
```



30.7 font

<https://bookdown.org/xiangyun/msg/system.html#subsec:font>

Chapter 31

notational system for design

⁹ p.51

NSD = notational system for design

⁵

31.1 graphic notation

⁹ p.51

- X : treatment or exposure to an agent or an event of interest
- P : **placebo**, i.e. blank treatment or exposure, or standard treatment, or exposure as an active control
- O : **observation** or process of measurement
- R : **randomization**, i.e. random assignment of research subjects to separate treatment or exposure groups
- subscript
 - g : **groups**
 - k : **kinds** of treatments, exposures, or placebos
 - t : **time** or sequential order

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

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

⁵ 5

31.2 pre-experimental design

⁵ p.6

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

Figure 31.1: pre- and true experimental designs (5 p.8)

31.2.1 one-shot case study

$X \quad O$

31.2.2 one-group pretest-posttest design

$O \quad X \quad O$

paired t test

⁹ p.62

$O \quad X \quad O$
 $O_t \quad X \quad O_t$
 $O_0 \quad X \quad O_1$

$O \quad X \quad O$
 $O_{gt} \quad X_g \quad O_{gt}$
 $O_{10} \quad X \quad O_{11}$

31.2.3 static-group comparison

$X \quad O$
 $X_g \quad O_{gt}$
 $X \quad O_{11}$
 O_{21}

	Sources of Invalidity								External			
	Internal							External				
	History	Maturation	Testing	Instrumentation	Regression	Selection	Mortality	Interaction of Selection and Maturation, etc.	Interaction of Testing and X	Interaction of Selection and X	Reactive Arrangements	Multiple-X Interference
<i>Quasi-Experimental Designs:</i>												
7. Time Series $O \ O \ O \ O X \ O \ O \ O$	-	+	+	?	+	+	+	+	-	?	?	
8. Equivalent Time Samples Design $X_1O \ X_2O \ X_3O \ X_4O$, etc.	+	+	+	+	+	+	+	+	-	?	-	-
9. Equivalent Materials Samples Design $M_1X_1O \ M_2X_2O \ M_3X_3O \ M_4X_4O$, etc.	+	+	+	+	+	+	+	+	-	?	?	-
10. Nonequivalent Control Group Design $O \ X \ O$	+	+	+	+	?	+	+	-	-	?	?	
$\frac{O}{O}$												
11. Counterbalanced Designs $X_1O \ X_2O \ X_3O \ X_4O$ $X_2O \ X_3O \ X_4O \ X_1O$ $X_3O \ X_4O \ X_1O \ X_2O$ $X_4O \ X_1O \ X_2O \ X_3O$	+	+	+	+	+	+	+	?	?	?	-	
12. Separate-Sample Pretest-Posttest Design $R \ O \ (X)$ $R \ X \ O$	-	-	+	?	+	+	-	-	+	+	+	
12a. $R \ O \ (X)$ $R \ X \ O$ $\frac{R}{R} \ O \ (X)$ $R \ X \ O$	+	-	+	?	+	+	-	+	+	+	+	
12b. $R \ O_1 \ (X)$ $R \ O_2 \ (X)$ $R \ X \ O_1$	-	+	+	?	+	+	-	?	+	+	+	
12c. $R \ O_1 \ X \ O_2$ $R \ X \ O_2$	-	-	+	?	+	+	+	-	+	+	+	

Figure 31.2: quasi-experimental designs (⁵ p.40)

	Sources of Invalidity								
	Internal					External			
	History	Maturity	Testing	Instrumentation	Regression	Selection	Mortality	Selection and Maturation, etc.	
<i>Quasi-Experimental Designs</i>									
<i>Continued:</i>									
13. Separate-Sample Pretest-Posttest Control Group Design	+ + + + + + + -							+ + +	
$R \ O \ (X)$ $R \ X \ O$ $\hline R \ O$ $R \ O$									
13a. { $R \ O \ (X)$ $R \ X \ O$ $\hline R' \ O \ (X)$ $R \ X \ O$ $\hline R \ O \ (X)$ $R \ X \ O$ $\hline R \ O$ $R \ O$ $\hline R' \ O$ $R \ O$ $\hline R \ O$ $R \ O$	+ + + + + + + +							+ + +	
14. Multiple Time-Series	+ + + + + + + +							- - ?	
$O \ O \ O \ X O \ O \ O$ $\hline O \ O \ O \ O \ O \ O$									
15. Institutional Cycle Design									
Class A X \bar{O}_1									
Class $B_1 \ R O_2 \ X O_3$									
Class $B_2 \ R \ X O_4$									
Class C $O_5 \ X$									
^a Gen. Pop. Con. Cl. B O_6									
^a Gen. Pop. Con. Cl. C O_7									
$O_2 < O_1 \}$	+ - + + ? - ?							+ ? +	
$O_5 < O_4 \}$	- - - ? ? + +							- ? +	
$O_2 < O_4$	- - + ? ? + ?							+ ? ?	
$O_5 = O_4 \}$	+ -								
$O_{2g} = O_{2o} \}$									
16. Regression Discontinuity	+ + + ? + + ? +							+ - + +	

• General Population Controls for Class B, etc.

Figure 31.3: quasi-experimental designs continued (⁵ p.56)

$$\begin{array}{ccc} X & O \\ X_g & O_{gt} \\ X & O_{11} \\ & O_{01} \end{array}$$

31.3 true experimental design

⁵ p.13

31.3.1 posttest-only control group design

basic experimental design

two-sample t test

⁹ p.53

$$\begin{array}{ccc} R & X & O \\ R & & O \end{array}$$

or, with a placebo or an active control,

$$\begin{array}{ccc} R & X & O \\ R & P & O \end{array}$$

$$R \quad X_g \quad O_{gt}$$

$$\begin{array}{lll} R & X_g = X_1 = X & O_{gt} = O_{11} \\ R & X_g = X_2 = \emptyset & O_{gt} = O_{21} \end{array}$$

or, with a placebo or an active control

$$\begin{array}{lll} R & X_g = X_1 = X & O_{gt} = O_{11} \\ R & X_g = X_2 = P & O_{gt} = O_{21} \end{array}$$

$$\begin{array}{ccc} R & X & O_{11} \\ R & & O_{21} \end{array}$$

or, with a placebo or an active control

$$\begin{array}{ccc} R & X & O_{11} \\ R & P & O_{21} \end{array}$$

$$\begin{array}{ccc} R & X_g & O_{gt} \\ R & X & O_{11} \\ R & P & O_{21} \end{array}$$

$$\begin{array}{ccc} R & X & O \\ R & X_g & O_{gt} \\ R & X & O_{11} \\ R & P & O_{21} \end{array}$$

31.3.2 pretest-posttest control group design

R	O	X	O
R	O_{gt}	X_g	O_{gt}
R	O_{10}	X	O_{11}
R	O_{20}		O_{21}

31.3.3 Solomon four-group design

⁹ p.52

Solomon 4-group design = pretest-posttest + posttest-only control group design

R	O_{gt}	X_g	O_{gt}
R	O_{10}	X	O_{11}
R	O_{20}		O_{21}
R		X	O_{31}
R			O_{41}

R	O	X	O
R	O_{gt}	X_g	O_{gt}
R	O_{10}	X	O_{11}
R	O_{20}		O_{21}
R		X	O_{31}
R			O_{41}

31.4 quasi-experimental design

⁵ p.34

31.5 correlational and ex post facto designs

⁵ p.64

31.6 graphic notation, advanced

⁹ p.74

- X : treatment or exposure to an agent or an event of interest
- P : **placebo**, i.e. blank treatment or exposure, or standard treatment, or exposure as an active control
- O : **observation** or process of measurement
- R : **randomization**, i.e. random assignment of research subjects to separate treatment or exposure groups
- subscript
 - $_g$: **groups**
 - $_k$: **kinds** of treatments, exposures, or placebos
 - $_t$: **time** or sequential order
- V : **variable(s)**
 - $B(V)$: **blocking** by the variable(s)
 - $M(V)$: **matching** by the variable(s)

- $S(V)$: **stratifying** by the variable(s)
- $L(V/L)$: **limiting** to the level(s) of the variable(s)
- M^* : research **material(s)** selected
- –: cohort

Chapter 32

design of experiment

experimental design = experiment design = design of experiments = DoE

⁹ p.72

question-design-analysis loop

32.1 notational system for design^[31]

graphic notation, advanced^[31.6]

32.2 terminology

- population
 - sample
 - * subsample
- unit
 - experimental unit
 - * response
 - * block: group of similar experimental unit (¹⁰ p.74)
 - observational unit / measurement unit ¹
- replication (⁹ p.76): an independent observation of the treatment (¹⁰ p.74)
 - treatment replication: experimental-unit-to-experimental-unit variation
 - measurement replication = subsample: measurement-to-measurement variation
- replicate
 - experimental replicate
 - biological replicate
 - technical replicate

¹⁰ p.73

Y_{ij} : the response observed from the j^{th} experimental unit assigned to the i^{th} treatment

μ_i : the mean response to the i^{th} treatment

ε_{ij} : the noise from other possible natural variation or nonrandom and random error

¹<https://passel2.unl.edu/view/lesson/2e09f0055f13/6>

$$Y_{ij} = \mu_i + \varepsilon_{ij}, \begin{cases} i \in \mathbb{N} \cap [1, n_i] & \mathbb{N} \ni n_i \text{ treatments} \\ j \in \mathbb{N} \cap [1, n_j] & \mathbb{N} \ni n_j \text{ experimental units per treatment} \end{cases}$$

Each treatment has n_j experimental units, so there are totally $n_i n_j$ experimental units.

If experimental units cannot be homogeneous, we can try to

- stratify them
- group them, and measure group to group variation
- block them

here n_j blocks each with n_i experimental units where **each treatment occurs once in each block**

$$\begin{aligned} Y_{ij} &= \mu_i + \varepsilon_{ij} \\ &= \mu_i + b_j + \varepsilon_{ij}^*, \begin{cases} i \in \mathbb{N} \cap [1, n_i] & \mathbb{N} \ni n_i \text{ experimental units per block} \\ j \in \mathbb{N} \cap [1, n_j] & \mathbb{N} \ni n_j \text{ blocks} \end{cases} \end{aligned}$$

where

$$\varepsilon_{ij} = b_j + \varepsilon_{ij}^*$$

i.e. the variation between groups or blocks of experimental units has been identified and isolated from ε_{ij}^* , which represents the variability of experimental units within a block. By isolating the block effect from the experimental units, the within-block variation can be used to compare treatment effects, which involves computing the estimated standard errors of contrasts of the treatments.

$$\begin{aligned} Y_{ij} - Y_{i'j} &= (\mu_i + b_j + \varepsilon_{ij}^*) \\ &\quad - (\mu_{i'} + b_j + \varepsilon_{i'j}^*) \\ &= (\mu_i - \mu_{i'}) + (\varepsilon_{ij}^* - \varepsilon_{i'j}^*) \end{aligned}$$

which does not depend on the block effect b_j or free of block effects. The result of this difference is that the variance of the difference of two treatment responses within a block depends on the within-block variation among the experimental units and not the between-block variation.

32.2.1 replication vs. subsample

It is very important to distinguish between a **subsample** and a **replication** since the error variance estimated from between subsamples is in general considerably smaller than the error variance estimated from replications or between experimental units. (¹⁰ p.77)

<https://www.researchgate.net/post/What-is-Experimental-Unit-Replicate-Total-sample-size-treatment-size>

32.2.2 replication vs. repeated measurements

32.2.3 replication, replicate

32.2.3.1 technical replicate, biological replicate

https://www.youtube.com/watch?v=c_cpl5YsBV8

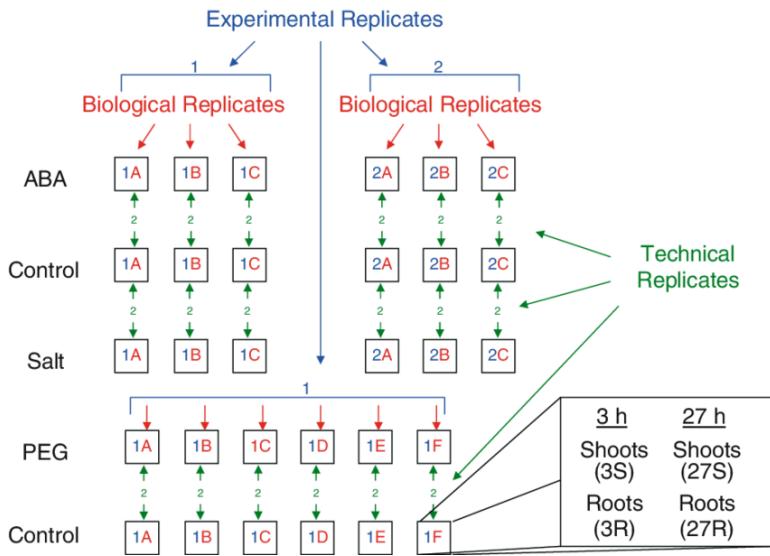


Figure 32.1: experimental, biological, technical replicates (11)

32.2.4 Latin square design

LSD = Latin square design

⁶ p.505~507

<https://tex.stackexchange.com/questions/501671/how-to-get-math-mode-curly-braces-in-tikz>

```
\usepackage{pgfplots} in engine.opts=list(extra.preamble=c("\usepackage{pgfplots}"))
\usetikzlibrary{decorations}
```

$p = 4$ columns			
$p = 4$ rows			
$p = \{A, B, C, D\} = 4$ treatments			
A	B	C	D
B	C	D	A
C	D	A	B
D	A	B	C

Figure 32.2: Latin square example

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + \varepsilon_{ijk}, \begin{cases} i \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ treatments} \\ j \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ rows} \\ k \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ columns} \end{cases}$$

$$\mathcal{E}_{ijk} \stackrel{\text{i.i.d.}}{\sim} n(0, \sigma^2)$$

ρ_i : i^{th} row

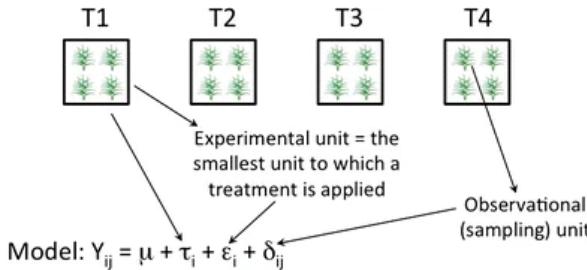
κ_j : j^{th} column

τ_k : k^{th} treatment

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + \mathcal{E}_{ijk}, \begin{cases} i \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ treatments} \\ j \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ rows} \\ k \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ columns} \end{cases}$$

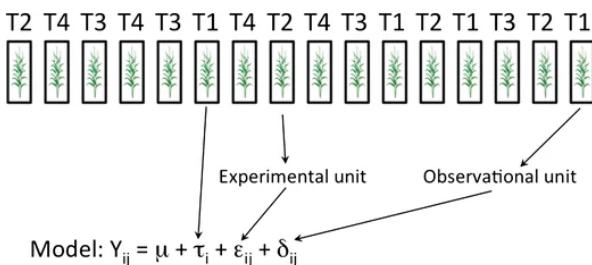
$$= \mu + \rho_i + \kappa_j + \tau_k + \mathcal{E}_{ijk}, \begin{cases} i \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ rows} \\ j \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ columns} \\ k \in \mathbb{N} \cap [1, p] & \mathbb{N} \ni p \text{ treatments} \end{cases}$$

32.2.5 model assumption and experimental unit, measurement/observational unit



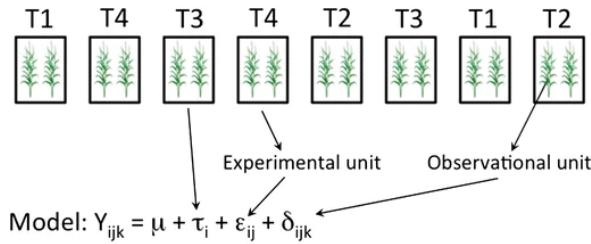
ANOVA Source of variation	df
Treatments + Experimental error	3 (fixed)
Observational error	12

Figure 32.3: model assumption and experimental unit 1 ([12 fig.1](#))



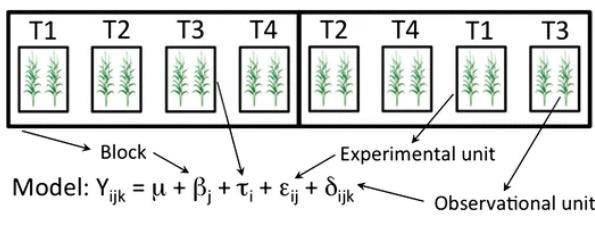
ANOVA Source of variation	df
Treatments	3 (fixed)
Error (experimental + observational)	12

Figure 32.4: model assumption and experimental unit 2 ([12 fig.2](#))



ANOVA Source of variation	df
Treatments	3 (fixed)
Experimental error	4
Observational error	8

Figure 32.5: model assumption and experimental unit 3 ([12](#) fig.3)



ANOVA Source of variation	df
Blocks	1
Treatments	3 (fixed)
Experimental error	3
Observational error	8

Figure 32.6: model assumption and experimental unit 4 ([12](#) fig.4)

$$Y_{ijk} = \mu + \tau_i + \beta_j + \epsilon_{ij} + \Delta_{ijk}$$

32.3 experiment structure

32.3.1 treatment structure

¹⁰ p.77

- 1-way treatment structure
- 2-way treatment structure
- factorial arrangement treatment structure
- *fractional* factorial arrangement treatment structure
- factorial arrangement with one or more controls

32.3.2 design structure

¹⁰ p.77

- CRD = completely randomized design
- RCBD = randomized complete block design
 - ? why not called CRBD = completely randomized block design
- LSD = Latin square design^[32.2.4]
- IBD = incomplete block design
 - BIBD = balanced IBD
- various combinations and generalizations

32.3.3 size of experimental unit

- split-plot design
 - split-split-plot design
 - split-split-split-plot design
- repeated measures design
 - cross-over design
 - change-over design
- nested design = hierarchical design
- variations and combinations
 - SSEU = several sizes of experimental units

32.4 approach to experimentation

⁹ p.75

- approach to experimentation
 - best-guess approach
 - one-factor-at-a-time approach = OFAT
 - factorial approach

32.5 sample size estimation

32.6 statistical analysis plan

32.7 protocol

⁹ p.95

- study objective
- study endpoint
 - primary endpoint
 - secondary endpoint(s)
- experimental unit(s)
- treatment structure^[32.3.1]
- design structure^[32.3.2]
- potential confounder(s)
- randomization
- blinding
- chance reduction
- sample size estimation^[32.5]
- data collection
- data management system
- statistical analysis plan^[32.6]
- DSMB / DSMC = data and safety monitoring board / committee

32.8 DoE course with six sigma and Minitab

<https://zhuanlan.zhihu.com/p/265914617>

<https://www.zhihu.com/question/416312693/answer/1426399810>

32.8.1 evolution

- Fisher
- Rao

Chapter 33

quine

```
s = 's = %r\nprint(s%%s)'  
print(s%s)
```

```
## s = 's = %r\nprint(s%%s)'  
## print(s%s)
```

This snippet is a clever example of a quine. A quine is a computer program that takes no input and produces a copy of its own source code as its output. The given code in Python is written to print its own source when executed. Let's break it down:

`s = 's = %r\nprint(s%%s)':` This line defines a string `s` that contains a format string. `%r` is a placeholder that gets replaced with the `repr()` of the argument provided to the `%` operator, which in this case will be the string `s` itself. This means it will insert the string representation of `s` into the format string at `%r`.

`print(s%s):` This line prints the result of `s%s`. Here, the `%` operator is used to format the string `s` with itself. The `%s` inside the print statement is replaced by the string `s`, leading to the entire string being printed out, including the print statement itself.

This is because the format operation replaces `%r` with the representation of the string `s`, and `%%` is a way to escape the `%` sign in format strings, resulting in a single `%` in the output. This output is exactly the same as the source code, making it a quine.

33.1 `%r`

The `%r` in Python string formatting represents the “representation” of a value, which is typically the way you would see it if you were to type it into a Python interpreter. It uses the `repr()` function to convert the value to a string. This is useful for debugging, among other things, because it shows strings with quotes around them and escapes special characters. Essentially, `%r` gives you the “developer’s view” of what a variable looks like.

Here's a simple example to illustrate `%r` versus `%s` in string formatting:

```
my_str = "Hello, World!\nNew line character is represented with \\n"  
print("Using %%s: %s" % my_str)
```

```
## Using %s: Hello, World!  
## New line character is represented with \n
```

```
print("Using %%r: %r" % my_str)
## Using %r: 'Hello, World!\nNew line character is represented with \\n'
```

In this example:

The `%s` specifier tells Python to convert the object using `str()`, which is designed to be readable and outputs the string "Hello, World!\nNew line character is represented with \n", interpreting the escape character `\n` as a newline.

The `%r` specifier tells Python to convert the object using `repr()`, which aims to generate output that could be used to recreate the object, outputting the string 'Hello, World!\nNew line character is represented with \\n', preserving the actual escape characters in the output.

Notice how `%r` preserves the string exactly as it is, including the quotes and escaped characters, making it clear it's a string and showing the escape sequence explicitly.

Chapter 34

quaternion

34.1 TaylorCatAlice

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

34.1.1 complex / dionion / bionion

$$\begin{aligned} c &= a + bi = a + ib, \begin{cases} c \in \mathbb{C} \\ i^2 = -1 \\ a, b \in \mathbb{R} \Leftrightarrow \langle a, b \rangle \in \mathbb{R}^2 \end{cases} \\ &= z = x + yi = x + iy, \begin{cases} z \in \mathbb{C} \\ i^2 = -1 \\ x, y \in \mathbb{R} \Leftrightarrow \langle x, y \rangle \in \mathbb{R}^2 \end{cases} \\ &= \sqrt{x^2 + y^2} \left(\frac{x}{\sqrt{x^2 + y^2}} + \frac{y}{\sqrt{x^2 + y^2}} i \right) = r (\cos \theta + i \sin \theta) = re^{i\theta} \end{aligned}$$

Also see complex group representation^[37.4].

34.1.2 trionion / triernion / triplex / ternion

<https://zh.wikipedia.org/zh-tw/%E4%B8%89%E5%85%83%E6%95%B8>

<https://math.stackexchange.com/questions/1784166/why-are-there-no-triernions-3-dimensional-analogue-of-complex-numbers-quot>

<https://math.stackexchange.com/questions/32100/is-there-a-third-dimension-of-numbers/4453131>

$$\begin{aligned}
t &= a + bi + cj = a + ib + jc, \quad \begin{cases} t \in \mathbb{T} \\ i^2 = -1 \\ j^2 = -1 \end{cases} \\
&= w = x + yi + zj = x + iy + jz, \quad \begin{cases} w \in \mathbb{T} \\ i^2 = -1 \\ j^2 = -1 \end{cases} \\
&= \sqrt{x^2 + y^2 + z^2} \left(\frac{x}{\sqrt{x^2 + y^2 + z^2}} + \frac{y}{\sqrt{x^2 + y^2 + z^2}}i + \frac{z}{\sqrt{x^2 + y^2 + z^2}}j \right) = ?
\end{aligned}$$

$$\begin{cases} A(BC) = (AB)C & (a) \text{ associativity} \\ A(B+C) = AB + AC & (d) \text{ distributivity} \end{cases}$$

$$\begin{aligned}
&\mathbb{T} \ni ij = X + Yi + Zj \in \mathbb{T} \\
-ij &= (i^2)j \stackrel{(a)}{=} i(ij) = i(X + Yi + Zj) \stackrel{(d)}{=} -Y + Xi + Zij \\
ij &= \frac{Y}{Z} - \frac{X}{Z}i - \frac{1}{Z}j \Rightarrow \begin{cases} X = \frac{Y}{Z} \\ Y = -\frac{X}{Z} \\ Z = -\frac{1}{Z} \end{cases} \Rightarrow Z^2 = -1 \Rightarrow Z \notin \mathbb{R} \\
-ij &= i(j^2) \stackrel{(a)}{=} (ij)j = (X + Yi + Zj)j \stackrel{(d)}{=} -Z + Xj + Yij \\
ij &= \frac{Z}{Y} - \frac{1}{Y}i - \frac{X}{Y}j \Rightarrow \begin{cases} X = \frac{Z}{Y} \\ Y = -\frac{1}{Y} \\ Z = -\frac{X}{Y} \end{cases} \Rightarrow Y^2 = -1 \Rightarrow Y \notin \mathbb{R}
\end{aligned}$$

34.1.3 quaternion

<https://en.wikipedia.org/wiki/Quaternion>

$$\begin{aligned}
q &= a + bi + cj + dk = a + ib + jc + kd, \quad \begin{cases} q \in \mathbb{H} \\ a, b, c, d \in \mathbb{R} \Leftrightarrow \langle a, b, c, d \rangle \in \mathbb{R}^4 \end{cases} \\
w &= t + xi + yj + zk = t + ix + jy + kz, \quad \begin{cases} w \in \mathbb{H} \\ t, x, y, z \in \mathbb{R} \Leftrightarrow \langle t, x, y, z \rangle \in \mathbb{R}^4 \end{cases} \\
&= ?
\end{aligned}$$

$$\begin{aligned}
q &= a + bi + cj + dk = a + ib + jc + kd, \begin{cases} q \in \mathbb{H} \\ i^2 = j^2 = k^2 = -1 = ijk \Rightarrow ij = k \\ a, b, c, d \in \mathbb{R} \end{cases} \Leftrightarrow \langle a, b, c, d \rangle \in \mathbb{R}^4 \\
w &= t + xi + yj + zk = t + ix + jy + kz, \begin{cases} w \in \mathbb{H} \\ i^2 = j^2 = k^2 = -1 = ijk \Rightarrow ij = k \\ t, x, y, z \in \mathbb{R} \end{cases} \Leftrightarrow \langle t, x, y, z \rangle \in \mathbb{R}^4 \\
&= t + (i \ j \ k) \begin{pmatrix} x \\ y \\ z \end{pmatrix} = x_0 + (i \ j \ k) \begin{pmatrix} x \\ y \\ z \end{pmatrix} = x_0 + (e_1 \ e_2 \ e_3) \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = x_0 + x, \begin{cases} e_1 = i = i \\ e_2 = j = j \\ e_3 = k = k \end{cases} \\
&= t + \frac{ix + jy + kz}{r} r, \begin{cases} r^2 = x^2 + y^2 + z^2 \\ \|n\|^2 = \left(\frac{ix + jy + kz}{r}\right)^2 = -1 \end{cases} |q|^2 = t^2 + r^2 \\
&= \sqrt{t^2 + r^2} \left(\frac{t}{\sqrt{t^2 + r^2}} + n \frac{r}{\sqrt{t^2 + r^2}} \right) = |q| \left(\cos \frac{\theta}{2} + n \sin \frac{\theta}{2} \right) = |q| e^{n \frac{\theta}{2}}
\end{aligned}$$

The quaternion set is denoted \mathbb{H} for Sir R.W. **Hamilton**, because he suddenly and strikingly realized

$$\begin{cases} ij = k \\ k \in \mathbb{H} \end{cases} \Rightarrow ij \in \mathbb{H} \text{ for closure property}$$

for the sake of rigorosity, see [group theory](#)^[37]

$$k^2 = -1$$

$$\begin{aligned}
ij &= k \\
ijk &= i(jk) \stackrel{(a)}{=} (ij)k = kk = k^2 = -1 \\
kij &= (ki)j \stackrel{(a)}{=} k(ij) = kk = k^2 = -1
\end{aligned}$$

$$\begin{aligned}
ij &= k \\
-j &= (i^2)j \stackrel{(a)}{=} i(ij) = ik \\
-i &= i(j^2) \stackrel{(a)}{=} (ij)j = kj
\end{aligned}$$

$$\begin{aligned}
-j &= (i^2) j \stackrel{(a)}{=} i(ij) = ik \\
1 &= -j^2 = j(-j) = j(ik) \stackrel{(a)}{=} (ji)k \\
k &= [1]k = [(ji)k]k \stackrel{(a)}{=} (ji)(k^2) = (ji)(-1) \\
&\quad -k = ji \\
-i &= i(j^2) \stackrel{(a)}{=} (ij)j = kj \\
1 &= (-i)i = (kj)i \stackrel{(a)}{=} k(ji) = kji \\
1 &= kji
\end{aligned}$$

There is no more **commutativity**^[34.1.3.2.1], i.e.

$$AB \not\equiv BA$$

but

$$AB + BA = 0 \Leftrightarrow AB = -BA$$

satisfying **anticommutativity**^[34.1.3.2.2].

$$\begin{cases} ij = k \\ ji = -k \end{cases} \Leftrightarrow ji = -k = -ij \\
\Leftrightarrow ji = -ij \\
\Leftrightarrow ij + ji = 0$$

$$\begin{cases} kij = -1 \\ kji = 1 \end{cases} \Leftrightarrow kij = -1 = -kji \\
\Leftrightarrow kij = -kji \\
\Leftrightarrow kij + kji = 0$$

$$\begin{aligned}
q &= a + bi + cj + dk = a + ib + jc + kd, \begin{cases} q \in \mathbb{H} \\ i^2 = j^2 = k^2 = -1 = ijk \Rightarrow ij = k \\ a, b, c, d \in \mathbb{R} \end{cases} \Leftrightarrow \langle a, b, c, d \rangle \in \mathbb{R}^4 \\
w &= t + xi + yj + zk = t + ix + jy + kz, \begin{cases} w \in \mathbb{H} \\ i^2 = j^2 = k^2 = -1 = ijk \Rightarrow ij = k \\ t, x, y, z \in \mathbb{R} \end{cases} \Leftrightarrow \langle t, x, y, z \rangle \in \mathbb{R}^4 \\
&= t + (i \quad j \quad k) \begin{pmatrix} x \\ y \\ z \end{pmatrix} = x_0 + (i \quad j \quad k) \begin{pmatrix} x \\ y \\ z \end{pmatrix} = x_0 + (e_1 \quad e_2 \quad e_3) \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = x_0 + x, \begin{cases} e_1 = i = i \\ e_2 = j = j \\ e_3 = k = k \end{cases}
\end{aligned}$$

.	1	i	j	k
1	1	i	j	k
i	i	-1	k	-j
j	j	-k	-1	i
k	k	j	-i	-1

.	1	i	j	k	-1	-i	-j	-k
1	1	i	j	k				
i	i	-1	k	-j				
j	j	-k	-1	i				
k	k	j	-i	-1				
-1								
-i								
-j								
-k								

Figure 34.1: quaternion basis group table

.	1	-1	i	-i	j	-j	k	-k
1								
-1								
i								
-i								
j								
-j								
k								
-k								

Figure 34.2: quaternion basis group table 2

34.1.3.1 true origin of (dot product & cross product) / (inner product & outer product)

product of two pure imaginary quaternions

$$\begin{aligned}
\mathbf{x}_1 \mathbf{x}_2 &= (x_{11}\mathbf{i} + x_{12}\mathbf{j} + x_{13}\mathbf{k})(x_{21}\mathbf{i} + x_{22}\mathbf{j} + x_{23}\mathbf{k}) \\
&= x_{11}x_{21}\mathbf{i}^2 + x_{11}x_{22}\mathbf{ij} + x_{11}x_{23}\mathbf{ik} \\
&\quad + x_{12}x_{21}\mathbf{ji} + x_{12}x_{22}\mathbf{j}^2 + x_{12}x_{23}\mathbf{jk} \\
&\quad + x_{13}x_{21}\mathbf{ki} + x_{13}x_{22}\mathbf{kj} + x_{13}x_{23}\mathbf{k}^2 \\
&= -(x_{11}x_{21} + x_{12}x_{22} + x_{13}x_{23}) \\
&\quad + (x_{12}x_{23} - x_{13}x_{22})\mathbf{jk} + (x_{13}x_{21} - x_{11}x_{23})\mathbf{ki} + (x_{11}x_{22} - x_{12}x_{21})\mathbf{ij} \\
&= -(x_{11}x_{21} + x_{12}x_{22} + x_{13}x_{23}) \\
&\quad + (x_{12}x_{23} - x_{13}x_{22})\mathbf{i} + (x_{13}x_{21} - x_{11}x_{23})\mathbf{j} + (x_{11}x_{22} - x_{12}x_{21})\mathbf{k} \\
&= -\mathbf{x}_1 \cdot \mathbf{x}_2 + \mathbf{x}_1 \times \mathbf{x}_2 \\
&= -(\mathbf{x}_1 \cdot \mathbf{x}_2) + (\mathbf{x}_1 \times \mathbf{x}_2), \quad \begin{cases} \mathbf{x}_1 \cdot \mathbf{x}_2 = x_{11}x_{21} + x_{12}x_{22} + x_{13}x_{23} \\ \mathbf{x}_1 \times \mathbf{x}_2 = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ x_{11} & x_{12} & x_{13} \\ x_{21} & x_{22} & x_{23} \end{vmatrix} \end{cases} \\
&= -\mathbf{x}_1 \cdot \mathbf{x}_2 + \mathbf{x}_1 \times \mathbf{x}_2
\end{aligned}$$

product of two general quaternions / ordinary quaternions = Grassmann product

$$\begin{aligned}
q_1 q_2 &= (q_{10} + q_{11}\mathbf{i} + q_{12}\mathbf{j} + q_{13}\mathbf{k})(q_{20} + q_{21}\mathbf{i} + q_{22}\mathbf{j} + q_{23}\mathbf{k}) \\
&= (x_{10} + \mathbf{x}_1)(x_{20} + \mathbf{x}_2), \quad \begin{cases} x_{i\mu} = q_{i\mu} & \mu \in \{0\} \cup (\mathbb{N} \cap [1, 3]) \\ \mathbf{x}_i = x_{ij}\mathbf{e}_j & i, j \in \mathbb{N} \cap [1, 3], \begin{cases} \mathbf{e}_1 = \mathbf{i} \\ \mathbf{e}_2 = \mathbf{j} \\ \mathbf{e}_3 = \mathbf{k} \end{cases} \end{cases} \\
&= x_{10}x_{20} + x_{10}\mathbf{x}_2 + x_{20}\mathbf{x}_1 + \mathbf{x}_1 \mathbf{x}_2 \\
&= x_{10}x_{20} + x_{10}\mathbf{x}_2 + x_{20}\mathbf{x}_1 - \mathbf{x}_1 \cdot \mathbf{x}_2 + \mathbf{x}_1 \times \mathbf{x}_2 \\
&= (x_{10}x_{20} - \mathbf{x}_1 \cdot \mathbf{x}_2) + (x_{10}\mathbf{x}_2 + x_{20}\mathbf{x}_1 + \mathbf{x}_1 \times \mathbf{x}_2) \\
x_{10}x_{20} - \mathbf{x}_1 \cdot \mathbf{x}_2 &= (q_{10} \quad q_{11} \quad q_{12} \quad q_{13}) \begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix} \begin{pmatrix} q_{20} \\ q_{21} \\ q_{22} \\ q_{23} \end{pmatrix} = q_1^\mu \eta_{\mu\nu} q_2^\nu \\
&= (q_{10} \quad q_{11} \quad q_{12} \quad q_{13}) \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} q_{20} \\ q_{21} \\ q_{22} \\ q_{23} \end{pmatrix} = \mathbf{q}_1^\top H \mathbf{q}_2, H = [\eta_{\mu\nu}]_{4 \times 4} = \eta_{\mu\nu}
\end{aligned}$$

$$\begin{aligned}
q_1 q_2 &= (x_{10}x_{20} - \mathbf{x}_1 \cdot \mathbf{x}_2) + (x_{10}\mathbf{x}_2 + x_{20}\mathbf{x}_1 + \mathbf{x}_1 \times \mathbf{x}_2) \\
QP &= (Q_0 P_0 - \mathbf{Q} \cdot \mathbf{P}) + (Q_0 \mathbf{P} + P_0 \mathbf{Q} + \mathbf{Q} \times \mathbf{P})
\end{aligned}$$

$$ab = (a_0 b_0 - \mathbf{a} \cdot \mathbf{b}) + (a_0 \mathbf{b} + b_0 \mathbf{a} + \mathbf{a} \times \mathbf{b})$$

Minkowski metric tensor

$$\eta = H = [\eta_{\mu\nu}]_{4 \times 4} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} = \begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix} = \eta_{\mu\nu}$$

and quaternions as 4-vectors or four-vectors

$$\mathbf{q}_1^T = (q_{10} \quad q_{11} \quad q_{12} \quad q_{13})$$

$$\mathbf{q}_2 = \begin{pmatrix} q_{20} \\ q_{21} \\ q_{22} \\ q_{23} \end{pmatrix}$$

34.1.3.2 commutativity vs. anticommutativity

34.1.3.2.1 commutativity 交換律 = 交換性 = 對易性

$$AB = BA \Leftrightarrow AB - BA = 0$$

$$AB = BA \Rightarrow AB \equiv BA$$

34.1.3.2.2 anticommutativity 反交換律 = 反交換性 = 反對易性

$$AB + BA = 0 \Leftrightarrow AB = -BA$$

$$AB = -BA \Rightarrow AB \neq BA$$

34.1.3.3 bracket

34.1.3.3.1 self-invented bracket 自創括號 = 自創括

34.1.3.3.1.1 commutative bracket 交換括號 = 對易式

$$[X, Y] = \frac{XY - YX}{2}$$

34.1.3.3.1.2 anticommutative bracket 反交換括號 = 反對易式

$$\{X, Y\} = \frac{XY + YX}{2}$$

34.1.3.3.2 Poisson bracket https://en.wikipedia.org/wiki/Poisson_bracket

34.1.3.3.3 Lagrange bracket

34.1.3.3.4 Lie bracket

34.1.3.4 triple product

product = double product = Grassmann product

$$ab = (a_0 b_0 - \mathbf{a} \cdot \mathbf{b}) + (a_0 \mathbf{b} + b_0 \mathbf{a} + \mathbf{a} \times \mathbf{b})$$

pure imaginary

$$ab = (a_0 b_0 - \mathbf{a} \cdot \mathbf{b}) + (a_0 \mathbf{b} + b_0 \mathbf{a} + \mathbf{a} \times \mathbf{b})$$

$$\begin{cases} a_0 = 0 \\ b_0 = 0 \\ = (00 - \mathbf{a} \cdot \mathbf{b}) + (0\mathbf{b} + 0\mathbf{a} + \mathbf{a} \times \mathbf{b}) \\ = -\mathbf{a} \cdot \mathbf{b} + \mathbf{a} \times \mathbf{b} \end{cases}$$

pure imaginary product can get both (real & imaginary) / (scalar & vector) parts

$$ab = \mathbf{a}\mathbf{b} = -\mathbf{a} \cdot \mathbf{b} + \mathbf{a} \times \mathbf{b}, \begin{cases} a = 0 + \mathbf{a} = \mathbf{a} \\ b = 0 + \mathbf{b} = \mathbf{b} \end{cases}$$

triple product

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

pure imaginary

$$\begin{cases} a = 0 + \mathbf{a} = \mathbf{a} \\ b = 0 + \mathbf{b} = \mathbf{b} \\ c = 0 + \mathbf{c} = \mathbf{c} \end{cases}$$

$$\begin{aligned} abc &= \mathbf{a}\mathbf{b}\mathbf{c} = (\mathbf{a}\mathbf{b})\mathbf{c} = (-\mathbf{a} \cdot \mathbf{b} + \mathbf{a} \times \mathbf{b})\mathbf{c} \\ &= \mathbf{a}(\mathbf{b}\mathbf{c}) = \mathbf{a}(-\mathbf{b} \cdot \mathbf{c} + \mathbf{b} \times \mathbf{c}) \end{aligned}$$

$$\begin{aligned} abc &= (\mathbf{a}\mathbf{b})\mathbf{c} = (-\mathbf{a} \cdot \mathbf{b} + \mathbf{a} \times \mathbf{b})\mathbf{c} \\ &= -(\mathbf{a} \cdot \mathbf{b})\mathbf{c} + (\mathbf{a} \times \mathbf{b})\mathbf{c} \\ &= -(\mathbf{a} \cdot \mathbf{b})\mathbf{c} + (-(\mathbf{a} \times \mathbf{b}) \cdot \mathbf{c} + (\mathbf{a} \times \mathbf{b}) \times \mathbf{c}) \\ &= [-(\mathbf{a} \times \mathbf{b}) \cdot \mathbf{c}] + [(\mathbf{a} \times \mathbf{b}) \times \mathbf{c} - (\mathbf{a} \cdot \mathbf{b})\mathbf{c}] \\ &= \mathbf{a}(\mathbf{b}\mathbf{c}) = \mathbf{a}(-\mathbf{b} \cdot \mathbf{c} + \mathbf{b} \times \mathbf{c}) \\ &= -\mathbf{a}(\mathbf{b} \cdot \mathbf{c}) + \mathbf{a}(\mathbf{b} \times \mathbf{c}) \\ &= -\mathbf{a}(\mathbf{b} \cdot \mathbf{c}) + (-\mathbf{a} \cdot (\mathbf{b} \times \mathbf{c}) + \mathbf{a} \times (\mathbf{b} \times \mathbf{c})) \\ &= [-\mathbf{a} \cdot (\mathbf{b} \times \mathbf{c})] + [\mathbf{a} \times (\mathbf{b} \times \mathbf{c}) - \mathbf{a}(\mathbf{b} \cdot \mathbf{c})] \end{aligned}$$

by comparing (real & imaginary) / (scalar & vector) parts,

$$\begin{aligned} &\begin{cases} -(\mathbf{a} \times \mathbf{b}) \cdot \mathbf{c} = -\mathbf{a} \cdot (\mathbf{b} \times \mathbf{c}) \\ (\mathbf{a} \times \mathbf{b}) \times \mathbf{c} - (\mathbf{a} \cdot \mathbf{b})\mathbf{c} = \mathbf{a} \times (\mathbf{b} \times \mathbf{c}) - \mathbf{a}(\mathbf{b} \cdot \mathbf{c}) \end{cases} \\ \Rightarrow &\begin{cases} (\mathbf{a} \times \mathbf{b}) \cdot \mathbf{c} = \mathbf{a} \cdot (\mathbf{b} \times \mathbf{c}) & (s) \\ (\mathbf{a} \times \mathbf{b}) \times \mathbf{c} - (\mathbf{a} \cdot \mathbf{b})\mathbf{c} = \mathbf{a} \times (\mathbf{b} \times \mathbf{c}) - \mathbf{a}(\mathbf{b} \cdot \mathbf{c}) & (v) \end{cases} \end{aligned}$$

permutation

$$\sigma = \begin{pmatrix} x_1 & x_2 & \cdots \\ \sigma(x_1) & \sigma(x_2) & \cdots \end{pmatrix}$$

$$\begin{pmatrix} a & b & c \\ a & b & c \end{pmatrix}, \begin{pmatrix} a & b & c \\ b & c & a \end{pmatrix}, \begin{pmatrix} a & b & c \\ c & a & b \end{pmatrix}, \begin{pmatrix} a & b & c \\ a & c & b \end{pmatrix}, \begin{pmatrix} a & b & c \\ b & a & c \end{pmatrix}, \begin{pmatrix} a & b & c \\ c & b & a \end{pmatrix}$$

$$(s) \Rightarrow \left\{ \begin{array}{ll} (\mathbf{a} \times \mathbf{b}) \cdot \mathbf{c} = \mathbf{a} \cdot (\mathbf{b} \times \mathbf{c}) & \begin{pmatrix} a & b & c \\ a & b & c \end{pmatrix}, s_1 \\ (\mathbf{b} \times \mathbf{c}) \cdot \mathbf{a} = \mathbf{b} \cdot (\mathbf{c} \times \mathbf{a}) & \begin{pmatrix} a & b & c \\ b & c & a \end{pmatrix}, s_2 \\ (\mathbf{c} \times \mathbf{a}) \cdot \mathbf{b} = \mathbf{c} \cdot (\mathbf{a} \times \mathbf{b}) & \begin{pmatrix} a & b & c \\ c & a & b \end{pmatrix}, s_3 \\ (\mathbf{b} \times \mathbf{a}) \cdot \mathbf{c} = \mathbf{b} \cdot (\mathbf{a} \times \mathbf{c}) & \begin{pmatrix} a & b & c \\ b & a & c \end{pmatrix}, s_4 \\ (\mathbf{a} \times \mathbf{c}) \cdot \mathbf{b} = \mathbf{a} \cdot (\mathbf{c} \times \mathbf{b}) & \begin{pmatrix} a & b & c \\ a & c & b \end{pmatrix}, s_5 \\ (\mathbf{c} \times \mathbf{b}) \cdot \mathbf{a} = \mathbf{c} \cdot (\mathbf{b} \times \mathbf{a}) & \begin{pmatrix} a & b & c \\ c & b & a \end{pmatrix}, s_6 \end{array} \right.$$

$$\stackrel{\text{commutative}}{\Rightarrow} (\mathbf{a} \times \mathbf{b}) \cdot \mathbf{c} \stackrel{s_1}{=} (\mathbf{b} \times \mathbf{c}) \cdot \mathbf{a} \stackrel{s_2}{=} (\mathbf{c} \times \mathbf{a}) \cdot \mathbf{b} \stackrel{s_3}{=} (\mathbf{a} \times \mathbf{b}) \cdot \mathbf{c}$$

$$\stackrel{\text{anticommutative}}{=} -(\mathbf{b} \times \mathbf{a}) \cdot \mathbf{c} \stackrel{s_6}{=} -(\mathbf{c} \times \mathbf{b}) \cdot \mathbf{a} \stackrel{s_5}{=} -(\mathbf{a} \times \mathbf{c}) \cdot \mathbf{b} \stackrel{s_4}{=} -(\mathbf{b} \times \mathbf{a}) \cdot \mathbf{c}$$

$$\Leftrightarrow \mathbf{a} \cdot (\mathbf{b} \times \mathbf{c}) = \mathbf{b} \cdot (\mathbf{c} \times \mathbf{a}) = \mathbf{c} \cdot (\mathbf{a} \times \mathbf{b})$$

$$= -\mathbf{a} \cdot (\mathbf{c} \times \mathbf{b}) = -\mathbf{b} \cdot (\mathbf{a} \times \mathbf{c}) = -\mathbf{c} \cdot (\mathbf{b} \times \mathbf{a})$$

$$(v) \Rightarrow \left\{ \begin{array}{l} (\mathbf{a} \times \mathbf{b}) \times \mathbf{c} - (\mathbf{a} \cdot \mathbf{b}) \mathbf{c} = \mathbf{a} \times (\mathbf{b} \times \mathbf{c}) - \mathbf{a}(\mathbf{b} \cdot \mathbf{c}) \\ (\mathbf{b} \times \mathbf{c}) \times \mathbf{a} - (\mathbf{b} \cdot \mathbf{c}) \mathbf{a} = \mathbf{b} \times (\mathbf{c} \times \mathbf{a}) - \mathbf{b}(\mathbf{c} \cdot \mathbf{a}) \\ (\mathbf{c} \times \mathbf{a}) \times \mathbf{b} - (\mathbf{c} \cdot \mathbf{a}) \mathbf{b} = \mathbf{c} \times (\mathbf{a} \times \mathbf{b}) - \mathbf{c}(\mathbf{a} \cdot \mathbf{b}) \\ (\mathbf{b} \times \mathbf{a}) \times \mathbf{c} - (\mathbf{b} \cdot \mathbf{a}) \mathbf{c} = \mathbf{b} \times (\mathbf{a} \times \mathbf{c}) - \mathbf{b}(\mathbf{a} \cdot \mathbf{c}) \\ (\mathbf{a} \times \mathbf{c}) \times \mathbf{b} - (\mathbf{a} \cdot \mathbf{c}) \mathbf{b} = \mathbf{a} \times (\mathbf{c} \times \mathbf{b}) - \mathbf{a}(\mathbf{c} \cdot \mathbf{b}) \\ (\mathbf{c} \times \mathbf{b}) \times \mathbf{a} - (\mathbf{c} \cdot \mathbf{b}) \mathbf{a} = \mathbf{c} \times (\mathbf{b} \times \mathbf{a}) - \mathbf{c}(\mathbf{b} \cdot \mathbf{a}) \end{array} \right. \quad \left\{ \begin{array}{l} \begin{pmatrix} a & b & c \\ a & b & c \\ a & b & c \\ b & c & a \\ a & b & c \\ c & a & b \end{pmatrix}, v_1 \\ \begin{pmatrix} a & b & c \\ a & b & c \\ a & b & c \\ b & c & a \\ a & b & c \\ b & a & c \end{pmatrix}, v_2 \\ \begin{pmatrix} a & b & c \\ a & b & c \\ a & b & c \\ c & a & b \\ a & b & c \\ a & c & b \end{pmatrix}, v_3 \\ \begin{pmatrix} a & b & c \\ a & b & c \\ a & b & c \\ b & a & c \\ a & b & c \\ b & a & c \end{pmatrix}, v_4 \\ \begin{pmatrix} a & b & c \\ a & b & c \\ a & c & b \\ a & b & c \\ a & c & b \\ a & b & c \end{pmatrix}, v_5 \\ \begin{pmatrix} a & b & c \\ a & b & c \\ c & b & a \\ c & b & a \end{pmatrix}, v_6 \end{array} \right.$$

$$\Rightarrow \left\{ \begin{array}{l} -Z - C = X - A \quad v_1 \\ -X - A = Y - B \quad v_2 \\ -Y - B = Z - C \quad v_3 \\ Z - C = -Y - B \quad v_4 \\ Y - B = -X - A \quad v_5 \\ X - A = -Z - C \quad v_6 \end{array} \right. , \left\{ \begin{array}{ll} \cdot \text{ and scalar-vector product} & \text{commutative} \\ \times & \text{anticommutative} \end{array} \right. ,$$

$$\left\{ \begin{array}{l} X = \mathbf{a} \times (\mathbf{b} \times \mathbf{c}) = -(\mathbf{b} \times \mathbf{c}) \times \mathbf{a} = -\mathbf{a} \times (\mathbf{c} \times \mathbf{b}) = (\mathbf{c} \times \mathbf{b}) \times \mathbf{a} \\ Y = \mathbf{b} \times (\mathbf{c} \times \mathbf{a}) = -(\mathbf{c} \times \mathbf{a}) \times \mathbf{b} = -\mathbf{b} \times (\mathbf{a} \times \mathbf{c}) = (\mathbf{a} \times \mathbf{c}) \times \mathbf{b} \\ Z = \mathbf{c} \times (\mathbf{a} \times \mathbf{b}) = -(\mathbf{a} \times \mathbf{b}) \times \mathbf{c} = -\mathbf{c} \times (\mathbf{b} \times \mathbf{a}) = (\mathbf{b} \times \mathbf{a}) \times \mathbf{c} \\ A = \mathbf{a}(\mathbf{b} \cdot \mathbf{c}) = \mathbf{a}(\mathbf{c} \cdot \mathbf{b}) = (\mathbf{c} \cdot \mathbf{b}) \mathbf{a} = (\mathbf{b} \cdot \mathbf{c}) \mathbf{a} \\ B = \mathbf{b}(\mathbf{c} \cdot \mathbf{a}) = \mathbf{b}(\mathbf{a} \cdot \mathbf{c}) = (\mathbf{a} \cdot \mathbf{c}) \mathbf{b} = (\mathbf{c} \cdot \mathbf{a}) \mathbf{b} \\ C = \mathbf{c}(\mathbf{a} \cdot \mathbf{b}) = \mathbf{c}(\mathbf{b} \cdot \mathbf{a}) = (\mathbf{b} \cdot \mathbf{a}) \mathbf{c} = (\mathbf{a} \cdot \mathbf{b}) \mathbf{c} \end{array} \right.$$

$$\Rightarrow \left\{ \begin{array}{l} -Z - C = X - A \quad v_1 = v_6 \\ -X - A = Y - B \quad v_2 = v_5 \\ -Y - B = Z - C \quad v_3 = v_4 \end{array} \right. \Leftrightarrow \left\{ \begin{array}{l} Z + X = A - C \\ X + Y = B - A \\ Y + Z = C - B \end{array} \right. \Leftrightarrow \left\{ \begin{array}{l} X + Y = B - A \\ Y + Z = C - B \\ Z + X = A - C \end{array} \right.$$

$$\Leftrightarrow \left\{ \begin{array}{l} 2(X + Y + Z) = 0 \Rightarrow X + Y + Z = 0 \\ Y + Z = C - B \Rightarrow X = B - C \Leftrightarrow \mathbf{a} \times (\mathbf{b} \times \mathbf{c}) = \mathbf{b}(\mathbf{c} \cdot \mathbf{a}) - \mathbf{c}(\mathbf{a} \cdot \mathbf{b}) \text{ "back cab"} \\ Z + X = A - C \Rightarrow Y = C - A \Leftrightarrow \mathbf{b} \times (\mathbf{c} \times \mathbf{a}) = \mathbf{c}(\mathbf{a} \cdot \mathbf{b}) - \mathbf{a}(\mathbf{b} \cdot \mathbf{c}) \\ X + Y = B - A \Rightarrow Z = A - B \Leftrightarrow \mathbf{c} \times (\mathbf{a} \times \mathbf{b}) = \mathbf{a}(\mathbf{b} \cdot \mathbf{c}) - \mathbf{b}(\mathbf{c} \cdot \mathbf{a}) \end{array} \right.$$

34.1.3.5 differential operator

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

34.1.3.5.1 4-differential operator 4-differential operator / four-differential operator = d'Alembert operator

$$\begin{aligned}
D &= \frac{\partial}{\partial t} + i \frac{\partial}{\partial x} + j \frac{\partial}{\partial y} + k \frac{\partial}{\partial z} = \partial_t + i \partial_x + j \partial_y + k \partial_z \\
&= \frac{\partial}{\partial t} + i \frac{\partial}{\partial x} + j \frac{\partial}{\partial y} + k \frac{\partial}{\partial z} = \partial_t + i \partial_x + j \partial_y + k \partial_z \\
&= \frac{\partial}{\partial x_0} + e_1 \frac{\partial}{\partial x_1} + e_2 \frac{\partial}{\partial x_2} + e_3 \frac{\partial}{\partial x_3} = \partial_0 + e_i \partial_i = \partial_0 + \nabla
\end{aligned}$$

$$D = \partial_0 + i \partial_1 + j \partial_2 + k \partial_3 = \partial_0 + \nabla = D_0 + \mathbf{D}$$

34.1.3.5.2 nabla nabla = spatial differential operator = 3-differential operator / three-differential operator

$$\nabla = e_i \partial_i = \sum_{i=1}^3 e_i \partial_i = \sum_{i=1}^3 e_i \frac{\partial}{\partial x_i} = \left(\frac{\partial}{\partial x} \quad \frac{\partial}{\partial y} \quad \frac{\partial}{\partial z} \right)^\top = \begin{pmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} \end{pmatrix}$$

34.1.3.5.3 Laplace operator Laplace operator = Laplacian

$$\Delta = \nabla^2 = \nabla \cdot \nabla = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

34.1.3.5.4 d'Alembert operator

$$\square = \square_c = \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial z^2} = \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \Delta = \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \nabla^2$$

$$\square_1 = \square_{c=1} = \frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial z^2} = \frac{\partial^2}{\partial t^2} - \Delta = \frac{\partial^2}{\partial t^2} - \nabla^2$$

34.1.3.6 electromagnetism

Maxwell

34.1.3.6.1 4-potential electromagnetic 4-potential / four-potential

$$A = A_0 + i A_1 + j A_2 + k A_3 = A_0 + \mathbf{A}$$

4-differential operator^[34.1.3.5.1]

$$D = \partial_0 + i \partial_1 + j \partial_2 + k \partial_3 = \partial_0 + \nabla = D_0 + \mathbf{D}$$

$$QP = (Q_0 P_0 - \mathbf{Q} \cdot \mathbf{P}) + (Q_0 \mathbf{P} + P_0 \mathbf{Q} + \mathbf{Q} \times \mathbf{P})$$

commutative bracket^[34.1.3.3.1.1]

$$\begin{aligned}
[\mathbf{D}, \mathbf{A}] &= \frac{\mathbf{D}\mathbf{A} - \mathbf{A}\mathbf{D}}{2} \\
2[\mathbf{D}, \mathbf{A}] &= \mathbf{D}\mathbf{A} - \mathbf{A}\mathbf{D} \\
&= (\partial_0 + i\partial_1 + j\partial_2 + k\partial_3)(A_0 + iA_1 + jA_2 + kA_3) \\
&\quad - (A_0 + iA_1 + jA_2 + kA_3)(\partial_0 + i\partial_1 + j\partial_2 + k\partial_3) \\
\mathbf{D}\mathbf{A} &= (\mathbf{D}_0\mathbf{A}_0 - \mathbf{D} \cdot \mathbf{A}) + (\mathbf{D}_0\mathbf{A} + \mathbf{A}_0\mathbf{D} + \mathbf{D} \times \mathbf{A}) \\
&= (\mathbf{D}_0\mathbf{A}_0 - \mathbf{D} \cdot \mathbf{A}) + (\mathbf{D}_0\mathbf{A} + \mathbf{D}\mathbf{A}_0 + \mathbf{D} \times \mathbf{A}) \\
&= \mathbf{D}_0(\mathbf{A}_0 + \mathbf{A}) - \mathbf{D} \cdot \mathbf{A} + \mathbf{D}\mathbf{A}_0 + \mathbf{D} \times \mathbf{A} \\
&= \mathbf{D}_0\mathbf{A} - \mathbf{D} \cdot \mathbf{A} + \mathbf{D}\mathbf{A}_0 + \mathbf{D} \times \mathbf{A} \\
&= \partial_0\mathbf{A} - \nabla \cdot \mathbf{A} + \nabla\mathbf{A}_0 + \nabla \times \mathbf{A} \\
\mathbf{A}\mathbf{D} &= (A_0\mathbf{D}_0 - \mathbf{A} \cdot \mathbf{D}) + (A_0\mathbf{D} + \mathbf{D}_0\mathbf{A} + \mathbf{A} \times \mathbf{D}) \\
&= (\mathbf{D}_0\mathbf{A}_0 - \mathbf{D} \cdot \mathbf{A}) + (\mathbf{D}\mathbf{A}_0 + \mathbf{D}_0\mathbf{A} - \mathbf{D} \times \mathbf{A}) \\
&= (\mathbf{D}_0\mathbf{A}_0 - \mathbf{D} \cdot \mathbf{A}) + (\mathbf{D}_0\mathbf{A} + \mathbf{D}\mathbf{A}_0 - \mathbf{D} \times \mathbf{A}) \\
&= \mathbf{D}_0(\mathbf{A}_0 + \mathbf{A}) - \mathbf{D} \cdot \mathbf{A} + \mathbf{D}\mathbf{A}_0 - \mathbf{D} \times \mathbf{A} \\
&= \mathbf{D}_0\mathbf{A} - \mathbf{D} \cdot \mathbf{A} + \mathbf{D}\mathbf{A}_0 - \mathbf{D} \times \mathbf{A} \\
&= \partial_0\mathbf{A} - \nabla \cdot \mathbf{A} + \nabla\mathbf{A}_0 - \nabla \times \mathbf{A}
\end{aligned}$$

$$\begin{aligned}
\mathbf{D}\mathbf{A} &= \mathbf{D}_0\mathbf{A} - \mathbf{D} \cdot \mathbf{A} + \mathbf{D}\mathbf{A}_0 + \mathbf{D} \times \mathbf{A} = \partial_0\mathbf{A} - \nabla \cdot \mathbf{A} + \nabla\mathbf{A}_0 + \nabla \times \mathbf{A} \\
\mathbf{A}\mathbf{D} &= \mathbf{D}_0\mathbf{A} - \mathbf{D} \cdot \mathbf{A} + \mathbf{D}\mathbf{A}_0 - \mathbf{D} \times \mathbf{A} = \partial_0\mathbf{A} - \nabla \cdot \mathbf{A} + \nabla\mathbf{A}_0 - \nabla \times \mathbf{A}
\end{aligned}$$

$$\begin{aligned}
\mathbf{D}\mathbf{A} - \mathbf{A}\mathbf{D} &= 2\mathbf{D} \times \mathbf{A} = 2\nabla \times \mathbf{A} \\
[\mathbf{D}, \mathbf{A}] &= \frac{\mathbf{D}\mathbf{A} - \mathbf{A}\mathbf{D}}{2} = \mathbf{D} \times \mathbf{A} = \nabla \times \mathbf{A}
\end{aligned}$$

anticommutative bracket^[34.1.3.3.1.2]

$$\begin{aligned}
\mathbf{D}\mathbf{A} + \mathbf{A}\mathbf{D} &= 2(\mathbf{D}_0\mathbf{A} - \mathbf{D} \cdot \mathbf{A} + \mathbf{D}\mathbf{A}_0) = 2(\partial_0\mathbf{A} - \nabla \cdot \mathbf{A} + \nabla\mathbf{A}_0) \\
\{\mathbf{D}, \mathbf{A}\} &= \frac{\mathbf{D}\mathbf{A} + \mathbf{A}\mathbf{D}}{2} = \mathbf{D}_0\mathbf{A} - \mathbf{D} \cdot \mathbf{A} + \mathbf{D}\mathbf{A}_0 = \partial_0\mathbf{A} - \nabla \cdot \mathbf{A} + \nabla\mathbf{A}_0
\end{aligned}$$

commutation and anticommutation on differential operator and any quaternion

$$\begin{aligned}
[\mathbf{D}, \mathbf{Q}] &= \nabla \times \mathbf{Q} \\
\{\mathbf{D}, \mathbf{Q}\} &= \partial_0\mathbf{Q} - \nabla \cdot \mathbf{Q} + \nabla Q_0
\end{aligned}$$

or more evident

$$\begin{aligned}
[\mathbf{D}, \mathbf{Q}] &= \nabla \times \mathbf{Q} \\
\{\mathbf{D}, \mathbf{Q}\} &= \partial_0\mathbf{Q} - \nabla \cdot \mathbf{Q} + \nabla Q_0 \\
&= \partial_0(Q_0 + \mathbf{Q}) - \nabla \cdot \mathbf{Q} + \nabla Q_0 \\
&= (\partial_0 Q_0 - \nabla \cdot \mathbf{Q}) + (\partial_0 \mathbf{Q} + \nabla Q_0) \\
&= \left(\frac{\partial Q_0}{\partial t} - \nabla \cdot \mathbf{Q} \right) + \left(\frac{\partial \mathbf{Q}}{\partial t} + \nabla Q_0 \right)
\end{aligned}$$

34.1.3.6.2 Maxwell compromise for both quaternion and 3-vector electric potential and vector potential

$$A = A_0 + iA_1 + jA_2 + kA_3 = A_0 + \mathbf{A} = U + \mathbf{A}$$

electric quaternion and electric field

$$\begin{aligned} E &= -\{\mathbf{D}, A\} \\ &= -(\partial_0 A - \nabla \cdot \mathbf{A} + \nabla A_0) \\ &= -\partial_0 A + \nabla \cdot \mathbf{A} - \nabla A_0 \\ &= -\partial_t (U + \mathbf{A}) + \nabla \cdot \mathbf{A} - \nabla U \\ &= -\frac{\partial U}{\partial t} + \nabla \cdot \mathbf{A} - \nabla U - \frac{\partial \mathbf{A}}{\partial t} \\ &= E_0 + \mathbf{E}, \quad \begin{cases} E_0 = -\frac{\partial U}{\partial t} + \nabla \cdot \mathbf{A} \\ \mathbf{E} = -\nabla U - \frac{\partial \mathbf{A}}{\partial t} \end{cases} \quad \text{electric field 3-vector} \end{aligned}$$

magnetic field

$$B = [\mathbf{D}, A] = \nabla \times \mathbf{A} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ A_1 & A_2 & A_3 \end{vmatrix} = \mathbf{B}$$

Work on time? Yes.

$$qE = qE_0 + q\mathbf{E} = qE_0 + \mathbf{F}_E$$

force equivalent on time

$$qE_0$$

$$\begin{cases} E = -\{\mathbf{D}, A\} = E_0 + \mathbf{E} \\ B = +[\mathbf{D}, A] = B_0 + \mathbf{B} = 0 + \mathbf{B} = \mathbf{B} \quad B_0 = 0 \end{cases}$$

for any quaternion commuting and anticommutating with differential operator

$$\begin{aligned} [\mathbf{D}, Q] &= \nabla \times \mathbf{Q} \\ \{\mathbf{D}, Q\} &= \partial_0 Q - \nabla \cdot \mathbf{Q} + \nabla Q_0 \\ &= \partial_0 (Q_0 + \mathbf{Q}) - \nabla \cdot \mathbf{Q} + \nabla Q_0 \\ &= (\partial_0 Q_0 - \nabla \cdot \mathbf{Q}) + (\partial_0 \mathbf{Q} + \nabla Q_0) \\ &= \left(\frac{\partial Q_0}{\partial t} - \nabla \cdot \mathbf{Q} \right) + \left(\frac{\partial \mathbf{Q}}{\partial t} + \nabla Q_0 \right) \end{aligned}$$

$$\begin{cases} [\mathbf{D}, \mathbf{E}] = \nabla \times \mathbf{E} = (0) + (\nabla \times \mathbf{E}) \\ \{\mathbf{D}, \mathbf{E}\} = (\partial_0 E_0 - \nabla \cdot \mathbf{E}) + (\partial_0 \mathbf{E} + \nabla E_0) = \left(\frac{\partial E_0}{\partial t} - \nabla \cdot \mathbf{E} \right) + \left(\frac{\partial \mathbf{E}}{\partial t} + \nabla E_0 \right) \\ [\mathbf{D}, \mathbf{B}] = \nabla \times \mathbf{B} = (0) + (\nabla \times \mathbf{B}) \\ \{\mathbf{D}, \mathbf{B}\} = (\partial_0 B_0 - \nabla \cdot \mathbf{B}) + (\partial_0 \mathbf{B} + \nabla B_0) \stackrel{B_0=0}{=} -\nabla \cdot \mathbf{B} + \partial_0 \mathbf{B} = (-\nabla \cdot \mathbf{B}) + \left(\frac{\partial \mathbf{B}}{\partial t} \right) \end{cases}$$

by comparing (real & imaginary) / (scalar & vector) parts,

Maxwell equations without source terms

$$\begin{aligned} \begin{cases} [\mathbf{D}, \mathbf{B}] = +\{\mathbf{D}, \mathbf{E}\} \Leftrightarrow (0) + (\nabla \times \mathbf{B}) = \left(\frac{\partial E_0}{\partial t} - \nabla \cdot \mathbf{E} \right) + \left(\frac{\partial \mathbf{E}}{\partial t} + \nabla E_0 \right) \\ \{\mathbf{D}, \mathbf{E}\} = -\{\mathbf{D}, \mathbf{B}\} \Leftrightarrow (0) + (\nabla \times \mathbf{E}) = (-\nabla \cdot \mathbf{B}) + \left(\frac{\partial \mathbf{B}}{\partial t} \right) \end{cases} \\ \Leftrightarrow \begin{cases} \frac{\partial E_0}{\partial t} - \nabla \cdot \mathbf{E} = 0 \Leftrightarrow \nabla \cdot \mathbf{E} = \frac{\partial E_0}{\partial t} \\ \frac{\partial \mathbf{E}}{\partial t} + \nabla E_0 = \nabla \times \mathbf{B} \Leftrightarrow \nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \nabla E_0 \text{ 動電生磁} \\ -\nabla \cdot \mathbf{B} = 0 \Leftrightarrow \nabla \cdot \mathbf{B} = 0 \\ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E} \Leftrightarrow \nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t} \text{ 動磁生電} \end{cases} \end{aligned}$$

34.1.3.7 Joule heat vs. Thomson heat (Kelvin heat?)

The Lord Kelvin = William Thomson

34.1.3.7.1 thermoelectric effect thermoelectric effect = Seebeck effect = Peltier effect = Thomson effect

34.1.3.8 source term

$$J = J_0 + iJ_1 + jJ_2 + kJ_3 = J_0 + \mathbf{J} = \rho + \mathbf{J}$$

Maxwell equations with source terms

$$\begin{aligned} \begin{cases} [\mathbf{D}, \mathbf{B}] = J + \{\mathbf{D}, \mathbf{E}\} \Leftrightarrow (0) + (\nabla \times \mathbf{B}) = \left(\rho + \frac{\partial E_0}{\partial t} - \nabla \cdot \mathbf{E} \right) + \left(\mathbf{J} + \frac{\partial \mathbf{E}}{\partial t} + \nabla E_0 \right) \\ \{\mathbf{D}, \mathbf{E}\} = 0 - \{\mathbf{D}, \mathbf{B}\} \Leftrightarrow (0) + (\nabla \times \mathbf{E}) = (-\nabla \cdot \mathbf{B}) + \left(\frac{\partial \mathbf{B}}{\partial t} \right) \end{cases} \\ \Leftrightarrow \begin{cases} \rho + \frac{\partial E_0}{\partial t} - \nabla \cdot \mathbf{E} = 0 \Leftrightarrow \nabla \cdot \mathbf{E} = \rho + \frac{\partial E_0}{\partial t} \\ \mathbf{J} + \frac{\partial \mathbf{E}}{\partial t} + \nabla E_0 = \nabla \times \mathbf{B} \Leftrightarrow \nabla \times \mathbf{B} = \mathbf{J} + \frac{\partial \mathbf{E}}{\partial t} + \nabla E_0 \text{ 動電生磁} \\ -\nabla \cdot \mathbf{B} = 0 \Leftrightarrow \nabla \cdot \mathbf{B} = 0 \\ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E} \Leftrightarrow \nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t} \text{ 動磁生電} \end{cases} \end{aligned}$$

34.1.4 quaternion group

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

group theory^[37]

or please first see quaternion group representation^[37.5].

34.1.4.1 2D rotation

34.1.4.1.1 matrix

$$\mathbf{r} = (x, y) = \langle x, y \rangle = \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} r \cos \alpha \\ r \sin \alpha \end{pmatrix}$$

$$\mathbf{r}' = (x', y') = \langle x', y' \rangle = \begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} r \cos(\alpha + \theta) \\ r \sin(\alpha + \theta) \end{pmatrix}$$

$$\begin{aligned} \mathbf{r}' &= \begin{pmatrix} r \cos(\alpha + \theta) \\ r \sin(\alpha + \theta) \end{pmatrix} = r \begin{pmatrix} \cos(\alpha + \theta) \\ \sin(\alpha + \theta) \end{pmatrix} \\ &= r \begin{pmatrix} \cos \alpha \cos \theta - \sin \alpha \sin \theta \\ \sin \alpha \cos \theta + \cos \alpha \sin \theta \end{pmatrix} = r \begin{pmatrix} \cos \theta \cos \alpha - \sin \theta \sin \alpha \\ \sin \theta \cos \alpha + \cos \theta \sin \alpha \end{pmatrix} \\ &= r \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \cos \alpha \\ \sin \alpha \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} r \cos \alpha \\ r \sin \alpha \end{pmatrix} \\ &= R \mathbf{r}, \quad \begin{cases} R = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} = R(\theta) = R_\theta \\ \mathbf{r} = \begin{pmatrix} r \cos \alpha \\ r \sin \alpha \end{pmatrix}, \mathbf{r}' = \begin{pmatrix} r \cos(\alpha + \theta) \\ r \sin(\alpha + \theta) \end{pmatrix} \end{cases} \end{aligned}$$

orthonormal matrix

$$\mathbf{r}' = O \mathbf{r}$$

$$\begin{aligned} |\mathbf{r}'|^2 &= |\mathbf{r}|^2 \\ \mathbf{r}' \cdot \mathbf{r}' &= \mathbf{r} \cdot \mathbf{r} \\ \mathbf{r}'^\top \mathbf{r}' &= \mathbf{r}^\top \mathbf{r} \\ (O \mathbf{r})^\top (O \mathbf{r}) &= \\ \mathbf{r}^\top O^\top O \mathbf{r} &= \\ \mathbf{r}^\top O^\top O \mathbf{r} &= \mathbf{r}^\top \mathbf{r} \\ O^\top O &= 1 = I = I_2 \end{aligned}$$

$$\begin{aligned} R^\top R &= \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}^\top \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \\ &= \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \\ &= \begin{pmatrix} \cos^2 \theta + \sin^2 \theta & -\cos \theta \sin \theta + \sin \theta \cos \theta \\ -\sin \theta \cos \theta + \cos \theta \sin \theta & \sin^2 \theta + \cos^2 \theta \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = 1 = I \end{aligned}$$

$$R^\top R = 1 \Rightarrow R \in \{O | O^\top O = 1\}$$

reflection matrix

$$\begin{cases} P_x = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} & P_x^\top P_x = P_x^2 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}^2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = 1 \Rightarrow P_x \in \{O | O^\top O = 1\} \\ P_y = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} & P_y^\top P_y = P_y^2 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}^2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = 1 \Rightarrow P_y \in \{O | O^\top O = 1\} \end{cases}$$

translation matrix?

$$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = 1$$

$$\begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = 1$$

$O(2)$ group

$$\begin{aligned} O(2) &= \{1, R, P_x, P_y\} \\ &= \{I_2, R_\theta, P_x, P_y\} \subseteq \{O | O^\top O = 1\} \end{aligned}$$

$$\begin{aligned} 1 &= O^\top O \\ 1 &= \det 1 = \det I = \det(I_2) \\ &= \det(O^\top O) = (\det O^\top)(\det O) = (\det O)(\det O) = (\det O)^2 \\ 1 &= (\det O)^2 \\ \det O &= \pm 1 \end{aligned}$$

$$\det R = \det R_\theta = \begin{vmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{vmatrix} = \cos^2 \theta - (-\sin^2 \theta) = \cos^2 \theta + \sin^2 \theta = 1$$

$$\begin{cases} P_x = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} & \det P_x = -1 \\ P_y = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} & \det P_y = -1 \end{cases}$$

special orthonormal group of degree 2

$$\begin{aligned} SO(2) &= \{1, R\} = \{I_2, R_\theta\} \subseteq \left\{ O \middle| \begin{cases} O^\top O = 1 & O \\ \det O = 1 & S \end{cases} \right\} \\ &\subset \{1, R, P_x, P_y\} = O(2) \subseteq \{O | O^\top O = 1\} \end{aligned}$$

34.1.4.1.2 complex

$$z = r(\cos \alpha + i \sin \alpha) = r e^{i\alpha}$$

$$z' = r(\cos(\alpha + \theta) + i \sin(\alpha + \theta)) = r e^{i(\alpha+\theta)}$$

$$z' = z_\theta z$$

$$z_\theta = \frac{z'}{z} = \frac{r' e^{i(\alpha+\theta)}}{r e^{i\alpha}} = \frac{r'}{r} e^{i\theta} = \frac{r'}{r} (\cos \theta + i \sin \theta)$$

$$\begin{aligned} z_\theta z &= \left[\frac{r'}{r} (\cos \theta + i \sin \theta) \right] [r (\cos \alpha + i \sin \alpha)] \\ &= r' [(\cos \theta \cos \alpha - \sin \theta \sin \alpha) + i (\sin \theta \cos \alpha + \cos \theta \sin \alpha)] \\ &= r' [\cos(\alpha + \theta) + i \sin(\alpha + \theta)] = z' \end{aligned}$$

$$\hat{z}_\theta = z_\theta \left(\frac{r'}{r} = 1 \right) = e^{i\theta} = \cos \theta + i \sin \theta$$

$$\hat{z}_\theta^* = \overline{\hat{z}_\theta} = e^{-i\theta} = \cos \theta - i \sin \theta$$

$$\hat{z}_\theta^* \hat{z}_\theta = e^{i\theta} e^{-i\theta} = e^{i\theta + (-i\theta)} = e^{i0} = e^0 = 1$$

unitary group of degree 1

$$U(1) = \{1, \hat{z}_\theta\} = \{e^{i0}, e^{i\theta}\}$$

34.1.4.1.3 $SO(2) \cong U(1) \quad \mathbb{C} \leftrightarrow \mathcal{M}_{2 \times 2}(\mathbb{R}) = \mathcal{M}_2(\mathbb{R})$ complex group representation^[37.4]

$$x + yi \leftrightarrow \begin{pmatrix} x & -y \\ y & x \end{pmatrix} = xI + yJ$$

$$\begin{aligned} U(1) &= \{1, \hat{z}_\theta\} = \{e^{i0}, e^{i\theta}\} \\ &= \{\cos 0 + i \sin 0, \cos \theta + i \sin \theta\} \\ &\leftrightarrow \left\{ \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \cos 0 + \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \sin 0, \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \cos \theta + \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \sin \theta \right\} \\ &= \left\{ \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} 1 + \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} 0, \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \cos \theta + \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \sin \theta \right\} \\ &= \left\{ \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \right\} = \{I_2, R_\theta\} = \{1, R\} = SO(2) \end{aligned}$$

$$U(1) \cong SO(2) \Leftrightarrow SO(2) \cong U(1)$$

unitary group of degree 1 and special orthonormal group of degree 2 are isomorphism

34.1.4.2 3D rotation**34.1.4.2.1 matrix**

34.1.4.2.1.1 construction with 2D rotation matrix

$$\begin{aligned} \mathbf{r}' &= \begin{pmatrix} r \cos(\alpha + \theta) \\ r \sin(\alpha + \theta) \\ z' \end{pmatrix} \stackrel{z' = z}{=} \begin{pmatrix} r \cos(\alpha + \theta) \\ r \sin(\alpha + \theta) \\ z \end{pmatrix} = \begin{pmatrix} R(\theta) & \\ & 1 \end{pmatrix} \begin{pmatrix} r \cos \alpha \\ r \sin \alpha \\ z \end{pmatrix} \\ &= \begin{pmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} r \cos \alpha \\ r \sin \alpha \\ z \end{pmatrix} = R_z(\theta) \mathbf{r}, \quad \begin{cases} R_z(\theta) = \begin{pmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ \mathbf{r} = \begin{pmatrix} r \cos \alpha \\ r \sin \alpha \\ z \end{pmatrix} \end{cases} \end{aligned}$$

$$\begin{aligned} \mathbf{r}' &= \begin{pmatrix} x' \\ r \cos(\alpha + \theta) \\ r \sin(\alpha + \theta) \end{pmatrix} \stackrel{x' = x}{=} \begin{pmatrix} x \\ r \cos(\alpha + \theta) \\ r \sin(\alpha + \theta) \end{pmatrix} = \begin{pmatrix} 1 & \\ & R(\theta) \end{pmatrix} \begin{pmatrix} x \\ r \cos \alpha \\ r \sin \alpha \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} x \\ r \cos \alpha \\ r \sin \alpha \end{pmatrix} = R_x(\theta) \mathbf{r}, \quad \begin{cases} R_x(\theta) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{pmatrix} \\ \mathbf{r} = \begin{pmatrix} x \\ r \cos \alpha \\ r \sin \alpha \end{pmatrix} \end{cases} \end{aligned}$$

$$\begin{aligned} \mathbf{r}' &= \begin{pmatrix} r \sin(\alpha + \theta) \\ y' \\ r \cos(\alpha + \theta) \end{pmatrix} \stackrel{y' = y}{=} \begin{pmatrix} r \sin(\alpha + \theta) \\ y \\ r \cos(\alpha + \theta) \end{pmatrix} \\ &= \begin{pmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{pmatrix} \begin{pmatrix} r \sin \alpha \\ y \\ r \cos \alpha \end{pmatrix} = R_y(\theta) \mathbf{r}, \quad \begin{cases} R_y(\theta) = \begin{pmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{pmatrix} \\ \mathbf{r} = \begin{pmatrix} r \sin \alpha \\ y \\ r \cos \alpha \end{pmatrix} \end{cases} \end{aligned}$$

34.1.4.2.1.2 Euler angle $z \rightarrow x \rightarrow z : \alpha \rightarrow \beta \rightarrow \gamma$

$$\begin{aligned} &R_z(\gamma) R_x(\beta) R_z(\alpha) \\ &= \begin{pmatrix} \cos \gamma & -\sin \gamma & 0 \\ \sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \beta & -\sin \beta \\ 0 & \sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} \cos \alpha & -\sin \alpha & 0 \\ \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ &= \begin{pmatrix} \cos \gamma & -\sin \gamma & 0 \\ \sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \alpha & -\sin \alpha & 0 \\ \cos \beta \sin \alpha & \cos \beta \cos \alpha & -\sin \beta \\ \sin \beta \sin \alpha & \sin \beta \cos \alpha & \cos \beta \end{pmatrix} \\ &= \begin{pmatrix} \cos \gamma \cos \alpha - \sin \gamma \cos \beta \sin \alpha & -\cos \gamma \sin \alpha - \sin \gamma \cos \beta \cos \alpha & \sin \gamma \sin \beta \\ \sin \gamma \cos \alpha + \cos \gamma \cos \beta \sin \alpha & -\sin \gamma \sin \alpha - \cos \gamma \cos \beta \cos \alpha & -\cos \gamma \sin \beta \\ \sin \beta \sin \alpha & \sin \beta \cos \alpha & \cos \beta \end{pmatrix} \end{aligned}$$

$x \rightarrow y \rightarrow z : \alpha \rightarrow \beta \rightarrow \gamma$

$$\begin{aligned}
& R_z(\gamma) R_y(\beta) R_x(\alpha) \\
&= \begin{pmatrix} \cos \gamma & -\sin \gamma & 0 \\ \sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \beta & 0 & \sin \beta \\ 0 & 1 & 0 \\ -\sin \beta & 0 & \cos \beta \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha \\ 0 & \sin \alpha & \cos \alpha \end{pmatrix} \\
&= \begin{pmatrix} \cos \gamma & -\sin \gamma & 0 \\ \sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \beta & \sin \beta \sin \alpha & \sin \beta \cos \alpha \\ 0 & \cos \alpha & -\sin \alpha \\ -\sin \beta & \cos \beta \sin \alpha & \cos \beta \cos \alpha \end{pmatrix} \\
&= \begin{pmatrix} \cos \gamma \cos \beta & \cos \gamma \sin \beta \sin \alpha - \sin \gamma \cos \alpha & \cos \gamma \sin \beta \cos \alpha + \sin \gamma \sin \alpha \\ \sin \gamma \cos \beta & \sin \gamma \sin \beta \sin \alpha + \cos \gamma \cos \alpha & \sin \gamma \sin \beta \cos \alpha - \cos \gamma \sin \alpha \\ -\sin \beta & \cos \beta \sin \alpha & \cos \beta \cos \alpha \end{pmatrix}
\end{aligned}$$

34.1.4.2.1.3 3D rotation about an arbitrary axis <https://math.stackexchange.com/questions/4550704/rotation-around-an-arbitrary-axis>

spherical coordinate unit vector

$$\begin{cases} \hat{x} = r \sin \theta \cos \phi & \stackrel{r=1}{=} \sin \theta \cos \phi \\ \hat{y} = r \sin \theta \sin \phi & \stackrel{r=1}{=} \sin \theta \sin \phi \\ \hat{z} = r \cos \theta & \stackrel{r=1}{=} \cos \theta \end{cases}$$

although I prefer θ and ϕ switched back to be compatible with 2D coordinate

$$\begin{cases} \hat{x} = r \sin \phi \cos \theta & \stackrel{r=1}{=} \sin \phi \cos \theta \\ \hat{y} = r \sin \phi \sin \theta & \stackrel{r=1}{=} \sin \phi \sin \theta \\ \hat{z} = r \cos \phi & \stackrel{r=1}{=} \cos \phi \end{cases}$$

or cos first in x, y -plane

$$\begin{cases} \hat{x} = r \cos \phi \cos \theta & \stackrel{r=1}{=} \cos \phi \cos \theta \\ \hat{y} = r \cos \phi \sin \theta & \stackrel{r=1}{=} \cos \phi \sin \theta \\ \hat{z} = r \sin \phi & \stackrel{r=1}{=} \sin \phi \end{cases}$$

still use the most convention

$$\hat{\mathbf{n}} = \begin{pmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{pmatrix} = \begin{pmatrix} \sin \theta \cos \phi \\ \sin \theta \sin \phi \\ \cos \theta \end{pmatrix}$$

$$\left\{ \begin{array}{l} \hat{n} = \begin{pmatrix} \sin \theta \cos \phi \\ \sin \theta \sin \phi \\ \cos \theta \end{pmatrix} \\ \hat{u} = \begin{pmatrix} \cos \theta \cos \phi \\ \cos \theta \sin \phi \\ -\sin \theta \end{pmatrix} \Leftrightarrow \cos \theta \sin \theta - \cos \theta \sin \theta = 0 \Rightarrow \hat{u} \cdot \hat{n} = 0 \Leftrightarrow \hat{u} \perp \hat{n} \\ \hat{v} = \hat{n} \times \hat{u} = \begin{vmatrix} i & j & k \\ \sin \theta \cos \phi & \sin \theta \sin \phi & \cos \theta \\ \cos \theta \cos \phi & \cos \theta \sin \phi & -\sin \theta \end{vmatrix} = \begin{pmatrix} -\sin \phi \\ \cos \phi \\ 0 \end{pmatrix} \Rightarrow \begin{cases} \hat{v} \perp \hat{n} \\ \hat{v} \perp \hat{u} \end{cases} \end{array} \right.$$

$S = \{\hat{n}, \hat{u}, \hat{v}\} = \{\hat{u}, \hat{v}, \hat{n}\}$ is a basis of the spherical coordinate

$$[\mathbf{V}]_S = \begin{pmatrix} u \\ v \\ n \end{pmatrix}$$

$$\begin{aligned} \mathbf{V} &= (\hat{u} \quad \hat{v} \quad \hat{n}) \begin{pmatrix} u \\ v \\ n \end{pmatrix} = u\hat{u} + v\hat{v} + n\hat{n} \\ &= \begin{pmatrix} \cos \theta \cos \phi & -\sin \phi & \sin \theta \cos \phi \\ \cos \theta \sin \phi & \cos \phi & \sin \theta \sin \phi \\ -\sin \theta & 0 & \cos \theta \end{pmatrix} \begin{pmatrix} u \\ v \\ n \end{pmatrix} = S [\mathbf{V}]_S \\ \begin{pmatrix} u \\ v \\ n \end{pmatrix} &= \begin{pmatrix} \cos \theta \cos \phi & -\sin \phi & \sin \theta \cos \phi \\ \cos \theta \sin \phi & \cos \phi & \sin \theta \sin \phi \\ -\sin \theta & 0 & \cos \theta \end{pmatrix}^{-1} \mathbf{V} \\ [\mathbf{V}]_S &= S^{-1} \mathbf{V} \end{aligned}$$

$$\begin{aligned} S^{-1} &= \begin{pmatrix} \cos \theta \cos \phi & -\sin \phi & \sin \theta \cos \phi \\ \cos \theta \sin \phi & \cos \phi & \sin \theta \sin \phi \\ -\sin \theta & 0 & \cos \theta \end{pmatrix}^{-1}, S \in \{O | O^T O = 1\} \\ &= \begin{pmatrix} \cos \theta \cos \phi & -\sin \phi & \sin \theta \cos \phi \\ \cos \theta \sin \phi & \cos \phi & \sin \theta \sin \phi \\ -\sin \theta & 0 & \cos \theta \end{pmatrix}^T \\ &= \begin{pmatrix} \cos \theta \cos \phi & \cos \theta \sin \phi & -\sin \theta \\ -\sin \phi & \cos \phi & 0 \\ \sin \theta \cos \phi & \sin \theta \sin \phi & \cos \theta \end{pmatrix} = \begin{pmatrix} \hat{u}^T \\ \hat{v}^T \\ \hat{n}^T \end{pmatrix} \\ S^{-1} S &= \begin{pmatrix} \cos \theta \cos \phi & \cos \theta \sin \phi & -\sin \theta \\ -\sin \phi & \cos \phi & 0 \\ \sin \theta \cos \phi & \sin \theta \sin \phi & \cos \theta \end{pmatrix} \begin{pmatrix} \cos \theta \cos \phi & -\sin \phi & \sin \theta \cos \phi \\ \cos \theta \sin \phi & \cos \phi & \sin \theta \sin \phi \\ -\sin \theta & 0 & \cos \theta \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} = 1 \end{aligned}$$

\hat{n} as z direction

$$\begin{aligned}
[\mathbf{V}]_S &= S^{-1} \mathbf{V} \\
[\mathbf{V}']_S &= R_z(\gamma) [\mathbf{V}]_S = R_z(\gamma) S^{-1} \mathbf{V} \\
\mathbf{V}' &= S [\mathbf{V}']_S = S R_z(\gamma) [\mathbf{V}]_S = S R_z(\gamma) S^{-1} \mathbf{V} \\
\mathbf{V}' &= S R_z(\gamma) S^{-1} \mathbf{V}
\end{aligned}$$

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

$$\begin{aligned}
&SR_z(\gamma) S^{-1} \\
&= \begin{pmatrix} \cos \theta \cos \phi & -\sin \phi & \sin \theta \cos \phi \\ \cos \theta \sin \phi & \cos \phi & \sin \theta \sin \phi \\ -\sin \theta & 0 & \cos \theta \end{pmatrix} \begin{pmatrix} \cos \gamma & -\sin \gamma & 0 \\ \sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta \cos \phi & \cos \theta \sin \phi & -\sin \theta \\ -\sin \phi & \cos \phi & 0 \\ \sin \theta \cos \phi & \sin \theta \sin \phi & \cos \theta \end{pmatrix} \\
&= \begin{pmatrix} c_1 c_2 & -s_2 & s_1 c_2 \\ c_1 s_2 & c_2 & s_1 s_2 \\ -s_1 & 0 & c_1 \end{pmatrix} \begin{pmatrix} c_3 & -s_3 & 0 \\ s_3 & c_3 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_1 c_2 & c_1 s_2 & -s_1 \\ -s_2 & c_2 & 0 \\ s_1 c_2 & s_1 s_2 & c_1 \end{pmatrix}, \begin{cases} c_1 = \cos \theta & s_1 = \sin \theta \\ c_2 = \cos \phi & s_2 = \sin \phi \\ c_3 = \cos \gamma & s_3 = \sin \gamma \end{cases} \\
&= \begin{pmatrix} c_1 c_2 & -s_2 & s_1 c_2 \\ c_1 s_2 & c_2 & s_1 s_2 \\ -s_1 & 0 & c_1 \end{pmatrix} \begin{pmatrix} c_3 c_1 c_2 + s_3 s_2 & c_3 c_1 s_2 - c_2 s_3 & -c_3 s_1 \\ c_1 c_2 s_3 - c_3 s_2 & c_3 c_2 + c_1 s_3 s_2 & -s_3 s_1 \\ c_2 s_1 & s_2 s_1 & c_1 \end{pmatrix} \\
&= \begin{pmatrix} c_1^2 c_2^2 c_3 + c_3 s_2^2 + c_2^2 s_1^2 & c_1 s_2 (c_1 c_2 c_3 - s_2 s_3) + c_2 (-c_1 c_2 s_3 - c_3 s_2) + c_2 s_2 s_1^2 \\ c_1 c_2 (c_1 c_3 s_2 + c_2 s_3) - s_2 (c_2 c_3 - c_1 s_2 s_3) + c_2 s_2 s_1^2 & c_1^2 c_3 s_2^2 + s_2^2 s_1^2 + c_2^2 c_3 \\ -c_1 c_2 c_3 s_1 - s_2 s_1 s_3 + c_1 c_2 s_1 & -c_1 c_3 s_2 s_1 + c_2 s_1 s_3 + c_1 s_2 s_1 \end{pmatrix}
\end{aligned}$$

34.1.4.2.2 quaternion <https://math.stackexchange.com/questions/328117/how-does-one-derive-this-rotation-quaternion-formula>

$$\begin{aligned}
q &= a + bi + cj + dk = a + ib + jc + kd, \begin{cases} q \in \mathbb{H} \\ i^2 = j^2 = k^2 = -1 = ijk \Rightarrow ij = k \\ a, b, c, d \in \mathbb{R} \end{cases} \Leftrightarrow \langle a, b, c, d \rangle \in \mathbb{R}^4 \\
w &= t + xi + yj + zk = t + ix + jy + kz, \begin{cases} w \in \mathbb{H} \\ i^2 = j^2 = k^2 = -1 = ijk \Rightarrow ij = k \\ t, x, y, z \in \mathbb{R} \end{cases} \Leftrightarrow \langle t, x, y, z \rangle \in \mathbb{R}^4 \\
t + (\mathbf{i} &\quad \mathbf{j} \quad \mathbf{k}) \begin{pmatrix} x \\ y \\ z \end{pmatrix} = x_0 + (\mathbf{i} \quad \mathbf{j} \quad \mathbf{k}) \begin{pmatrix} x \\ y \\ z \end{pmatrix} = x_0 + (\mathbf{e}_1 \quad \mathbf{e}_2 \quad \mathbf{e}_3) \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = x_0 + \mathbf{x}, \begin{cases} \mathbf{e}_1 = \mathbf{i} = \mathbf{i} \\ \mathbf{e}_2 = \mathbf{j} = \mathbf{j} \\ \mathbf{e}_3 = \mathbf{k} = \mathbf{k} \end{cases}
\end{aligned}$$

$$q_1 q_2 = (x_{10} x_{20} - \mathbf{x}_1 \cdot \mathbf{x}_2) + (x_{10} \mathbf{x}_2 + x_{20} \mathbf{x}_1 + \mathbf{x}_1 \times \mathbf{x}_2)$$

$$QP = (Q_0 P_0 - \mathbf{Q} \cdot \mathbf{P}) + (Q_0 \mathbf{P} + P_0 \mathbf{Q} + \mathbf{Q} \times \mathbf{P})$$

$$q = q_0 + \mathbf{q} = q_0 + q_1 \mathbf{i} + q_2 \mathbf{j} + q_3 \mathbf{k} = q_0 + q_1 \mathbf{i} + q_2 \mathbf{j} + q_3 \mathbf{k}$$

$$\begin{aligned}
q^* &= \bar{q} = \overline{q_0 + \mathbf{q}} = q_0 - \mathbf{q} \\
&= \overline{q_0 + q_1 \mathbf{i} + q_2 \mathbf{j} + q_3 \mathbf{k}} = q_0 - q_1 \mathbf{i} - q_2 \mathbf{j} - q_3 \mathbf{k} \\
&= q_0 - q_1 \mathbf{i} - q_2 \mathbf{j} - q_3 \mathbf{k}
\end{aligned}$$

$$v = v_0 + \mathbf{v} = v_0 + v_1 \mathbf{i} + v_2 \mathbf{j} + v_3 \mathbf{k} = v_0 + v_1 \mathbf{i} + v_2 \mathbf{j} + v_3 \mathbf{k}$$

$$\mathbf{v} = v_1 \mathbf{i} + v_2 \mathbf{j} + v_3 \mathbf{k} = v_1 \mathbf{i} + v_2 \mathbf{j} + v_3 \mathbf{k}$$

$$\begin{aligned}
q\mathbf{v} &= (q_0 v_0 - \mathbf{q} \cdot \mathbf{v}) + (q_0 \mathbf{v} + v_0 \mathbf{q} + \mathbf{q} \times \mathbf{v}) \\
&\stackrel{v_0=0}{=} (q_0 0 - \mathbf{q} \cdot \mathbf{v}) + (q_0 \mathbf{v} + 0 \mathbf{q} + \mathbf{q} \times \mathbf{v}) \\
&= (-\mathbf{q} \cdot \mathbf{v}) + (q_0 \mathbf{v} + \mathbf{q} \times \mathbf{v}) \\
q\mathbf{v} &= (-\mathbf{q} \cdot \mathbf{v}) + (q_0 \mathbf{v} + \mathbf{q} \times \mathbf{v})
\end{aligned}$$

$$\begin{aligned}
v\bar{q} &= (v_0 q_0 - \mathbf{v} \cdot \bar{\mathbf{q}}) + (v_0 \bar{\mathbf{q}} + q_0 \mathbf{v} + \mathbf{v} \times \bar{\mathbf{q}}) \\
&\stackrel{v_0=0}{=} (0 q_0 - \mathbf{v} \cdot \bar{\mathbf{q}}) + (0 \bar{\mathbf{q}} + q_0 \mathbf{v} + \mathbf{v} \times \bar{\mathbf{q}}) \\
&= (-\mathbf{v} \cdot \bar{\mathbf{q}}) + (q_0 \mathbf{v} + \mathbf{v} \times \bar{\mathbf{q}}) \\
&= (-\mathbf{v} \cdot (-\mathbf{q})) + (q_0 \mathbf{v} + \mathbf{v} \times (-\mathbf{q})) \\
&= (\mathbf{v} \cdot \mathbf{q}) + (q_0 \mathbf{v} - \mathbf{v} \times \mathbf{q}) \\
v\bar{q} &= (\mathbf{v} \cdot \mathbf{q}) + (q_0 \mathbf{v} - \mathbf{v} \times \mathbf{q})
\end{aligned}$$

<https://math.stackexchange.com/questions/41574/can-eulers-identity-be-extended-to-quaternions>

$$\begin{aligned}
q &= a + bi + cj + dk = a + ib + jc + kd \\
&= a + r \frac{ib + jc + kd}{r}, r^2 = b^2 + c^2 + d^2 \\
&= a + \theta \frac{ib + jc + kd}{\theta}, \theta^2 = b^2 + c^2 + d^2
\end{aligned}$$

$$\begin{aligned}
\left(\frac{ib + jc + kd}{r} \right)^2 &= \frac{-b^2 - c^2 - d^2 + bc(ij + ji) + cd(jk + kj) + db(ki + ik)}{r^2} \\
&= \frac{-b^2 - c^2 - d^2 + bc(k - k) + cd(i - i) + db(j - j)}{r^2} \\
&= \frac{-b^2 - c^2 - d^2 + bc0 + cd0 + db0}{r^2} = \frac{-b^2 - c^2 - d^2}{r^2} \\
&= \frac{-b^2 - c^2 - d^2}{b^2 + c^2 + d^2} = -1 \\
\frac{ib + jc + kd}{r} &= \pm \sqrt{-1}
\end{aligned}$$

$$\begin{aligned}
e^q &= e^{a+ib+jc+kd} \\
&= e^{a+r\sqrt{-1}} = e^a e^{r\sqrt{-1}} = e^{a+\theta\sqrt{-1}} = e^a e^{\theta\sqrt{-1}} \\
&= e^a (\cos r + \sqrt{-1} \sin r) = e^a (\cos \theta + \sqrt{-1} \sin \theta) \\
&= e^a \left(\cos r + \frac{ib+jc+kd}{r} \sin r \right) = e^a \left[\cos r + (ib+jc+kd) \frac{\sin r}{r} \right] \\
&= e^a \left(\cos \theta + \frac{ib+jc+kd}{\theta} \sin \theta \right) = e^a \left[\cos \theta + (ib+jc+kd) \frac{\sin \theta}{\theta} \right]
\end{aligned}$$

$$\begin{aligned}
q &= a + bi + cj + dk = a + ib + jc + kd \\
&= a + r \frac{ib+jc+kd}{r}, r^2 = b^2 + c^2 + d^2 \\
&= \sqrt{a^2 + r^2} \left(\frac{a}{\sqrt{a^2 + r^2}} + \frac{ib+jc+kd}{r} \frac{r}{\sqrt{a^2 + r^2}} \right) \\
&= \rho (\cos \phi + \sqrt{-1} \sin \phi), \begin{cases} \rho = \sqrt{a^2 + r^2} \\ \tan \phi = \frac{r}{a} \Leftrightarrow \phi = \arctan \frac{r}{a} \end{cases} \\
&= \rho e^{\phi\sqrt{-1}}
\end{aligned}$$

$$q = \rho e^{\phi\sqrt{-1}}, \begin{cases} q = a + ib + jc + kd \\ \rho = \sqrt{a^2 + r^2} = \sqrt{a^2 + b^2 + c^2 + d^2} \\ \tan \phi = \frac{r}{a} \Leftrightarrow \phi = \arctan \frac{r}{a} = \arctan \frac{\pm \sqrt{b^2 + c^2 + d^2}}{a} \end{cases}$$

$$\begin{aligned}
\rho e^{-\phi\sqrt{-1}} &= \rho [\cos(-\phi) + \sqrt{-1} \sin(-\phi)] \\
&= \rho [\cos \phi - \sqrt{-1} \sin \phi] \\
&= \sqrt{a^2 + r^2} \left[\frac{a}{\sqrt{a^2 + r^2}} - \frac{ib+jc+kd}{r} \frac{r}{\sqrt{a^2 + r^2}} \right] \\
&= a - (ib + jc + kd) = a - ib - jc - kd = \bar{q} = q^*
\end{aligned}$$

34.1.5 octonion

34.2 Krasjet

<https://github.com/Krasjet/quaternion>

<https://krasjet.github.io/quaternion/>

https://krasjet.github.io/quaternion/bonus_gimbal_lock.pdf

34.2.1 Rodrigues rotation

$$\mathbf{v} \rightarrow \mathbf{v}'$$

$$\mathbf{v} \xrightarrow{\text{rotate about } \mathbf{u}} \mathbf{v}'$$

$$\mathbf{v} \xrightarrow{\text{rotate about } \mathbf{n}} \mathbf{v}'$$

$$\begin{cases} \mathbf{v} = \mathbf{v}_{\parallel n} + \mathbf{v}_{\perp n} = \mathbf{v}_{\parallel} + \mathbf{v}_{\perp} \Rightarrow \mathbf{v}_{\perp} = \mathbf{v} - \mathbf{v}_{\parallel} \\ \mathbf{v}' = \mathbf{v}'_{\parallel n} + \mathbf{v}'_{\perp n} = \mathbf{v}'_{\parallel} + \mathbf{v}'_{\perp} \Rightarrow \mathbf{v}'_{\perp} = \mathbf{v}' - \mathbf{v}'_{\parallel} \end{cases}$$

$$\begin{aligned} \mathbf{v}_{\parallel n} &= \mathbf{v}_{\parallel} = \text{proj}_n \mathbf{v} = \frac{\mathbf{v} \cdot \mathbf{n}}{\|\mathbf{n}\|} \hat{\mathbf{n}} \\ &= \frac{\mathbf{v} \cdot \mathbf{n}}{\|\mathbf{n}\|} \frac{\mathbf{n}}{\|\mathbf{n}\|} = \frac{\mathbf{v} \cdot \mathbf{n}}{\|\mathbf{n}\|^2} \mathbf{n} \end{aligned}$$

$$\begin{aligned} \mathbf{v}_{\parallel n} &= \mathbf{v}_{\parallel} = \text{proj}_{\hat{\mathbf{n}}} \mathbf{v} = \frac{\mathbf{v} \cdot \hat{\mathbf{n}}}{\|\hat{\mathbf{n}}\|} \hat{\mathbf{n}} \stackrel{\|\hat{\mathbf{n}}\|=1}{=} (\mathbf{v} \cdot \hat{\mathbf{n}}) \hat{\mathbf{n}} = \mathbf{v} \cdot \hat{\mathbf{n}} \hat{\mathbf{n}} \\ &= \frac{\mathbf{v} \cdot \hat{\mathbf{n}}}{\|\hat{\mathbf{n}}\|} \frac{\hat{\mathbf{n}}}{\|\hat{\mathbf{n}}\|} = \frac{\mathbf{v} \cdot \hat{\mathbf{n}}}{\|\hat{\mathbf{n}}\|^2} \hat{\mathbf{n}} \stackrel{\|\hat{\mathbf{n}}\|=1}{=} (\mathbf{v} \cdot \hat{\mathbf{n}}) \hat{\mathbf{n}} = \mathbf{v} \cdot \hat{\mathbf{n}} \hat{\mathbf{n}} \end{aligned}$$

$$\mathbf{n} = \hat{\mathbf{n}}$$

$$\begin{aligned} \mathbf{v}_{\parallel n} &= \mathbf{v}_{\parallel} = \text{proj}_n \mathbf{v} = \frac{\mathbf{v} \cdot \mathbf{n}}{\|\mathbf{n}\|} \hat{\mathbf{n}} \stackrel{\|\mathbf{n}\|=1}{=} (\mathbf{v} \cdot \hat{\mathbf{n}}) \hat{\mathbf{n}} = \mathbf{v} \cdot \hat{\mathbf{n}} \hat{\mathbf{n}} \\ &= \frac{\mathbf{v} \cdot \mathbf{n}}{\|\mathbf{n}\|} \frac{\mathbf{n}}{\|\mathbf{n}\|} = \frac{\mathbf{v} \cdot \mathbf{n}}{\|\mathbf{n}\|^2} \mathbf{n} \stackrel{\|\mathbf{n}\|=1}{=} (\mathbf{v} \cdot \mathbf{n}) \mathbf{n} = \mathbf{v} \cdot \mathbf{n} \mathbf{n} \end{aligned}$$

$$\mathbf{v}_{\parallel} = (\mathbf{v} \cdot \mathbf{n}) \mathbf{n}$$

$$\mathbf{v}_{\perp} = \mathbf{v} - \mathbf{v}_{\parallel} = \mathbf{v} - (\mathbf{v} \cdot \mathbf{n}) \mathbf{n}$$

$$\mathbf{v}_{\parallel} + \mathbf{v}_{\perp} = \mathbf{v} \xrightarrow{\text{rotate about } \mathbf{n}} \mathbf{v}' = \mathbf{v}'_{\parallel} + \mathbf{v}'_{\perp}$$

$$\mathbf{v}_{\parallel} \xrightarrow{\text{rotate about } \mathbf{n}} \mathbf{v}'_{\parallel}$$

$$\mathbf{v}_{\parallel} = \mathbf{v}_{\parallel n} = \mathbf{v}'_{\parallel n} = \mathbf{v}'_{\parallel}$$

$$\mathbf{v}_{\parallel} = \mathbf{v}'_{\parallel}$$

$$\mathbf{v}'_{\parallel} = \mathbf{v}_{\parallel}$$

$$\begin{cases} \mathbf{u} = \mathbf{n} \times \mathbf{v}_{\perp} \\ \|\mathbf{u}\| = \|\mathbf{n} \times \mathbf{v}_{\perp}\| = \|\mathbf{n}\| \|\mathbf{v}_{\perp}\| \sin \frac{\pi}{2} = \|\mathbf{v}_{\perp}\| \end{cases} \quad \begin{cases} \mathbf{u} \perp \mathbf{n} \\ \mathbf{u} \perp \mathbf{v}_{\perp} \\ \mathbf{n} \perp \mathbf{v}_{\perp} \\ \|\mathbf{n}\| = 1 \end{cases}$$

$$\begin{aligned}
\mathbf{v}'_{\perp} &= \mathbf{v}'_{\parallel v_{\perp}} + \mathbf{v}'_{\parallel u} \\
&= (\cos \theta) \mathbf{v}_{\perp} + (\sin \theta) \mathbf{u}, \theta = \angle \mathbf{v}'_{\perp} \mathbf{v}_{\perp} \\
&= \cos \theta \mathbf{v}_{\perp} + \sin \theta \mathbf{u} \\
&= \cos \theta \mathbf{v}_{\perp} + \sin \theta (\mathbf{n} \times \mathbf{v}_{\perp}) \\
\mathbf{v}'_{\perp} &= \cos \theta \mathbf{v}_{\perp} + \sin \theta (\mathbf{n} \times \mathbf{v}_{\perp})
\end{aligned}$$

$$\mathbf{v}'_{\perp} = \cos \theta \mathbf{v}_{\perp} + \sin \theta (\mathbf{n} \times \mathbf{v}_{\perp}), \theta = \angle \mathbf{v}'_{\perp} \mathbf{v}_{\perp}$$

$$\mathbf{v}'_{\perp} = \cos \theta \mathbf{v}_{\perp} + \sin \theta (\mathbf{n} \times \mathbf{v}_{\perp})$$

$$\begin{aligned}
\mathbf{v}' &= \mathbf{v}'_{\parallel} + \mathbf{v}'_{\perp}, \begin{cases} \mathbf{v}'_{\parallel} = \mathbf{v}_{\parallel} \\ \mathbf{v}'_{\perp} = \cos \theta \mathbf{v}_{\perp} + \sin \theta (\mathbf{n} \times \mathbf{v}_{\perp}), \theta = \angle \mathbf{v}'_{\perp} \mathbf{v}_{\perp} \end{cases} \\
&= \mathbf{v}_{\parallel} + \cos \theta \mathbf{v}_{\perp} + \sin \theta (\mathbf{n} \times \mathbf{v}_{\perp}), \theta = \angle \mathbf{v}'_{\perp} \mathbf{v}_{\perp} \\
&= \mathbf{v}_{\parallel} + \cos \theta \mathbf{v}_{\perp} + \sin \theta (\mathbf{n} \times \mathbf{v}_{\perp}), \begin{cases} \mathbf{v}_{\parallel} = (\mathbf{v} \cdot \mathbf{n}) \mathbf{n} \\ \mathbf{v}_{\perp} = \mathbf{v} - \mathbf{v}_{\parallel} = \mathbf{v} - (\mathbf{v} \cdot \mathbf{n}) \mathbf{n} \end{cases} \\
&= (\mathbf{v} \cdot \mathbf{n}) \mathbf{n} + \cos \theta [\mathbf{v} - (\mathbf{v} \cdot \mathbf{n}) \mathbf{n}] + \sin \theta [\mathbf{n} \times (\mathbf{v} - \mathbf{v}_{\parallel})] \\
&= (\mathbf{v} \cdot \mathbf{n}) \mathbf{n} + \cos \theta \mathbf{v} - \cos \theta (\mathbf{v} \cdot \mathbf{n}) \mathbf{n} + \sin \theta [\mathbf{n} \times \mathbf{v} - \mathbf{n} \times \mathbf{v}_{\parallel}] \\
&= \cos \theta \mathbf{v} + (1 - \cos \theta) (\mathbf{v} \cdot \mathbf{n}) \mathbf{n} + \sin \theta [\mathbf{n} \times \mathbf{v} - \mathbf{0}] \\
&= \cos \theta \mathbf{v} + (1 - \cos \theta) (\mathbf{v} \cdot \mathbf{n}) \mathbf{n} + \sin \theta \mathbf{n} \times \mathbf{v}
\end{aligned}$$

$$\mathbf{v}' = \cos \theta \mathbf{v} + (1 - \cos \theta) (\mathbf{v} \cdot \mathbf{n}) \mathbf{n} + \sin \theta \mathbf{n} \times \mathbf{v}$$

$$\begin{aligned}
\mathbf{v}' &= \cos \theta \mathbf{v} + (1 - \cos \theta) (\mathbf{v} \cdot \mathbf{n}) \mathbf{n} + \sin \theta \mathbf{n} \times \mathbf{v} \\
&= \cos \theta \mathbf{v} + \left[1 - \left(1 - 2 \sin^2 \frac{\theta}{2} \right) \right] (\mathbf{v} \cdot \mathbf{n}) \mathbf{n} + \left[2 \sin \frac{\theta}{2} \cos \frac{\theta}{2} \right] \mathbf{n} \times \mathbf{v} \\
&= \cos \theta \mathbf{v} + \left[2 \sin^2 \frac{\theta}{2} \right] (\mathbf{v} \cdot \mathbf{n}) \mathbf{n} + \left[2 \sin \frac{\theta}{2} \cos \frac{\theta}{2} \right] \mathbf{n} \times \mathbf{v} \\
&= \cos \theta \mathbf{v} + 2 \sin \frac{\theta}{2} \left[\left(\sin \frac{\theta}{2} \right) (\mathbf{v} \cdot \mathbf{n}) \mathbf{n} + \left(\cos \frac{\theta}{2} \right) \mathbf{n} \times \mathbf{v} \right] \\
&= \cos \theta \mathbf{v} + 2 \sin \frac{\theta}{2} \left[\left(\cos \frac{\theta}{2} \right) \mathbf{n} \times \mathbf{v} + \left(\sin \frac{\theta}{2} \right) (\mathbf{v} \cdot \mathbf{n}) \mathbf{n} \right] \\
&= \left[2 \cos^2 \frac{\theta}{2} - 1 \right] \mathbf{v} + 2 \sin \frac{\theta}{2} \left[\left(\cos \frac{\theta}{2} \right) \mathbf{n} \times \mathbf{v} + \left(\sin \frac{\theta}{2} \right) (\mathbf{v} \cdot \mathbf{n}) \mathbf{n} \right]
\end{aligned}$$

34.2.2 quaternion operation

$$q = a + bi + cj + dk$$

$$\varrho = \alpha + \beta i + \gamma j + \delta k$$

$$\begin{aligned}
& \begin{pmatrix} a \\ b \\ c \\ d \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \\ \gamma \\ \delta \end{pmatrix} \leftarrow q\varrho = (a + bi + cj + dk)(\alpha + \beta i + \gamma j + \delta k) \\
& = a(\alpha + \beta i + \gamma j + \delta k) \\
& + bi(\alpha + \beta i + \gamma j + \delta k) \\
& + cj(\alpha + \beta i + \gamma j + \delta k) \\
& + dk(\alpha + \beta i + \gamma j + \delta k) \\
& = a\alpha + a\beta i + a\gamma j + a\delta k \\
& + b\alpha i - b\beta + b\gamma k - b\delta j \\
& + c\alpha j - c\beta k - c\gamma + c\delta i \\
& + d\alpha k + d\beta j - d\gamma i - d\delta \\
& = (a\alpha - b\beta - c\gamma - d\delta) \\
& + (b\alpha + a\beta - d\gamma + c\delta)i \\
& + (c\alpha + d\beta + a\gamma - b\delta)j \\
& + (d\alpha - c\beta + b\gamma + a\delta)k \\
& \begin{pmatrix} a & -b & -c & -d \\ b & a & -d & c \\ c & d & a & -b \\ d & -c & b & a \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \\ \gamma \\ \delta \end{pmatrix} \leftarrow \\
& = (\alpha a - \beta b - \gamma c - \delta d) \\
& + (\beta a + \alpha b + \delta c - \gamma d)i \\
& + (\gamma a - \delta b + \alpha c + \beta d)j \\
& + (\delta a + \gamma b - \beta c + \alpha d)k \\
& \begin{pmatrix} \alpha & -\beta & -\gamma & -\delta \\ \beta & \alpha & \delta & -\gamma \\ \gamma & -\delta & \alpha & \beta \\ \delta & \gamma & -\beta & \alpha \end{pmatrix} \begin{pmatrix} a \\ b \\ c \\ d \end{pmatrix} \leftarrow \\
& qv \leftrightarrow \begin{pmatrix} a & -b & -c & -d \\ b & a & -d & c \\ c & d & a & -b \\ d & -c & b & a \end{pmatrix} \begin{pmatrix} v_0 \\ v_1 \\ v_2 \\ v_3 \end{pmatrix} = Q_i v
\end{aligned}$$

concept like quaternion group representation^[37.5]

$$\begin{aligned}
L(q) = Q_i &= \begin{pmatrix} a & -b & -c & -d \\ b & a & -d & c \\ c & d & a & -b \\ d & -c & b & a \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} a + \begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix} b \\
&+ \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix} c + \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} d \\
&\leftrightarrow 1a + ib + jc + kd
\end{aligned}$$

$$\begin{aligned}
ij \leftrightarrow & \begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \leftrightarrow k \\
ji \leftrightarrow & \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix} = - \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \leftrightarrow -k \\
ki \leftrightarrow & \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix} \leftrightarrow j
\end{aligned}$$

$$Q_i = \begin{pmatrix} a & -b & -c & -d \\ b & a & -d & c \\ c & d & a & -b \\ d & -c & b & a \end{pmatrix} = \begin{pmatrix} \begin{pmatrix} a \\ b \\ c \\ d \end{pmatrix} & \begin{pmatrix} -b & c & d \\ a & -d & c \\ d & a & -b \\ -c & b & a \end{pmatrix} \end{pmatrix} = \begin{pmatrix} q_0 & -\mathbf{q}^\top \\ \mathbf{q} & Q_i \end{pmatrix}, \quad \begin{cases} a = q_0 \\ \mathbf{q} = \begin{pmatrix} b \\ c \\ d \end{pmatrix} \\ Q_i = \begin{pmatrix} a & -d & c \\ d & a & -b \\ -c & b & a \end{pmatrix} \end{cases}$$

Grassmann product

$$qv \leftrightarrow \begin{pmatrix} a & -b & -c & -d \\ b & a & -d & c \\ c & d & a & -b \\ d & -c & b & a \end{pmatrix} \begin{pmatrix} v_0 \\ v_1 \\ v_2 \\ v_3 \end{pmatrix} = Q_i v = \begin{pmatrix} q_0 & -\mathbf{q}^\top \\ \mathbf{q} & Q_i \end{pmatrix} \begin{pmatrix} v_0 \\ v \end{pmatrix} = \begin{pmatrix} q_0 v_0 - \mathbf{q}^\top v \\ \mathbf{q} v_0 + Q_i v \end{pmatrix} = \begin{pmatrix} q_0 v_0 - \mathbf{q} \cdot v \\ \mathbf{q} v_0 + q_0 v + \mathbf{q} \times v \end{pmatrix}$$

$$vq \leftrightarrow \begin{pmatrix} a & -b & -c & -d \\ b & a & d & -c \\ c & -d & a & b \\ d & c & -b & a \end{pmatrix} \begin{pmatrix} v_0 \\ v_1 \\ v_2 \\ v_3 \end{pmatrix} = Q_r v$$

$$\begin{aligned}
R(q) = Q_r = & \begin{pmatrix} a & -b & -c & -d \\ b & a & d & -c \\ c & -d & a & b \\ d & c & -b & a \end{pmatrix} = a \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} + b \begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix} \\
& + c \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} + d \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \\
& \leftrightarrow a1 + bi + cj + dk
\end{aligned}$$

$$ij \leftrightarrow \begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} = - \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \leftrightarrow -k$$

$$ji \leftrightarrow \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \leftrightarrow k$$

$$ki \leftrightarrow \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix} = -\begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \leftrightarrow -j$$

$$\begin{aligned} R(q) = Q_r &= \begin{pmatrix} a & -b & -c & -d \\ b & a & d & -c \\ c & -d & a & b \\ d & c & -b & a \end{pmatrix} \leftrightarrow \begin{pmatrix} a+bi & -c+di \\ c+di & a-bi \end{pmatrix} \\ &= \begin{pmatrix} \alpha & -\bar{\beta} \\ \beta & \bar{\alpha} \end{pmatrix}, \begin{cases} \alpha = a+bi & \bar{\alpha} = a-bi \\ \beta = c+di & \bar{\beta} = c-di \end{cases} \end{aligned}$$

$$Q_r = \begin{pmatrix} a & -b & -c & -d \\ b & a & d & -c \\ c & -d & a & b \\ d & c & -b & a \end{pmatrix} = \begin{pmatrix} \begin{pmatrix} a \\ b \\ c \\ d \end{pmatrix} & \begin{pmatrix} -b & c & d \\ a & d & -c \\ -d & a & b \\ c & -b & a \end{pmatrix} \end{pmatrix} = \begin{pmatrix} q_0 & -\mathbf{q}^\top \\ \mathbf{q} & Q_i^\top \end{pmatrix}, \begin{cases} a = q_0 \\ b \\ c \\ d \\ Q_i = \begin{pmatrix} a & -d & c \\ d & a & -b \\ -c & b & a \end{pmatrix} \end{cases}$$

$$vq \leftrightarrow \begin{pmatrix} a & -b & -c & -d \\ b & a & d & -c \\ c & -d & a & b \\ d & c & -b & a \end{pmatrix} \begin{pmatrix} v_0 \\ v_1 \\ v_2 \\ v_3 \end{pmatrix} = Q_r v = \begin{pmatrix} q_0 & -\mathbf{q}^\top \\ \mathbf{q} & Q_i^\top \end{pmatrix} \begin{pmatrix} v_0 \\ v \end{pmatrix} = \begin{pmatrix} v_0 q_0 - \mathbf{q}^\top v \\ v_0 \mathbf{q} + Q_i^\top v \end{pmatrix} = \begin{pmatrix} v_0 q_0 - \mathbf{v} \cdot \mathbf{q} \\ v_0 \mathbf{q} + q_0 \mathbf{v} + \mathbf{v} \times \mathbf{q} \end{pmatrix} = \begin{pmatrix} \mathbf{q} \end{pmatrix}$$

$$\begin{cases} qv \leftrightarrow Q_l v = \begin{pmatrix} q_0 & -\mathbf{q}^\top \\ \mathbf{q} & Q_i \end{pmatrix} \begin{pmatrix} v_0 \\ v \end{pmatrix} = \begin{pmatrix} q_0 v_0 - \mathbf{q}^\top v \\ \mathbf{q} v_0 + Q_i v \end{pmatrix} = \begin{pmatrix} q_0 v_0 - \mathbf{q} \cdot \mathbf{v} \\ \mathbf{q} v_0 + q_0 \mathbf{v} + \mathbf{q} \times \mathbf{v} \end{pmatrix} = \begin{pmatrix} q_0 v_0 - \mathbf{q} \cdot \mathbf{v} \\ \mathbf{q} v_0 + q_0 \mathbf{v} + \mathbf{q} \times \mathbf{v} \end{pmatrix} \\ vq \leftrightarrow Q_r v = \begin{pmatrix} q_0 & -\mathbf{q}^\top \\ \mathbf{q} & Q_i^\top \end{pmatrix} \begin{pmatrix} v_0 \\ v \end{pmatrix} = \begin{pmatrix} v_0 q_0 - \mathbf{q}^\top v \\ v_0 \mathbf{q} + Q_i^\top v \end{pmatrix} = \begin{pmatrix} v_0 q_0 - \mathbf{v} \cdot \mathbf{q} \\ v_0 \mathbf{q} + v_0 q_0 + \mathbf{v} \times \mathbf{q} \end{pmatrix} = \begin{pmatrix} q_0 v_0 - \mathbf{q} \cdot \mathbf{v} \\ \mathbf{q} v_0 + q_0 \mathbf{v} - \mathbf{q} \times \mathbf{v} \end{pmatrix} \end{cases}$$

$$\begin{cases} qv = \begin{pmatrix} q_0 \\ \mathbf{q} \end{pmatrix} \begin{pmatrix} v_0 \\ v \end{pmatrix} = L(q)v = Q_l v = \begin{pmatrix} q_0 & -\mathbf{q}^\top \\ \mathbf{q} & Q_i \end{pmatrix} \begin{pmatrix} v_0 \\ v \end{pmatrix} \\ vq = \begin{pmatrix} v_0 \\ \mathbf{v} \end{pmatrix} \begin{pmatrix} q_0 \\ \mathbf{q} \end{pmatrix} = R(q)v = Q_r v = \begin{pmatrix} q_0 & -\mathbf{q}^\top \\ \mathbf{q} & Q_i^\top \end{pmatrix} \begin{pmatrix} v_0 \\ v \end{pmatrix} \end{cases}$$

$$\begin{aligned}
& \left\{ \begin{array}{l} \mathbf{v} \xrightarrow{\text{rotate about } \mathbf{n}} \mathbf{v}' \\ \left\{ \begin{array}{l} \mathbf{v} = \mathbf{v}_{\parallel n} + \mathbf{v}_{\perp n} = \mathbf{v}_{\parallel} + \mathbf{v}_{\perp} = \Rightarrow \mathbf{v}_{\perp} = \mathbf{v} - \mathbf{v}_{\parallel} \\ \mathbf{v}' = \mathbf{v}'_{\parallel n} + \mathbf{v}'_{\perp n} = \mathbf{v}'_{\parallel} + \mathbf{v}'_{\perp} \Rightarrow \mathbf{v}'_{\perp} = \mathbf{v}' - \mathbf{v}'_{\parallel} \end{array} \right. \\ \left\{ \begin{array}{l} \mathbf{u} = \mathbf{n} \times \mathbf{v}_{\perp} \\ \|\mathbf{u}\| = \|\mathbf{n} \times \mathbf{v}_{\perp}\| = \|\mathbf{n}\| \|\mathbf{v}_{\perp}\| \sin \frac{\pi}{2} = \|\mathbf{v}_{\perp}\| \end{array} \right. \quad \left\{ \begin{array}{l} \mathbf{u} \perp \mathbf{n} \\ \mathbf{u} \perp \mathbf{v}_{\perp} \\ \mathbf{n} \perp \mathbf{v}_{\perp} \\ \|\mathbf{n}\| = 1 \end{array} \right. \\ \left\{ \begin{array}{l} \mathbf{v}'_{\parallel} = \mathbf{v}_{\parallel} \\ \mathbf{v}'_{\perp} = \cos \theta \mathbf{v}_{\perp} + \sin \theta (\mathbf{n} \times \mathbf{v}_{\perp}), \theta = \angle \mathbf{v}'_{\perp} \mathbf{v}_{\perp} \end{array} \right. \end{array} \right. \\
& \Leftrightarrow \left\{ \begin{array}{l} v \xrightarrow{\text{rotate about } n} v' \\ \left\{ \begin{array}{l} v = \begin{pmatrix} 0 \\ \mathbf{v} \end{pmatrix} = \begin{pmatrix} 0 \\ \mathbf{v}_{\parallel n} \end{pmatrix} + \begin{pmatrix} 0 \\ \mathbf{v}_{\perp n} \end{pmatrix} = \begin{pmatrix} 0 \\ \mathbf{v}_{\parallel} \end{pmatrix} + \begin{pmatrix} 0 \\ \mathbf{v}_{\perp} \end{pmatrix} = v_{\parallel} + v_{\perp} \Rightarrow v_{\perp} = v - v_{\parallel} \\ v' = \begin{pmatrix} 0 \\ \mathbf{v}' \end{pmatrix} = \begin{pmatrix} 0 \\ \mathbf{v}'_{\parallel n} \end{pmatrix} + \begin{pmatrix} 0 \\ \mathbf{v}'_{\perp n} \end{pmatrix} = \begin{pmatrix} 0 \\ \mathbf{v}'_{\parallel} \end{pmatrix} + \begin{pmatrix} 0 \\ \mathbf{v}'_{\perp} \end{pmatrix} = v'_{\parallel} + v'_{\perp} \Rightarrow v'_{\perp} = v' - v'_{\parallel} \end{array} \right. \\ \left\{ \begin{array}{l} u = \begin{pmatrix} 0 \\ \mathbf{u} \end{pmatrix} = \begin{pmatrix} 0 \\ \mathbf{n} \times \mathbf{v}_{\perp} \end{pmatrix} = \begin{pmatrix} 0 \\ 00 - 0 \end{pmatrix} = \begin{pmatrix} n_0 v_{\perp 0} - \mathbf{n} \cdot \mathbf{v}_{\perp} \\ \mathbf{n} v_{\perp 0} + n_0 \mathbf{v}_{\perp} + \mathbf{n} \times \mathbf{v}_{\perp} \end{pmatrix} = n v_{\perp} \end{array} \right. \quad \left\{ \begin{array}{l} \mathbf{u} \perp \mathbf{n} \\ \mathbf{u} \perp \mathbf{v}_{\perp} \\ \mathbf{n} \perp \mathbf{v}_{\perp} \\ \|\mathbf{n}\| = 1 \end{array} \right. \\ \left\{ \begin{array}{l} \|\mathbf{u}\| = \|\mathbf{n} \times \mathbf{v}_{\perp}\| = \|\mathbf{n}\| \|\mathbf{v}_{\perp}\| \sin \frac{\pi}{2} = \|\mathbf{v}_{\perp}\| \\ \mathbf{v}'_{\parallel} = \begin{pmatrix} 0 \\ \mathbf{v}'_{\parallel} \end{pmatrix} = \begin{pmatrix} 0 \\ \mathbf{v}_{\parallel} \end{pmatrix} = v_{\parallel} \\ \mathbf{v}'_{\perp} = \begin{pmatrix} 0 \\ \mathbf{v}'_{\perp} \end{pmatrix} = \cos \theta \begin{pmatrix} 0 \\ \mathbf{v}_{\perp} \end{pmatrix} + \sin \theta \begin{pmatrix} 0 \\ \mathbf{n} \times \mathbf{v}_{\perp} \end{pmatrix} = \cos \theta v_{\perp} + \sin \theta n v_{\perp} = (\cos \theta + \sin \theta n) v_{\perp} \end{array} \right. \end{array} \right. \end{aligned}$$

$$v'_{\perp} = (\cos \theta + \sin \theta n) v_{\perp}$$

$$v'_{\perp} = p v_{\perp}, p = \cos \theta + \sin \theta n = \cos \theta \begin{pmatrix} 1 \\ \mathbf{0} \end{pmatrix} + \sin \theta \begin{pmatrix} 0 \\ \mathbf{n} \end{pmatrix} = \begin{pmatrix} \cos \theta \\ \sin \theta \mathbf{n} \end{pmatrix}$$

$$p = \begin{pmatrix} p_0 \\ \mathbf{p} \end{pmatrix} = \begin{pmatrix} \cos \theta \\ \sin \theta \mathbf{n} \end{pmatrix} = \cos \theta + \sin \theta n, \|\mathbf{n}\| = 1$$

$$|p| = \left\| \begin{pmatrix} \cos \theta \\ \sin \theta \mathbf{n} \end{pmatrix} \right\| = \sqrt{\begin{pmatrix} \cos \theta \\ \sin \theta \mathbf{n} \end{pmatrix}^T \begin{pmatrix} \cos \theta \\ \sin \theta \mathbf{n} \end{pmatrix}} = \sqrt{\cos^2 \theta + \sin^2 \theta \|\mathbf{n}\|^2} = \sqrt{\cos^2 \theta + \sin^2 \theta} = 1$$

$$|p| = \left\| \begin{pmatrix} \cos \theta \\ \sin \theta \mathbf{n} \end{pmatrix} \right\| = 1$$

$$p^* = \bar{p} = \begin{pmatrix} p_0 \\ -\mathbf{p} \end{pmatrix} = \begin{pmatrix} \cos \theta \\ -\sin \theta \mathbf{n} \end{pmatrix} = \cos \theta - \sin \theta n$$

$$\begin{aligned}
p^* p &= \bar{p} p = \begin{pmatrix} p_0 \\ -\mathbf{p} \end{pmatrix} \begin{pmatrix} p_0 \\ \mathbf{p} \end{pmatrix} = \begin{pmatrix} p_0 p_0 - (-\mathbf{p}) \cdot \mathbf{p} \\ -\mathbf{p} p_0 + p_0 \mathbf{p} + (-\mathbf{p}) \times \mathbf{p} \end{pmatrix} \\
&= \begin{pmatrix} p_0 p_0 + \mathbf{p} \cdot \mathbf{p} \\ \mathbf{0} + \mathbf{0} \end{pmatrix} = p_0 p_0 + \mathbf{p} \cdot \mathbf{p} = p_0^2 + \|\mathbf{p}\|^2 = |p|^2 = 1^2 = 1 \\
&= \begin{pmatrix} p_0 p_0 - \mathbf{p} \cdot (-\mathbf{p}) \\ \mathbf{p} p_0 + p_0 (-\mathbf{p}) + \mathbf{p} \times (-\mathbf{p}) \end{pmatrix} = p \bar{p} = pp^*
\end{aligned}$$

$$p^* p = \bar{p} p = 1 = p \bar{p} = pp^* = |p|^2 = p_0^2 + \|\mathbf{p}\|^2 \Rightarrow p^* = \frac{1}{p} = p^{-1}$$

$$\begin{aligned}
p^2 &= pp = \begin{pmatrix} p_0 p_0 - \mathbf{p} \cdot \mathbf{p} \\ \mathbf{p} p_0 + p_0 \mathbf{p} + \mathbf{p} \times \mathbf{p} \end{pmatrix} = \begin{pmatrix} \cos^2 \theta - \sin^2 \theta \|\mathbf{n}\|^2 \\ 2(\sin \theta \mathbf{n}) \cos \theta + \mathbf{0} \end{pmatrix} \\
&= \begin{pmatrix} \cos^2 \theta - \sin^2 \theta \\ 2 \sin \theta \cos \theta \mathbf{n} \end{pmatrix} = \begin{pmatrix} \cos 2\theta \\ \sin 2\theta \mathbf{n} \end{pmatrix} \\
&\left(\begin{pmatrix} \cos \theta \\ \sin \theta \mathbf{n} \end{pmatrix} \right)^2 = \begin{pmatrix} \cos 2\theta \\ \sin 2\theta \mathbf{n} \end{pmatrix} \\
q^2 &= \left(\begin{pmatrix} \cos \frac{\theta}{2} \\ \sin \frac{\theta}{2} \mathbf{n} \end{pmatrix} \right)^2 = \begin{pmatrix} \cos \theta \\ \sin \theta \mathbf{n} \end{pmatrix} = p
\end{aligned}$$

$$qv_{\parallel} = v_{\parallel} q$$

$$\begin{aligned}
\begin{pmatrix} \alpha \\ \beta \mathbf{n} \end{pmatrix} v_{\parallel \mathbf{n}} &= \begin{pmatrix} \alpha \\ \beta \mathbf{n} \end{pmatrix} v_{\parallel} = \begin{pmatrix} \alpha \\ \beta \mathbf{n} \end{pmatrix} \begin{pmatrix} 0 \\ \mathbf{v}_{\parallel} \end{pmatrix} \\
&= \begin{pmatrix} \alpha 0 - \beta \mathbf{n} \cdot \mathbf{v}_{\parallel} \\ \beta \mathbf{n} 0 + \alpha \mathbf{v}_{\parallel} + \beta \mathbf{n} \times \mathbf{v}_{\parallel} \end{pmatrix} = \begin{pmatrix} -\beta \mathbf{n} \cdot \mathbf{v}_{\parallel} \\ \alpha \mathbf{v}_{\parallel} + \mathbf{0} \end{pmatrix} = \begin{pmatrix} -\beta \mathbf{n} \cdot \mathbf{v}_{\parallel} \\ \alpha \mathbf{v}_{\parallel} \end{pmatrix} \\
&= \begin{pmatrix} 0\alpha - \mathbf{v}_{\parallel} \cdot \beta \mathbf{n} \\ \mathbf{v}_{\parallel} \alpha + 0\beta \mathbf{n} + \mathbf{v}_{\parallel} \times \beta \mathbf{n} \end{pmatrix} = \begin{pmatrix} -\mathbf{v}_{\parallel} \cdot \beta \mathbf{n} \\ \alpha \mathbf{v}_{\parallel} + \mathbf{0} \end{pmatrix} = \begin{pmatrix} -\beta \mathbf{n} \cdot \mathbf{v}_{\parallel} \\ \alpha \mathbf{v}_{\parallel} \end{pmatrix} \\
&= \begin{pmatrix} 0 \\ \mathbf{v}_{\parallel} \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \mathbf{n} \end{pmatrix} = v_{\parallel} \begin{pmatrix} \alpha \\ \beta \mathbf{n} \end{pmatrix} = v_{\parallel \mathbf{n}} \begin{pmatrix} \alpha \\ \beta \mathbf{n} \end{pmatrix} \\
\begin{pmatrix} \alpha \\ \beta \mathbf{n} \end{pmatrix} v_{\parallel} &= v_{\parallel} \begin{pmatrix} \alpha \\ \beta \mathbf{n} \end{pmatrix}
\end{aligned}$$

$$qv_{\perp} = v_{\perp} q^*$$

$$\begin{aligned}
\begin{pmatrix} \alpha \\ \beta \mathbf{n} \end{pmatrix} v_{\perp \mathbf{n}} &= \begin{pmatrix} \alpha \\ \beta \mathbf{n} \end{pmatrix} v_{\perp} = \begin{pmatrix} \alpha \\ \beta \mathbf{n} \end{pmatrix} \begin{pmatrix} 0 \\ \mathbf{v}_{\perp} \end{pmatrix} \\
&= \begin{pmatrix} \alpha 0 - \beta \mathbf{n} \cdot \mathbf{v}_{\perp} \\ \beta \mathbf{n} 0 + \alpha \mathbf{v}_{\perp} + \beta \mathbf{n} \times \mathbf{v}_{\perp} \end{pmatrix} = \begin{pmatrix} 0 - 0 \\ \alpha \mathbf{v}_{\perp} + \beta \mathbf{n} \times \mathbf{v}_{\perp} \end{pmatrix} = \begin{pmatrix} 0 \\ \alpha \mathbf{v}_{\perp} + \mathbf{v}_{\perp} \times (-\beta \mathbf{n}) \end{pmatrix} \\
&= \begin{pmatrix} 0\alpha - \mathbf{v}_{\perp} \cdot (-\beta \mathbf{n}) \\ \mathbf{v}_{\perp} \alpha + 0(-\beta \mathbf{n}) + \mathbf{v}_{\perp} \times (-\beta \mathbf{n}) \end{pmatrix} = \begin{pmatrix} 0 - 0 \\ \alpha \mathbf{v}_{\perp} + \mathbf{v}_{\perp} \times (-\beta \mathbf{n}) \end{pmatrix} = \begin{pmatrix} 0 \\ \alpha \mathbf{v}_{\perp} + \beta \mathbf{n} \times \mathbf{v}_{\perp} \end{pmatrix} \\
&= \begin{pmatrix} 0 \\ \mathbf{v}_{\perp} \end{pmatrix} \begin{pmatrix} \alpha \\ -\beta \mathbf{n} \end{pmatrix} = v_{\perp} \begin{pmatrix} \alpha \\ -\beta \mathbf{n} \end{pmatrix} = v_{\perp \mathbf{n}} \begin{pmatrix} \alpha \\ -\beta \mathbf{n} \end{pmatrix} \\
\begin{pmatrix} \alpha \\ \beta \mathbf{n} \end{pmatrix} v_{\perp} &= v_{\perp} \begin{pmatrix} \alpha \\ -\beta \mathbf{n} \end{pmatrix} = v_{\perp} \begin{pmatrix} \alpha \\ \beta \mathbf{n} \end{pmatrix}^* = v_{\perp} \overline{\begin{pmatrix} \alpha \\ \beta \mathbf{n} \end{pmatrix}}
\end{aligned}$$

$$\begin{aligned}
q = \cos \frac{\theta}{2} + \sin \frac{\theta}{2} n &\in \left\{ p \left| \begin{array}{l} p = \cos \theta + \sin \theta n \\ n = \begin{pmatrix} 0 \\ \mathbf{n} \end{pmatrix}, \|n\| = 1 \end{array} \right. \right\} \subset \left\{ \begin{pmatrix} \alpha \\ \beta \mathbf{n} \end{pmatrix} \left| \begin{array}{l} \alpha, \beta \in \mathbb{R} \\ \|\mathbf{n}\| = 1 \end{array} \right. \right\} \\
&\Rightarrow \begin{cases} q^* q = \bar{q} q = 1 = q \bar{q} = q q^* = |q|^2 = q_0^2 + \|\mathbf{q}\|^2 \Rightarrow q^* = \frac{1}{q} = q^{-1} & (u) \text{ unit quaternion} \\ q v_{\parallel} = v_{\parallel} q \\ q v_{\perp} = v_{\perp} q^* = v_{\perp} \bar{q} \Leftrightarrow \begin{pmatrix} \cos \frac{\theta}{2} \\ \sin \frac{\theta}{2} \mathbf{n} \end{pmatrix} v_{\perp} = v_{\perp} \begin{pmatrix} \cos \frac{\theta}{2} \\ -\sin \frac{\theta}{2} \mathbf{n} \end{pmatrix} & (c) \text{ commutativity} \\ & (a) \text{ anticommutativity} \end{cases}
\end{aligned}$$

$$\begin{aligned}
v' &= v'_{\parallel} + v'_{\perp}, \begin{cases} v'_{\parallel} = v_{\parallel} & q = \cos \frac{\theta}{2} + \sin \frac{\theta}{2} n, |n| = 1 \\ v'_{\perp} = p v_{\perp} = q^2 v_{\perp} & p = q^2 = \cos \theta + \sin \theta n \end{cases} \\
&= v_{\parallel} + q^2 v_{\perp} \stackrel{(u)}{=} 1 v_{\parallel} + q q v_{\perp} \\
&\stackrel{(a)}{=} q q^* v_{\parallel} + q v_{\perp} q^* \stackrel{(c)}{=} q v_{\parallel} q^* + q v_{\perp} q^* \\
&= q (v_{\parallel} + v_{\perp}) q^* = q (v) q^* = q v q^*
\end{aligned}$$

$$\begin{aligned}
v' &= q v q^{-1}, q = \cos \frac{\theta}{2} + \sin \frac{\theta}{2} n, |n| = 1 \\
&= q v q^* = q (v_{\parallel} + v_{\perp}) q^* \\
&= q v_{\parallel} q^* + q v_{\perp} q^* = q q^* v_{\parallel} + q q v_{\perp} = 1 v_{\parallel} + q^2 v_{\perp} \\
&= v_{\parallel} + p v_{\perp}, p = q^2 = \cos \theta + \sin \theta n
\end{aligned}$$

$$\begin{aligned}
v' &= q v q^* = q (v q^*) \leftrightarrow L(q) R(q^*) v = Q_l Q_r v = \begin{pmatrix} q_0 & -\mathbf{q}^T \\ \mathbf{q} & Q_i \end{pmatrix} \begin{pmatrix} q_0 & -\mathbf{q}^T \\ \mathbf{q} & Q_i^T \end{pmatrix} \begin{pmatrix} v_0 \\ \mathbf{v} \end{pmatrix} \\
&= (q v) q^* \leftrightarrow R(q^*) L(q) v = Q_r Q_l v = \begin{pmatrix} q_0 & -\mathbf{q}^T \\ \mathbf{q} & Q_i^T \end{pmatrix} \begin{pmatrix} q_0 & -\mathbf{q}^T \\ \mathbf{q} & Q_i \end{pmatrix} \begin{pmatrix} v_0 \\ \mathbf{v} \end{pmatrix} \\
\begin{pmatrix} q_0 & -\mathbf{q}^T \\ \mathbf{q} & Q_i \end{pmatrix} \begin{pmatrix} q_0 & -\mathbf{q}^T \\ \mathbf{q} & Q_i^T \end{pmatrix} &= \begin{pmatrix} q_0^2 - \mathbf{q}^T \mathbf{q} & -q_0 \mathbf{q}^T - \mathbf{q}^T Q_i^T \\ \mathbf{q} q_0 + Q_i \mathbf{q} & -\mathbf{q} \mathbf{q}^T + Q_i Q_i^T \end{pmatrix} = L(q) R(q^*) \\
\begin{pmatrix} q_0 & -\mathbf{q}^T \\ \mathbf{q} & Q_i^T \end{pmatrix} \begin{pmatrix} q_0 & -\mathbf{q}^T \\ \mathbf{q} & Q_i \end{pmatrix} &= \begin{pmatrix} q_0^2 - \mathbf{q}^T \mathbf{q} & -q_0 \mathbf{q}^T - \mathbf{q}^T Q_i \\ \mathbf{q} q_0 + Q_i^T \mathbf{q} & -\mathbf{q} \mathbf{q}^T + Q_i^T Q_i \end{pmatrix} = R(q^*) L(q)
\end{aligned}$$

$$\begin{aligned}
q &= a + bi + cj + dk = \cos \frac{\theta}{2} + \sin \frac{\theta}{2} n = \cos \frac{\theta}{2} + bi + cj + dk \\
\Rightarrow Q_i Q_i^T &= \begin{pmatrix} a & -d & c \\ d & a & -b \\ -c & b & a \end{pmatrix} \begin{pmatrix} a & d & -c \\ -d & a & b \\ c & -b & a \end{pmatrix} = \begin{pmatrix} a^2 + d^2 + c^2 & -cb & -db \\ -cb & d^2 + a^2 + b^2 & -dc \\ -db & -dc & c^2 + b^2 + a^2 \end{pmatrix} \\
&= Q_i^T Q_i = \begin{pmatrix} a & d & -c \\ -d & a & b \\ c & -b & a \end{pmatrix} \begin{pmatrix} a & -d & c \\ d & a & -b \\ -c & b & a \end{pmatrix} = \begin{pmatrix} a^2 + d^2 + c^2 & -cb & -db \\ -cb & d^2 + a^2 + b^2 & -dc \\ -db & -dc & c^2 + b^2 + a^2 \end{pmatrix} \\
\mathbf{q}^T Q_i^T &= (b \quad c \quad d) \begin{pmatrix} a & d & -c \\ -d & a & b \\ c & -b & a \end{pmatrix} = (ba \quad ca \quad da) \\
&= \mathbf{q}^T Q_i = (b \quad c \quad d) \begin{pmatrix} a & -d & c \\ d & a & -b \\ -c & b & a \end{pmatrix} = (ba \quad ca \quad da) \\
Q_i \mathbf{q} &= \begin{pmatrix} a & -d & c \\ d & a & -b \\ -c & b & a \end{pmatrix} \begin{pmatrix} b \\ c \\ d \end{pmatrix} = \begin{pmatrix} ab \\ ac \\ ad \end{pmatrix} \\
&= Q_i^T \mathbf{q} = \begin{pmatrix} a & d & -c \\ -d & a & b \\ c & -b & a \end{pmatrix} \begin{pmatrix} b \\ c \\ d \end{pmatrix} = \begin{pmatrix} ab \\ ac \\ ad \end{pmatrix}
\end{aligned}$$

$$\begin{aligned}
&\begin{pmatrix} q_0 & -\mathbf{q}^T \\ \mathbf{q} & Q_i \end{pmatrix} \begin{pmatrix} q_0 & -\mathbf{q}^T \\ \mathbf{q} & Q_i^T \end{pmatrix} = \begin{pmatrix} q_0^2 - \mathbf{q}^T \mathbf{q} & -q_0 \mathbf{q}^T - \mathbf{q}^T Q_i^T \\ \mathbf{q} q_0 + Q_i \mathbf{q} & -\mathbf{q} \mathbf{q}^T + Q_i Q_i^T \end{pmatrix} = L(q) R(q^*) \\
&= \begin{pmatrix} q_0 & -\mathbf{q}^T \\ \mathbf{q} & Q_i^T \end{pmatrix} \begin{pmatrix} q_0 & -\mathbf{q}^T \\ \mathbf{q} & Q_i \end{pmatrix} = \begin{pmatrix} q_0^2 - \mathbf{q}^T \mathbf{q} & -q_0 \mathbf{q}^T - \mathbf{q}^T Q_i \\ \mathbf{q} q_0 + Q_i^T \mathbf{q} & -\mathbf{q} \mathbf{q}^T + Q_i^T Q_i \end{pmatrix} = R(q^*) L(q) \\
&\Downarrow \\
L(q) R(q^*) &= R(q^*) L(q) \\
&\Updownarrow \\
v' &= qvq^* = q(vq^*) = (qv)q^*
\end{aligned}$$

$$a = \cos \frac{\theta}{2} \Rightarrow \theta = 2 \arccos a = 2 \cos^{-1} a$$

$$\sin \frac{\theta}{2} n = \sin \frac{2 \arccos a}{2} n = \sin (\cos^{-1} a) n$$

$$n = \begin{pmatrix} 0 \\ \mathbf{n} \end{pmatrix} = \begin{pmatrix} 0 \\ \hat{\mathbf{n}} \end{pmatrix}, \|n\| = 1, \mathbf{n} = \begin{pmatrix} \sin \gamma \cos \alpha \\ \sin \gamma \sin \alpha \\ \cos \gamma \end{pmatrix}, \begin{cases} \alpha = \angle \hat{\mathbf{n}}_{xy} \hat{\mathbf{x}} \\ \gamma = \angle \hat{\mathbf{n}} \hat{\mathbf{z}} \end{cases}$$

$$\begin{aligned}
q &= a + bi + cj + dk \\
&= \cos \frac{\theta}{2} + \sin \frac{\theta}{2} n, n = \begin{pmatrix} 0 \\ \mathbf{n} \end{pmatrix} = \begin{pmatrix} 0 \\ \hat{\mathbf{n}} \end{pmatrix} = \begin{pmatrix} 0 \\ \sin \gamma \cos \alpha \\ \sin \gamma \sin \alpha \\ \cos \gamma \end{pmatrix}, \|\mathbf{n}\| = 1, \begin{cases} \alpha = \angle \hat{\mathbf{n}}_{xy} \hat{\mathbf{x}} \\ \gamma = \angle \hat{\mathbf{n}} \hat{\mathbf{z}} \end{cases} \\
&= \cos \frac{\theta}{2} + \sin \frac{\theta}{2} \mathbf{n}, \mathbf{n} = (\sin \gamma \cos \alpha) \mathbf{i} + (\sin \gamma \sin \alpha) \mathbf{j} + (\cos \gamma) \mathbf{k} \\
&= \cos \frac{\theta}{2} + \sin \frac{\theta}{2} [(\sin \gamma \cos \alpha) \mathbf{i} + (\sin \gamma \sin \alpha) \mathbf{j} + (\cos \gamma) \mathbf{k}] \\
&= \cos \frac{\theta}{2} + \mathbf{n} \sin \frac{\theta}{2} \\
q^{-1} &= q^* = \cos \frac{\theta}{2} - \mathbf{n} \sin \frac{\theta}{2} \\
&= \cos \frac{\theta}{2} - \sin \frac{\theta}{2} [(\sin \gamma \cos \alpha) \mathbf{i} + (\sin \gamma \sin \alpha) \mathbf{j} + (\cos \gamma) \mathbf{k}] \\
\mathbf{v}' &= v' = qvq^{-1} = q\mathbf{v}q^{-1}, \begin{cases} v = \mathbf{v} = v_1 \mathbf{i} + v_2 \mathbf{j} + v_3 \mathbf{k} \\ v' = \mathbf{v}' = v'_1 \mathbf{i} + v'_2 \mathbf{j} + v'_3 \mathbf{k} \end{cases} \\
&= \left\{ \cos \frac{\theta}{2} + \sin \frac{\theta}{2} [(\sin \gamma \cos \alpha) \mathbf{i} + (\sin \gamma \sin \alpha) \mathbf{j} + (\cos \gamma) \mathbf{k}] \right\} \mathbf{v} \\
&\quad \left\{ \cos \frac{\theta}{2} - \sin \frac{\theta}{2} [(\sin \gamma \cos \alpha) \mathbf{i} + (\sin \gamma \sin \alpha) \mathbf{j} + (\cos \gamma) \mathbf{k}] \right\} \\
&= q(\theta, \gamma, \alpha) \mathbf{v} q^{-1}(\theta, \gamma, \alpha) \\
&= \left\{ \cos \frac{\theta}{2} + \sin \frac{\theta}{2} [n_x \mathbf{i} + n_y \mathbf{j} + n_z \mathbf{k}] \right\} \mathbf{v} \left\{ \cos \frac{\theta}{2} - \sin \frac{\theta}{2} [n_x \mathbf{i} + n_y \mathbf{j} + n_z \mathbf{k}] \right\} \\
&= \left\{ \cos \frac{\theta}{2} + \sin \frac{\theta}{2} [n_x \mathbf{i} \pm \sqrt{1 - n_x^2 - n_z^2} \mathbf{j} + n_z \mathbf{k}] \right\} \mathbf{v} \\
&\quad \left\{ \cos \frac{\theta}{2} - \sin \frac{\theta}{2} [n_x \mathbf{i} \pm \sqrt{1 - n_x^2 - n_z^2} \mathbf{j} + n_z \mathbf{k}] \right\} \\
&= q(\theta, n_z, n_x) \mathbf{v} q^{-1}(\theta, n_z, n_x)
\end{aligned}$$

$$\mathbf{v}' = v' = qvq^{-1} = q\mathbf{v}q^{-1}, \begin{cases} v = \mathbf{v} = v_1 \mathbf{i} + v_2 \mathbf{j} + v_3 \mathbf{k} \\ v' = \mathbf{v}' = v'_1 \mathbf{i} + v'_2 \mathbf{j} + v'_3 \mathbf{k} \\ q = \cos \frac{\theta}{2} + \sin \frac{\theta}{2} [(\sin \gamma \cos \alpha) \mathbf{i} + (\sin \gamma \sin \alpha) \mathbf{j} + (\cos \gamma) \mathbf{k}] \\ q^{-1} = \cos \frac{\theta}{2} - \sin \frac{\theta}{2} [(\sin \gamma \cos \alpha) \mathbf{i} + (\sin \gamma \sin \alpha) \mathbf{j} + (\cos \gamma) \mathbf{k}] \end{cases}$$

34.2.3 matrix form

$$q \stackrel{|q|=1}{=} a + bi + cj + dk, \begin{cases} a = \cos \frac{\theta}{2} \\ b = \sin \frac{\theta}{2} \sin \gamma \cos \alpha \\ c = \sin \frac{\theta}{2} \sin \gamma \sin \alpha \\ d = \sin \frac{\theta}{2} \cos \gamma \end{cases}$$

$$L(q) = Q_l = \begin{pmatrix} a & -b & -c & -d \\ b & a & -d & c \\ c & d & a & -b \\ d & -c & b & a \end{pmatrix}$$

$$R(q) = Q_r = \begin{pmatrix} a & -b & -c & -d \\ b & a & d & -c \\ c & -d & a & b \\ d & c & -b & a \end{pmatrix}$$

$$R(q^*) = \begin{pmatrix} a & b & c & d \\ -b & a & -d & c \\ -c & d & a & -b \\ -d & -c & b & a \end{pmatrix}$$

$$\begin{aligned} v' &= qvq^* = (qv)q^* \leftrightarrow R(q^*)L(q)v \\ &= q(vq^*) \leftrightarrow L(q)R(q^*)v \\ &= \begin{pmatrix} a & -b & -c & -d \\ b & a & -d & c \\ c & d & a & -b \\ d & -c & b & a \end{pmatrix} \begin{pmatrix} a & b & c & d \\ -b & a & -d & c \\ -c & d & a & -b \\ -d & -c & b & a \end{pmatrix} v \\ &= \begin{pmatrix} a^2 + b^2 + c^2 + d^2 & 0 & 0 & 0 \\ 0 & b^2 + a^2 - d^2 - c^2 & -2ad + 2bc & 2ac + 2bd \\ 0 & 2ad + 2bc & c^2 - d^2 + a^2 - b^2 & 2cd - 2ab \\ 0 & -2ac + 2bd & 2cd + 2ab & d^2 - c^2 - b^2 + a^2 \end{pmatrix} v \\ &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 - 2(d^2 + c^2) & 2(bc - ad) & 2(bd + ac) \\ 0 & 2(bc + ad) & 1 - 2(d^2 + b^2) & 2(cd - ab) \\ 0 & 2(bd - ac) & 2(cd + ab) & 1 - 2(c^2 + b^2) \end{pmatrix} v \\ \begin{pmatrix} 0 \\ v' \end{pmatrix} &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 - 2(d^2 + c^2) & 2(bc - ad) & 2(bd + ac) \\ 0 & 2(bc + ad) & 1 - 2(d^2 + b^2) & 2(cd - ab) \\ 0 & 2(bd - ac) & 2(cd + ab) & 1 - 2(c^2 + b^2) \end{pmatrix} \begin{pmatrix} 0 \\ v \end{pmatrix} \end{aligned}$$

$$\mathbf{v}' = \begin{pmatrix} 1 - 2(d^2 + c^2) & 2(bc - ad) & 2(bd + ac) \\ 2(bc + ad) & 1 - 2(d^2 + b^2) & 2(cd - ab) \\ 2(bd - ac) & 2(cd + ab) & 1 - 2(c^2 + b^2) \end{pmatrix} \mathbf{v}$$

$$q \stackrel{|q|=1}{=} a + bi + cj + dk, \quad \begin{cases} a = \cos \frac{\theta}{2} \\ b = \sin \frac{\theta}{2} \sin \gamma \cos \alpha \\ c = \sin \frac{\theta}{2} \sin \gamma \sin \alpha \\ d = \sin \frac{\theta}{2} \cos \gamma \end{cases}$$

34.2.4 exponential form

$$\begin{aligned}
 q &= a + bi + cj + dk = a + ib + jc + kd \\
 &= a + r \frac{ib + jc + kd}{r}, r^2 = b^2 + c^2 + d^2 \\
 &\stackrel{|q|=1}{=} \cos \frac{\theta}{2} + \sin \frac{\theta}{2} \mathbf{n}, \begin{cases} a = \cos \frac{\theta}{2} & \cos \frac{\theta}{2} = a \\ r = \sin \frac{\theta}{2} & \sin \frac{\theta}{2} = r \\ \frac{ib + jc + kd}{r} = \mathbf{n} & \mathbf{n} = \frac{ib + jc + kd}{r} \end{cases}
 \end{aligned}$$

$$\begin{aligned}
 \|\mathbf{n}\|^2 &= \left(\frac{ib + jc + kd}{r} \right)^2 = \frac{-b^2 - c^2 - d^2 + bc(ij + ji) + cd(jk + kj) + db(ki + ik)}{r^2} \\
 &= \frac{-b^2 - c^2 - d^2 + bc(k - k) + cd(i - i) + db(j - j)}{r^2} \\
 &= \frac{-b^2 - c^2 - d^2 + bc0 + cd0 + db0}{r^2} = \frac{-b^2 - c^2 - d^2}{r^2} \\
 &= \frac{-b^2 - c^2 - d^2}{b^2 + c^2 + d^2} = -1 \\
 \mathbf{n} &= \frac{ib + jc + kd}{r} = \pm \sqrt{-1}
 \end{aligned}$$

$$\begin{aligned}
 q &= a + bi + cj + dk = a + ib + jc + kd \\
 &= a + r \frac{ib + jc + kd}{r}, r^2 = b^2 + c^2 + d^2 \\
 &= \sqrt{a^2 + r^2} \left(\frac{a}{\sqrt{a^2 + r^2}} + \frac{ib + jc + kd}{r} \frac{r}{\sqrt{a^2 + r^2}} \right) \\
 &= \rho (\cos \phi + \sqrt{-1} \sin \phi), \begin{cases} \rho = \sqrt{a^2 + r^2} \\ \tan \phi = \frac{r}{a} \Leftrightarrow \phi = \arctan \frac{r}{a} = \frac{\theta}{2} \end{cases} \\
 &= \rho e^{\phi \sqrt{-1}} \stackrel{|q|=1}{=} |q| e^{\mathbf{n} \frac{\theta}{2}} = e^{\mathbf{n} \frac{\theta}{2}}
 \end{aligned}$$

$$q = \rho e^{\phi \sqrt{-1}} \stackrel{|q|=1}{=} e^{\mathbf{n} \frac{\theta}{2}}, \begin{cases} q = a + ib + jc + kd \\ \rho = \sqrt{a^2 + r^2} = |q| = \sqrt{a^2 + b^2 + c^2 + d^2} = 1 \\ \tan \frac{\theta}{2} = \frac{r}{a} \Leftrightarrow \frac{\theta}{2} = \arctan \frac{r}{a} = \arctan \frac{\pm \sqrt{b^2 + c^2 + d^2}}{a} \end{cases}$$

$$\begin{aligned}
\mathbf{v}' &= v' = qvq^{-1} = q\mathbf{v}q^{-1}, \quad \left\{ \begin{array}{l} v = \mathbf{v} = v_1\mathbf{i} + v_2\mathbf{j} + v_3\mathbf{k} \\ v' = \mathbf{v}' = v'_1\mathbf{i} + v'_2\mathbf{j} + v'_3\mathbf{k} \end{array} \right., \quad \mathbf{n} = \begin{pmatrix} \sin \gamma \cos \alpha \\ \sin \gamma \sin \alpha \\ \cos \gamma \end{pmatrix}, \quad \left\{ \begin{array}{l} \alpha = \angle \hat{\mathbf{n}}_{xy} \hat{\mathbf{x}} \\ \gamma = \angle \hat{\mathbf{n}} \hat{\mathbf{z}} \end{array} \right. \\
&= \left\{ \cos \frac{\theta}{2} + \sin \frac{\theta}{2} [(\sin \gamma \cos \alpha) \mathbf{i} + (\sin \gamma \sin \alpha) \mathbf{j} + (\cos \gamma) \mathbf{k}] \right\} \mathbf{v} \\
&\quad \left\{ \cos \frac{\theta}{2} - \sin \frac{\theta}{2} [(\sin \gamma \cos \alpha) \mathbf{i} + (\sin \gamma \sin \alpha) \mathbf{j} + (\cos \gamma) \mathbf{k}] \right\} \\
&= q(\theta, \gamma, \alpha) \mathbf{v} q^{-1}(\theta, \gamma, \alpha) = q\left(\frac{\theta}{2}, \gamma, \alpha\right) \mathbf{v} q^{-1}\left(\frac{\theta}{2}, \gamma, \alpha\right) \\
&= \left\{ \cos \frac{\theta}{2} + \sin \frac{\theta}{2} [n_x \mathbf{i} + n_y \mathbf{j} + n_z \mathbf{k}] \right\} \mathbf{v} \left\{ \cos \frac{\theta}{2} - \sin \frac{\theta}{2} [n_x \mathbf{i} + n_y \mathbf{j} + n_z \mathbf{k}] \right\} \\
&= \left\{ \cos \frac{\theta}{2} + \sin \frac{\theta}{2} \left[n_x \mathbf{i} \pm \sqrt{1 - n_x^2 - n_z^2} \mathbf{j} + n_z \mathbf{k} \right] \right\} \mathbf{v} \\
&\quad \left\{ \cos \frac{\theta}{2} - \sin \frac{\theta}{2} \left[n_x \mathbf{i} \pm \sqrt{1 - n_x^2 - n_z^2} \mathbf{j} + n_z \mathbf{k} \right] \right\} \\
&= q(\theta, n_z, n_x) \mathbf{v} q^{-1}(\theta, n_z, n_x) = q\left(\frac{\theta}{2}, n_z, n_x\right) \mathbf{v} q^{-1}\left(\frac{\theta}{2}, n_z, n_x\right) \\
&= e^{\mathbf{n} \frac{\theta}{2}} \mathbf{v} e^{-\mathbf{n} \frac{\theta}{2}}
\end{aligned}$$

$$\mathbf{v}' = e^{\mathbf{n} \frac{\theta}{2}} \mathbf{v} e^{-\mathbf{n} \frac{\theta}{2}}$$

general quaternion exponential form

$$\begin{aligned}
q &= \rho e^{\phi \sqrt{-1}} = |q| e^{\mathbf{n} \phi}, \quad \left\{ \begin{array}{l} q = a + ib + jc + kd = a + r \frac{ib + jc + kd}{r} = a + r\mathbf{n} \\ \rho = \sqrt{a^2 + r^2} = |q| = \sqrt{a^2 + b^2 + c^2 + d^2} \\ \tan \phi = \frac{r}{a} \Leftrightarrow \phi = \arctan \frac{r}{a} = \arctan \frac{\pm \sqrt{b^2 + c^2 + d^2}}{a} \end{array} \right. \\
&= e^{\ln |q|} e^{\mathbf{n} \phi} = e^{\ln |q| + \mathbf{n} \phi}
\end{aligned}$$

34.2.5 double cover

34.2.6 right-hand vs. left-hand

34.2.7 gimbal lock

https://krasjet.github.io/quaternion/bonus_gimbal_lock.pdf

34.2.8 Lie group

34.2.8.1 special unitary group

34.2.9 geometric algebra and Clifford algebra

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

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

John Vince_2009_Geometric Algebra_ An Algebraic System for Computer Games and Animation
<https://www.amazon.com/Geometric-Algebra-Algebraic-Computer-Animation/dp/1848823789>

34.2.10 dual quaternion

34.2.11 interpolation

34.2.11.1 Lerp

34.2.11.2 Nlerp

34.2.11.3 Slerp

34.3 3Blue1Brown

34.3.1 Ben Eater

<https://eater.net/quaternions/video/intro>

<https://eater.net/quaternions>

34.3.2 3B1B

34.3.3 Sutrabla

<https://www.newscientist.com/article/mg20427391-600-alices-adventures-in-algebra-wonderland-solved/>

<https://threejs.org/>

34.4 CCJou: LA Revelation

<https://ccjou.wordpress.com/2014/04/21/四元數/>

Chapter 35

DICOM

35.1 Innolitics: DICOM Standard Browser

<https://dicom.innolitics.com/ciods>

<https://dicom.innolitics.com/ciods/parametric-map/parametric-map-multi-frame-functional-groups/52009229/0048021a/0040072a>

35.2 David Clunie: Medical Image Format Site

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

Chapter 36

tendon pathophysiology

Mark E. Schweitzer, MD

<https://www.youtube.com/watch?v=uIo58pQgxhY>

36.1 histology

Chapter 37

group theory

[https://en.wikipedia.org/wiki/Group_\(mathematics\)](https://en.wikipedia.org/wiki/Group_(mathematics))

37.1 matrix group

subset of two-by-two matrices at least excluding zero matrix

$$\mathcal{M} = (\mathcal{M}, \cdot) \subset (\mathcal{M}_{2 \times 2}(\mathbb{C}) - \{0\}, \cdot) = \mathcal{M}_{2 \times 2}(\mathbb{C}) - \left\{ \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \right\}$$

matrix multiplication

$$\begin{aligned} & \forall \langle M_1, M_2 \rangle \in \mathcal{M}^2, \exists M_1 M_2 \in \mathcal{M} [M_1 M_2 = M_1 \cdot M_2] \\ \Leftrightarrow & \cdot : \mathcal{M} \times \mathcal{M} = \mathcal{M}^2 \rightarrow \mathcal{M} \\ \Leftrightarrow & \cdot : \mathcal{M} \times \mathcal{M} \rightarrow \mathcal{M} \\ \Leftrightarrow & \mathcal{M} \times \mathcal{M} \stackrel{\cdot}{\rightarrow} \mathcal{M} \\ \Leftrightarrow & \mathcal{M}^2 \stackrel{\cdot}{\rightarrow} \mathcal{M} \end{aligned}$$

matrix group

$$\begin{cases} \forall \langle M_1, M_2, M_3 \rangle \in \mathcal{M}^3 [M_1 (M_2 M_3) = (M_1 M_2) M_3] & \text{associativity} \\ \exists I = I_2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \in \mathcal{M}, \forall M \in \mathcal{M} [IM = M] & \text{left unit element} \\ \forall M \in \mathcal{M}, \exists M^{-1} \in \mathcal{M} [M^{-1} M = I] & \text{left inverse (element)} \end{cases}$$

$\Rightarrow \mathcal{M} = (\mathcal{M}, \cdot)$ is a matrix group

37.2 group definition and basic theorem

[https://en.wikipedia.org/wiki/Group_\(mathematics\)#Elementary_consequences_of_the_group_axioms](https://en.wikipedia.org/wiki/Group_(mathematics)#Elementary_consequences_of_the_group_axioms)

Definition 37.1 (group). group definition by a set and a binary operation on the set

$$\begin{cases}
 \circ : G \times G = G^2 \rightarrow G & \text{binary operation} \\
 \forall \langle g_1, g_2, g_3 \rangle \in G^3 [g_1 \circ (g_2 \circ g_3) = (g_1 \circ g_2) \circ g_3] & \text{associativity} \\
 \exists e = \in G, \forall g \in G [e \circ g = g] & \text{left unit element} \\
 \forall g \in G, \exists g^{-1} \in G [g^{-1} \circ g = e] & \text{left inverse (element)} \\
 \Leftrightarrow G = (G, \circ) \text{ is a group}
 \end{cases}$$

Theorem 37.1. *group left inverses equal right inverses*

Proof:

to be proved

□

37.3 Polya enumeration theorem

37.4 complex group representation

37.4.1 complex basis group

$$\begin{aligned}
 G &= \{1, i, -1, -i\} \\
 &= \{i^0, i^1, i^2, i^3\}
 \end{aligned}$$

$$\begin{aligned}
 &\forall \langle g_1, g_2 \rangle \in G^2, \exists g_1 g_2 \in G [g_1 g_2 = g_1 \cdot g_2] \\
 \Leftrightarrow &\cdot : G \times G = G^2 \rightarrow G
 \end{aligned}$$

<https://tex.stackexchange.com/questions/627708/tikz-how-to-put-tables-within-arbitrarily-placed-nodes>

.	1	i	-1	-i
1	1	i	-1	-i
i	i	-1	-i	1
-1	-1	-i	1	i
-i	-i	1	i	-1

.	1	i	-1	-i
1	1	i	-1	-i
i	i	-1	-i	1
-1	-1	-i	1	i
-i	-i	1	i	-1

Figure 37.1: complex basis group table

37.4.2 $\mathbb{C} \rightarrow \mathcal{M}_{2 \times 2}(\mathbb{R})$

$$1 \leftrightarrow \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = I_2 = I$$

$$\begin{aligned} c_1 \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + c_2 \begin{pmatrix} a & b \\ c & d \end{pmatrix} &= x \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + y \begin{pmatrix} a & b \\ c & d \end{pmatrix}, \langle a, b, c, d \rangle \in \mathbb{R}^4 \\ &= xI + yJ, J = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathcal{M}_{2 \times 2}(\mathbb{R}), \langle x, y \rangle \in \mathbb{R}^2 \end{aligned}$$

$$J^2 = -I$$

$$J^2 = -I$$

$$\begin{pmatrix} a^2 + bc & ab + bd \\ ca + cd & cb + d^2 \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} a & b \\ c & d \end{pmatrix} = - \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\begin{cases} a^2 + bc = -1 & b = 0 \Rightarrow a^2 = -1 \Leftrightarrow a \in \mathbb{R} \Rightarrow b \neq 0 \\ ab + bd = 0 & (b = 0) \vee (a = -d) \xrightarrow[b \neq 0]{\text{if } a = d} a = -d \\ ca + cd = 0 & \\ cb + d^2 = -1 & a^2 = d^2 \Rightarrow (a = d) \vee (a = -d) \end{cases} \Rightarrow a = d = 0 \Rightarrow bc = -1$$

$$J = \begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} a & b \\ \frac{-a^2 - 1}{b} & -a \end{pmatrix} = J(a, b), b \neq 0$$

$$J(a, b) = \begin{pmatrix} a & b \\ \frac{-a^2 - 1}{b} & -a \end{pmatrix}, b \neq 0$$

$$J(a = 1, b) = \begin{pmatrix} 1 & b \\ -2 & -1 \end{pmatrix} \Rightarrow J^2(a = 1, b) = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} = -I$$

$$xI + yJ(a = 1, b) = \begin{pmatrix} x + y & yb \\ y \cdot \frac{-2}{b} & x - y \end{pmatrix}$$

$$J(a = 0, b) = \begin{pmatrix} 0 & b \\ -1 & 0 \end{pmatrix}$$

$$J(a = 0, b = 1) = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$\begin{aligned} J(a=0, b=-1) &= \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} = - \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} = -J(a=0, b=1) \\ \Rightarrow J^2(a=0, b=-1) &= \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} = -I \end{aligned}$$

$$\begin{aligned} J = J(a=0, b=-1) &= \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \\ \Rightarrow &\begin{cases} 1 \leftrightarrow I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\ i \leftrightarrow J = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \end{cases} \\ \Rightarrow x + yi &\leftrightarrow xI + yJ \\ = x &\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + y \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} = \begin{pmatrix} x & -y \\ y & x \end{pmatrix} \end{aligned}$$

$$x + yi \leftrightarrow \begin{pmatrix} x & -y \\ y & x \end{pmatrix} = xI + yJ$$

realizing

$$\mathbb{C} \rightarrow \mathcal{M}_{2 \times 2}(\mathbb{R}) = \mathcal{M}_2(\mathbb{R})$$

37.4.3 (determinant of complex group representation) equivalent to (squared modulus of complex number)

$$\det(xI + yJ) = \det \begin{pmatrix} x & -y \\ y & x \end{pmatrix} = \left| \begin{matrix} x & -y \\ y & x \end{matrix} \right| = x^2 + y^2 = |x + yi|^2$$

37.4.3.1 Lagrange identity

Lagrange identity

generalization of Brahmagupta–Fibonacci identity

specialization of Binet–Cauchy identity

cf. Euler identity^[37.5.1.1]

$$\begin{aligned} &\det[(aI + bJ)(cI + dJ)] \\ &= \det \left[\begin{pmatrix} a & -b \\ b & a \end{pmatrix} \begin{pmatrix} c & -d \\ d & c \end{pmatrix} \right] \\ &= \det \begin{pmatrix} ac - bd & -ad - bc \\ ad + bc & ac - bd \end{pmatrix} = |(ac - bd) + (ad + bc)i|^2 = (ac - bd)^2 + (ad + bc)^2 \\ &= \left[\det \begin{pmatrix} a & -b \\ b & a \end{pmatrix} \right] \left[\det \begin{pmatrix} c & -d \\ d & c \end{pmatrix} \right] = |a + bi|^2 |c + di|^2 = (a^2 + b^2)(c^2 + d^2) \end{aligned}$$

$$|a + bi|^2 |c + di|^2 = (a^2 + b^2)(c^2 + d^2) = (ac - bd)^2 + (ad + bc)^2$$

$$\begin{aligned}
& \det [(x_1 I + y_1 J)(x_2 I + y_2 J)] \\
&= \det \left[\begin{pmatrix} x_1 & -y_1 \\ y_1 & x_1 \end{pmatrix} \begin{pmatrix} x_2 & -y_2 \\ y_2 & x_2 \end{pmatrix} \right] \\
&= \det \begin{pmatrix} x_1 x_2 - y_1 y_2 & -x_1 y_2 - y_1 x_2 \\ x_1 y_2 + y_1 x_2 & x_1 x_2 - y_1 y_2 \end{pmatrix} = |(x_1 x_2 - y_1 y_2) + (x_1 y_2 + y_1 x_2) i|^2 = (x_1 x_2 - y_1 y_2)^2 + (x_1 y_2 + y_1 x_2)^2 \\
&= \left[\det \begin{pmatrix} x_1 & -y_1 \\ y_1 & x_1 \end{pmatrix} \right] \left[\det \begin{pmatrix} x_2 & -y_2 \\ y_2 & x_2 \end{pmatrix} \right] = |x_1 + y_1 i|^2 |x_2 + y_2 i|^2 = (x_1^2 + y_1^2) (x_2^2 + y_2^2)
\end{aligned}$$

$$|x_1 + y_1 i|^2 |x_2 + y_2 i|^2 = (x_1^2 + y_1^2) (x_2^2 + y_2^2) = (x_1 x_2 - y_1 y_2)^2 + (x_1 y_2 + y_1 x_2)^2$$

37.4.4 Euler formula proved by complex group representation

$$\begin{aligned}
\begin{pmatrix} x' \\ y' \end{pmatrix} &= \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = R_\theta \begin{pmatrix} x \\ y \end{pmatrix} \\
&= \begin{pmatrix} \cos n \frac{\theta}{n} & -\sin n \frac{\theta}{n} \\ \sin n \frac{\theta}{n} & \cos n \frac{\theta}{n} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \left(\cos \frac{\theta}{n} \quad -\sin \frac{\theta}{n} \right)^n \begin{pmatrix} x \\ y \end{pmatrix} = R_{\frac{\theta}{n}}^n \begin{pmatrix} x \\ y \end{pmatrix}
\end{aligned}$$

$$\begin{aligned}
\lim_{n \rightarrow \infty} R_{\frac{\theta}{n}} &= \lim_{n \rightarrow \infty} \begin{pmatrix} \cos \frac{\theta}{n} & -\sin \frac{\theta}{n} \\ \sin \frac{\theta}{n} & \cos \frac{\theta}{n} \end{pmatrix} = \begin{pmatrix} 1 & -\frac{\theta}{n} \\ \frac{\theta}{n} & 1 \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{\theta}{n} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{\theta}{n} \begin{pmatrix} \cos \frac{\pi}{2} & -\sin \frac{\pi}{2} \\ \sin \frac{\pi}{2} & \cos \frac{\pi}{2} \end{pmatrix} \\
&= I + \frac{\theta}{n} R_{\frac{\pi}{2}}
\end{aligned}$$

$$\lim_{n \rightarrow \infty} R_{\frac{\theta}{n}} = \lim_{n \rightarrow \infty} \begin{pmatrix} \cos \frac{\theta}{n} & -\sin \frac{\theta}{n} \\ \sin \frac{\theta}{n} & \cos \frac{\theta}{n} \end{pmatrix} = \begin{pmatrix} 1 & -\frac{\theta}{n} \\ \frac{\theta}{n} & 1 \end{pmatrix} = I + \frac{\theta}{n} R_{\frac{\pi}{2}}$$

$$\begin{aligned}
\begin{pmatrix} x' \\ y' \end{pmatrix} &= \lim_{n \rightarrow \infty} \begin{pmatrix} x' \\ y' \end{pmatrix} = \lim_{n \rightarrow \infty} R_{\frac{\theta}{n}}^n \begin{pmatrix} x \\ y \end{pmatrix} = \left[\lim_{n \rightarrow \infty} R_{\frac{\theta}{n}}^n \right] \left[\lim_{n \rightarrow \infty} \begin{pmatrix} x \\ y \end{pmatrix} \right] = \left[\lim_{n \rightarrow \infty} R_{\frac{\theta}{n}}^n \right] \begin{pmatrix} x \\ y \end{pmatrix} \\
&= \lim_{n \rightarrow \infty} \left[\lim_{n \rightarrow \infty} R_{\frac{\theta}{n}} \right]^n \begin{pmatrix} x \\ y \end{pmatrix} = \lim_{n \rightarrow \infty} \left[I + \frac{\theta}{n} R_{\frac{\pi}{2}} \right]^n \begin{pmatrix} x \\ y \end{pmatrix} \\
&= \lim_{n \rightarrow \infty} \left[I + \frac{\theta}{n} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \right]^n \begin{pmatrix} x \\ y \end{pmatrix} = \lim_{n \rightarrow \infty} \left[I + \frac{\theta J}{n} \right]^n \begin{pmatrix} x \\ y \end{pmatrix}, J = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \\
&= e^{J\theta} \begin{pmatrix} x \\ y \end{pmatrix}
\end{aligned}$$

$$\begin{aligned} \begin{cases} \begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \\ \begin{pmatrix} x' \\ y' \end{pmatrix} = e^{J\theta} \begin{pmatrix} x \\ y \end{pmatrix} \end{cases} \\ \Rightarrow e^{J\theta} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \xrightarrow{x+y \leftrightarrow x-y} \begin{pmatrix} x & -y \\ y & x \end{pmatrix} = xI + yJ \\ e^{i\theta} = \cos \theta + i \sin \theta \end{aligned}$$

□

37.5 quaternion group representation

https://groupprops.subwiki.org/wiki/Linear_representation_theory_of_quaternion_group#Two-dimensional_irreducible_representation_over_a_splitting_field

$$\begin{aligned} q = a + bi + cj + dk &= a + ib + jc + kd, \begin{cases} q \in \mathbb{H} \\ a, b, c, d \in \mathbb{R} \end{cases} \Leftrightarrow \langle a, b, c, d \rangle \in \mathbb{R}^4 \\ w = t + xi + yj + zk &= t + ix + jy + kz, \begin{cases} w \in \mathbb{H} \\ t, x, y, z \in \mathbb{R} \end{cases} \Leftrightarrow \langle t, x, y, z \rangle \in \mathbb{R}^4 \\ a1 + bi + cj + dk &= t1 + xi + yj + zk = x_0 1 + e_i x_i \end{aligned}$$

37.5.1 $\mathbb{H} \rightarrow \mathcal{M}_{2 \times 2}(\mathbb{C})$

$$1 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = 1_2 = 1$$

$$\begin{aligned} e = \begin{pmatrix} a & b \\ c & d \end{pmatrix} &= \begin{pmatrix} a & b \\ -a^2 - 1 & -a \end{pmatrix} \\ &= \begin{cases} \begin{pmatrix} a & b \\ -a^2 - 1 & -a \end{pmatrix} = \begin{pmatrix} 0 & b \\ -1 & 0 \end{pmatrix} = \begin{pmatrix} 0 & \beta \\ -\beta & 0 \end{pmatrix} \Rightarrow e_2 = J = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} = j & a = 0 \\ \begin{pmatrix} a & b \\ -a^2 - 1 & -a \end{pmatrix} = \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix} & a \neq 0 \end{cases} \end{aligned}$$

$$\begin{pmatrix} \alpha^2 + \beta^2 & 0 \\ 0 & \beta^2 + \alpha^2 \end{pmatrix} = \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix} \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix} = e^2 = -1 = - \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$$

\Downarrow

$$\alpha^2 + \beta^2 = -1 \Leftrightarrow \beta^2 + \alpha^2 = -1$$

$$\alpha^2 + \beta^2 = -1 \Rightarrow \langle \alpha, \beta \rangle \notin \mathbb{R}^2 \Rightarrow \langle \alpha, \beta \rangle \in \mathbb{R}^2 \Rightarrow \alpha^2 + \beta^2 \geq 0$$

quaternion group has no irreducible two-dimensional representation over the reals ¹

¹https://groupprops.subwiki.org/wiki/Linear_representation_theory_of_quaternion_group#Four-dimensional_irreducible_representation_over_a_non-splitting_field

$$\langle \alpha, \beta \rangle \in \mathbb{C}^2 - \mathbb{R}^2$$

$$\alpha^2 + \beta^2 = -1 = \beta^2 + \alpha^2$$

$$\begin{pmatrix} \beta & \alpha \\ \alpha & -\beta \end{pmatrix} \begin{pmatrix} \beta & \alpha \\ \alpha & -\beta \end{pmatrix} = \begin{pmatrix} \beta^2 + \alpha^2 & 0 \\ 0 & \alpha^2 + \beta^2 \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} = - \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = -1$$

$$1 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{e}_1 = \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix}, \mathbf{e}_2 = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

$$1 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, i = \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix}, j = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

$$ij = \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} = \begin{pmatrix} \beta & -\alpha \\ -\alpha & -\beta \end{pmatrix} = k$$

$$1 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{e}_1 = \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix}, \mathbf{e}_2 = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, \mathbf{e}_3 = \begin{pmatrix} \beta & -\alpha \\ -\alpha & -\beta \end{pmatrix}$$

$$1 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, i = \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix}, j = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, k = \begin{pmatrix} \beta & -\alpha \\ -\alpha & -\beta \end{pmatrix}$$

$$jk = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \beta & -\alpha \\ -\alpha & -\beta \end{pmatrix} = \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix} = i$$

	$\alpha^2 + \beta^2 = -1$	$\begin{cases} \alpha = \sqrt{-1} \\ \beta = 0 \end{cases}$	$\begin{cases} \alpha = \sqrt{-2} \\ \beta = 1 \end{cases}$	$\beta = \alpha^2, n \in \{1, 2, 4, 5\}$
1	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$
-1	$\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$	$\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$	$\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$	$\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$
i	$\begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix}$	$\begin{pmatrix} \sqrt{-1} & 0 \\ 0 & -\sqrt{-1} \end{pmatrix}$	$\begin{pmatrix} \sqrt{-2} & 1 \\ 1 & -\sqrt{-2} \end{pmatrix}$	$\begin{pmatrix} e^{\pi \frac{n}{3}\sqrt{-1}} & e^{\pi \frac{2n}{3}\sqrt{-1}} \\ e^{\pi \frac{2n}{3}\sqrt{-1}} & -e^{\pi \frac{n}{3}\sqrt{-1}} \end{pmatrix}$
-i	$\begin{pmatrix} -\alpha & -\beta \\ -\beta & \alpha \end{pmatrix}$	$\begin{pmatrix} -\sqrt{-1} & 0 \\ 0 & \sqrt{-1} \end{pmatrix}$	$\begin{pmatrix} -\sqrt{-2} & -1 \\ -1 & \sqrt{-2} \end{pmatrix}$	$\begin{pmatrix} -e^{\pi \frac{n}{3}\sqrt{-1}} & -e^{\pi \frac{2n}{3}\sqrt{-1}} \\ -e^{\pi \frac{2n}{3}\sqrt{-1}} & e^{\pi \frac{n}{3}\sqrt{-1}} \end{pmatrix}$
j	$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$
-j	$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$
k	$\begin{pmatrix} \beta & -\alpha \\ -\alpha & -\beta \end{pmatrix}$	$\begin{pmatrix} 0 & -\sqrt{-1} \\ -\sqrt{-1} & 0 \end{pmatrix}$	$\begin{pmatrix} 1 & -\sqrt{-2} \\ -\sqrt{-2} & -1 \end{pmatrix}$	$\begin{pmatrix} e^{\pi \frac{2n}{3}\sqrt{-1}} & -e^{\pi \frac{n}{3}\sqrt{-1}} \\ -e^{\pi \frac{n}{3}\sqrt{-1}} & -e^{\pi \frac{2n}{3}\sqrt{-1}} \end{pmatrix}$
-k	$\begin{pmatrix} -\beta & \alpha \\ \alpha & \beta \end{pmatrix}$	$\begin{pmatrix} 0 & \sqrt{-1} \\ \sqrt{-1} & 0 \end{pmatrix}$	$\begin{pmatrix} -1 & \sqrt{-2} \\ \sqrt{-2} & 1 \end{pmatrix}$	$\begin{pmatrix} -e^{\pi \frac{2n}{3}\sqrt{-1}} & e^{\pi \frac{n}{3}\sqrt{-1}} \\ e^{\pi \frac{n}{3}\sqrt{-1}} & e^{\pi \frac{2n}{3}\sqrt{-1}} \end{pmatrix}$

$$\begin{aligned}
-1 &= \alpha^2 + \beta^2 \\
&\stackrel{\beta=\alpha^2}{=} \alpha^2 + \alpha^4 \\
\alpha^4 + \alpha^2 + 1 &= 0, \alpha^4 + \alpha^2 + 1 = (\alpha^2 + \alpha + 1)(\alpha^2 - \alpha + 1) \\
(\alpha^2 - 1)(\alpha^4 + \alpha^2 + 1) &= 0 \\
\alpha^6 - 1 &= 0 \\
\alpha^6 &= 1 = e^{2\pi k \sqrt{-1}}, k \in \mathbb{Z} \\
\alpha &= e^{2\pi \frac{n}{6} \sqrt{-1}}, n \in \{0, 1, 2, 3, 4, 5\} - \{0, 3\} \\
&= e^{\pi \frac{n}{3} \sqrt{-1}}, n \in \{1, 2, 4, 5\}
\end{aligned}$$

$$\begin{array}{llll}
\alpha^2 + \beta^2 = -1 & \begin{cases} \alpha = i \\ \beta = 0 \end{cases} & \begin{cases} \alpha = \sqrt{2}i \\ \beta = 1 \end{cases} & \omega = e^{i\pi \frac{n}{3}}, n \in \{1, 2, 4, 5\} \\
1 & \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} & \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} & \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\
-1 & \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} & \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} & \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} \\
i & \begin{pmatrix} \alpha & \beta \\ \beta & -\alpha \end{pmatrix} & \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix} & \begin{pmatrix} \sqrt{2}i & 1 \\ 1 & -\sqrt{2}i \end{pmatrix} \\
-i & \begin{pmatrix} -\alpha & -\beta \\ -\beta & \alpha \end{pmatrix} & \begin{pmatrix} -i & 0 \\ 0 & i \end{pmatrix} & \begin{pmatrix} -\sqrt{2}i & -1 \\ -1 & \sqrt{2}i \end{pmatrix} \\
j & \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} & \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} & \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \\
-j & \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} & \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} & \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \\
k & \begin{pmatrix} \beta & -\alpha \\ -\alpha & -\beta \end{pmatrix} & \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} & \begin{pmatrix} 1 & -\sqrt{2}i \\ -\sqrt{2}i & -1 \end{pmatrix} \\
-k & \begin{pmatrix} -\beta & \alpha \\ \alpha & \beta \end{pmatrix} & \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix} & \begin{pmatrix} -1 & \sqrt{2}i \\ \sqrt{2}i & 1 \end{pmatrix}
\end{array}$$

realizing

$$\mathbb{H} \rightarrow \mathcal{M}_{2 \times 2}(\mathbb{C}) = \mathcal{M}_2(\mathbb{C})$$

37.5.1.1 Euler identity

cf. Lagrange identity^[37.4.3.1]

$$\begin{aligned}
&\det(a + bi + cj + dk) \\
&= \det \left[a \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + b \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix} + c \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} + d \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \right] \\
&= \det \begin{pmatrix} a + bi & -c - di \\ c - di & a - bi \end{pmatrix} = \begin{vmatrix} a + bi & -c - di \\ c - di & a - bi \end{vmatrix} \\
&= (a^2 + b^2) + (c^2 + d^2) = a^2 + b^2 + c^2 + d^2
\end{aligned}$$

$$\det(a + bi + cj + dk) = \det \begin{pmatrix} a + bi & -c - di \\ c - di & a - bi \end{pmatrix} = a^2 + b^2 + c^2 + d^2$$

$$\begin{aligned}
& \det [(q_{10} + q_{11}\mathbf{i} + q_{12}\mathbf{j} + q_{13}\mathbf{k})(q_{20} + q_{21}\mathbf{i} + q_{22}\mathbf{j} + q_{23}\mathbf{k})] = \det [(a + b\mathbf{i} + c\mathbf{j} + d\mathbf{k})(\alpha + \beta\mathbf{i} + \gamma\mathbf{j} + \delta\mathbf{k})] \\
&= \det \left\{ \left[q_{10} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + q_{11} \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix} + q_{12} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} + q_{13} \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \right] \right. \\
&\quad \left. \left[q_{20} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + q_{21} \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix} + q_{22} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} + q_{23} \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \right] \right\} \\
&= \det \left\{ \left[a \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + b \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix} + c \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} + d \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \right] \right. \\
&\quad \left. \left[\alpha \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \beta \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix} + \gamma \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} + \delta \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \right] \right\} \\
&= \det \left\{ \begin{pmatrix} a + bi & -c - di \\ c - di & a - bi \end{pmatrix} \begin{pmatrix} \alpha + \beta i & -\gamma - \delta i \\ \gamma - \delta i & \alpha - \beta i \end{pmatrix} \right\} \\
&= \det \begin{pmatrix} a + bi & -c - di \\ c - di & a - bi \end{pmatrix} \det \begin{pmatrix} \alpha + \beta i & -\gamma - \delta i \\ \gamma - \delta i & \alpha - \beta i \end{pmatrix} = (a^2 + b^2 + c^2 + d^2)(\alpha^2 + \beta^2 + \gamma^2 + \delta^2) \\
&= \det \left\{ \begin{pmatrix} [a + bi][\alpha + \beta i] - [c + di][\gamma - \delta i] & [a + bi][- \gamma - \delta i] - [c + di][\alpha - \beta i] \\ [c - di][\alpha + \beta i] + [a - bi][\gamma - \delta i] & [c - di][- \gamma - \delta i] + [a - bi][\alpha - \beta i] \end{pmatrix} \right\} \\
&= \det \left\{ \begin{pmatrix} (a\alpha - b\beta - c\gamma - d\delta) + i(a\beta + b\alpha + c\delta - d\gamma) & -(a\gamma - b\delta + c\alpha + d\beta) - i(a\delta + b\gamma - c\beta + d\alpha) \\ (a\gamma - b\delta + c\alpha + d\beta) - i(a\delta + b\gamma - c\beta + d\alpha) & (a\alpha - b\beta - c\gamma - d\delta) - i(a\beta + b\alpha + c\delta - d\gamma) \end{pmatrix} \right\} \\
&= \det \{(a\alpha - b\beta - c\gamma - d\delta) + (a\beta + b\alpha + c\delta - d\gamma)\mathbf{i} + (a\gamma - b\delta + c\alpha + d\beta)\mathbf{j} + (a\delta + b\gamma - c\beta + d\alpha)\mathbf{k}\} \\
&= (a\alpha - b\beta - c\gamma - d\delta)^2 + (a\beta + b\alpha + c\delta - d\gamma)^2 + (a\gamma - b\delta + c\alpha + d\beta)^2 + (a\delta + b\gamma - c\beta + d\alpha)^2 \\
&= (q_{10}q_{20} - q_{11}q_{21} - q_{12}q_{22} - q_{13}q_{23})^2 + (q_{10}q_{21} + q_{11}q_{20} + q_{12}q_{23} - q_{13}q_{22})^2 \\
&\quad + (q_{10}q_{22} - q_{11}q_{23} + q_{12}q_{20} + q_{13}q_{21})^2 + (q_{10}q_{23} + q_{11}q_{22} - q_{12}q_{21} + q_{13}q_{20})^2 \\
&\quad (a^2 + b^2 + c^2 + d^2)(\alpha^2 + \beta^2 + \gamma^2 + \delta^2) \\
&\quad = (a\alpha - b\beta - c\gamma - d\delta)^2 + (a\beta + b\alpha + c\delta - d\gamma)^2 \\
&\quad \quad + (a\gamma - b\delta + c\alpha + d\beta)^2 + (a\delta + b\gamma - c\beta + d\alpha)^2
\end{aligned}$$

Theorem 37.2. For any two integers greater than zero, their multiplication can be the summation of squared four integers greater than zero.

$$\forall \langle m_1, m_2 \rangle \in (\mathbb{N} \cup \{0\})^2, \exists \langle k_1, k_2, k_3, k_4 \rangle \in (\mathbb{N} \cup \{0\})^4 [m_1 m_2 = k_1^2 + k_2^2 + k_3^2 + k_4^2]$$

Proof:

$$\text{Let } \begin{cases} m_1 = a^2 + b^2 + c^2 + d^2 & \langle a, b, c, d \rangle \in (\mathbb{N} \cup \{0\})^4 \\ m_2 = \alpha^2 + \beta^2 + \gamma^2 + \delta^2 & \langle \alpha, \beta, \gamma, \delta \rangle \in (\mathbb{N} \cup \{0\})^4 \end{cases} \xrightarrow{\text{closure property}} \begin{pmatrix} m_1 \\ m_2 \end{pmatrix} = \begin{pmatrix} a^2 + b^2 + c^2 + d^2 \\ \alpha^2 + \beta^2 + \gamma^2 + \delta^2 \end{pmatrix} \in (\mathbb{N} \cup \{0\})^2,$$

$$\begin{aligned}
m_1 m_2 &= (a^2 + b^2 + c^2 + d^2) (a^2 + \beta^2 + \gamma^2 + \delta^2) \\
&\stackrel{\text{Euler identity}}{=} (a\alpha - b\beta - c\gamma - d\delta)^2 + (a\beta + b\alpha + c\delta - d\gamma)^2 \\
&\quad + (a\gamma - b\delta + c\alpha + d\beta)^2 + (a\delta + b\gamma - c\beta + d\alpha)^2 \\
&= |a\alpha - b\beta - c\gamma - d\delta|^2 \\
&\quad + |a\beta + b\alpha + c\delta - d\gamma|^2 \\
&\quad + |a\gamma - b\delta + c\alpha + d\beta|^2 \\
&\quad + |a\delta + b\gamma - c\beta + d\alpha|^2 \\
&= k_1^2 + k_2^2 + k_3^2 + k_4^2, \quad \begin{pmatrix} k_1 \\ k_2 \\ k_3 \\ k_4 \end{pmatrix} = \begin{pmatrix} |a\alpha - b\beta - c\gamma - d\delta| \\ |a\beta + b\alpha + c\delta - d\gamma| \\ |a\gamma - b\delta + c\alpha + d\beta| \\ |a\delta + b\gamma - c\beta + d\alpha| \end{pmatrix} \in (\mathbb{N} \cup \{0\})^4 \\
&\therefore \begin{cases} \langle a, b, c, d \rangle \in (\mathbb{N} \cup \{0\})^4 \\ \langle \alpha, \beta, \gamma, \delta \rangle \in (\mathbb{N} \cup \{0\})^4 \end{cases} \\
&\xrightarrow{\text{closure property}} \begin{pmatrix} |a\alpha - b\beta - c\gamma - d\delta| \\ |a\beta + b\alpha + c\delta - d\gamma| \\ |a\gamma - b\delta + c\alpha + d\beta| \\ |a\delta + b\gamma - c\beta + d\alpha| \end{pmatrix} \in (\mathbb{N} \cup \{0\})^4
\end{aligned}$$

□

37.5.2 $\mathbb{H} \rightarrow \mathcal{M}_{4 \times 4}(\mathbb{R})$

https://groupprops.subwiki.org/wiki/Linear_representation_theory_of_quaternion_group#Four-dimensional_irreducible_representation_over_a_non-splitting_field

$$\mathbb{H} \rightarrow \mathcal{M}_2(\mathbb{C}) \xrightarrow{\mathbb{C} \rightarrow \mathcal{M}_2(\mathbb{R})} \mathcal{M}_{4 \times 4}(\mathbb{R}) = \mathcal{M}_4(\mathbb{R})$$

$$\mathbb{C} \rightarrow \mathcal{M}_2(\mathbb{R}) \Leftarrow \begin{cases} 1 \rightarrow \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\ i \rightarrow \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \end{cases}$$

$$1 \rightarrow \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \rightarrow \begin{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} & \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \\ \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} & \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$-1 \rightarrow \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} \rightarrow \begin{pmatrix} \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} & \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \\ \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} & \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} \end{pmatrix} \rightarrow \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$\begin{array}{ll}
 \left\{ \begin{array}{l} \alpha = i \\ \beta = 0 \end{array} \right. & \left\{ \begin{array}{l} 1 \rightarrow \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\ i \rightarrow \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \end{array} \right. \\
 1 & \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \left\{ \begin{array}{l} \alpha = \sqrt{2}i \\ \beta = 1 \end{array} \right. \\
 & \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \left\{ \begin{array}{l} 1 \rightarrow \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\ i \rightarrow \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \end{array} \right. \\
 -1 & \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} \quad \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \quad \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} \quad \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \\
 i & \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix} \quad \begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix} \quad \begin{pmatrix} \sqrt{2}i & 1 \\ 1 & -\sqrt{2}i \end{pmatrix} \quad \begin{pmatrix} 0 & -\sqrt{2} & 1 & 0 \\ \sqrt{2} & 0 & 0 & 1 \\ 1 & 0 & 0 & \sqrt{2} \\ 0 & 1 & -\sqrt{2} & 0 \end{pmatrix} \\
 -i & \begin{pmatrix} -i & 0 \\ 0 & i \end{pmatrix} \quad \begin{pmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \quad \begin{pmatrix} -\sqrt{2}i & -1 \\ -1 & \sqrt{2}i \end{pmatrix} \quad \begin{pmatrix} 0 & -1 & -1 & 0 \\ 1 & 0 & 0 & -1 \\ -1 & 0 & 0 & 1 \\ 0 & -1 & -1 & 0 \end{pmatrix} \\
 j & \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \\
 -j & \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix} \\
 k & \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 1 & -\sqrt{2}i \\ -\sqrt{2}i & -1 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 & 0 & \sqrt{2} \\ 0 & 1 & -\sqrt{2} & 0 \\ 0 & \sqrt{2} & -1 & 0 \\ -\sqrt{2} & 0 & 0 & -1 \end{pmatrix} \\
 -k & \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \quad \begin{pmatrix} -1 & \sqrt{2}i \\ \sqrt{2}i & 1 \end{pmatrix} \quad \begin{pmatrix} -1 & 0 & 0 & -\sqrt{2} \\ 0 & -1 & \sqrt{2} & 0 \\ 0 & -\sqrt{2} & 1 & 0 \\ \sqrt{2} & 0 & 0 & 1 \end{pmatrix}
 \end{array}$$

some examinations

$$ij \rightarrow \begin{pmatrix} 0 & -\sqrt{2} & 1 & 0 \\ \sqrt{2} & 0 & 0 & 1 \\ 1 & 0 & 0 & \sqrt{2} \\ 0 & 1 & -\sqrt{2} & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & \sqrt{2} \\ 0 & 1 & -\sqrt{2} & 0 \\ 0 & \sqrt{2} & -1 & 0 \\ -\sqrt{2} & 0 & 0 & -1 \end{pmatrix} \leftarrow k$$

Chapter 38

tensor

38.1 Einstein summation convention

38.1.1 dummy index

38.1.2 free index

38.2 Elliot Schneider

- Elliot Schneider: Physics with Elliot

38.2.1 Fundamentals of Cartesian Tensors

<https://courses.physicswithelliot.com/products/part-i-fundamentals-of-cartesian-tensors/categories/2154478208/posts/2176662131>

<https://courses.physicswithelliot.com/products/part-i-fundamentals-of-cartesian-tensors/categories/2154478208/posts/2174076341>

<https://courses.physicswithelliot.com/products/part-i-fundamentals-of-cartesian-tensors/categories/2154478208/posts/2174076344>

38.2.2 Fundamentals of Curvilinear Tensors

38.2.3 Fundamentals of Spacetime Tensors

Chapter 39

dual space

dual space and linear functional

<https://ccjou.wordpress.com/2011/06/13/%E7%BA%BF%E6%8D%AE%E6%97%A5%E5%8A%A8%E4%BD%9C/>

39.1 linear equations

$$\begin{aligned} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n &= b_1 \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n &= b_2 \end{aligned}$$

⋮

$$a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n = b_m$$

$$\begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{pmatrix}$$

$$Ax = b$$

$$(a_{i1} \quad a_{i2} \quad \cdots \quad a_{in}) \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} = (b_i) = b_i$$

$$(a_{i1} \quad \cdots \quad a_{ij} \quad \cdots \quad a_{in}) \begin{pmatrix} x_1 \\ \vdots \\ x_j \\ \vdots \\ x_n \end{pmatrix} = (b_i) = b_i$$

$$\begin{pmatrix} \cdots & a_{ij} & \cdots \end{pmatrix} \begin{pmatrix} \vdots \\ x_j \\ \vdots \end{pmatrix} = b_i$$

$$\mathbf{a}_i^\top \mathbf{x} = \mathbf{a}_i \cdot \mathbf{x} = b_i$$

$$a_{ij}x_j = \mathbf{a}_i^\top \mathbf{x} = \mathbf{a}_i \cdot \mathbf{x} = b_i$$

$$\mathbf{a}_i \cdot \mathbf{x} = \mathbf{a}_i^\top \mathbf{x} = a_{ij}x_j = \cdots + a_{ij}x_j + \cdots$$

if finite,

$$\mathbf{a}_i \cdot \mathbf{x} = \mathbf{a}_i^\top \mathbf{x} = a_{ij}x_j = a_{i1}x_1 + \cdots + a_{ij}x_j + \cdots + a_{in}x_n$$

39.2 matrix multiplication

$$\begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{pmatrix} \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1p} \\ x_{21} & x_{22} & \cdots & x_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{np} \end{pmatrix} = \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1p} \\ b_{21} & b_{22} & \cdots & b_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ b_{m1} & b_{m2} & \cdots & b_{mp} \end{pmatrix}$$

$$AX = B$$

$$(a_{i1} \quad a_{i2} \quad \cdots \quad a_{in}) \begin{pmatrix} x_{1k} \\ x_{2k} \\ \vdots \\ x_{nk} \end{pmatrix} = (b_{ik}) = b_{ik}$$

$$(a_{i1} \quad \cdots \quad a_{ij} \quad \cdots \quad a_{in}) \begin{pmatrix} x_{1k} \\ \vdots \\ x_{jk} \\ \vdots \\ x_{nk} \end{pmatrix} = (b_{ik}) = b_{ik}$$

$$(\cdots \quad a_{ij} \quad \cdots) \begin{pmatrix} \vdots \\ x_{jk} \\ \vdots \end{pmatrix} = b_{ik}$$

$$a_{ij}x_j = \mathbf{a}_i^\top \mathbf{x} = \mathbf{a}_i \cdot \mathbf{x} = b_i$$

$$\mathbf{a}_i \cdot \mathbf{x} = \mathbf{a}_i^\top \mathbf{x} = a_{ij}x_j$$

\iddots in MathJax

<https://math.meta.stackexchange.com/questions/23273/mathjax-and-iddots-udots-or-reflectbox>

$$b_{ik} = a_{ij}x_{jk} = \mathbf{a}_i \cdot \mathbf{x}_k = \mathbf{a}_i^\top \mathbf{x}_k$$

$$\text{row}(A) \text{ col}(X) = b_{\text{row}, \text{col}}$$

$$\mathbf{a}_i \cdot \mathbf{x}_k = \mathbf{a}_i^\top \mathbf{x}_k = a_{ij}x_{jk}$$

$$\mathbf{a}_i \cdot \mathbf{x}_j = \mathbf{a}_i^\top \mathbf{x}_j = a_{ik}x_{kj}$$

$$\mathbf{a}_i \cdot \mathbf{x}_j = \mathbf{a}_i^\top \mathbf{x}_j = a_{ik}x_{kj} = \cdots + a_{ik}x_{kj} + \cdots$$

if finite,

$$\mathbf{a}_i \cdot \mathbf{x}_j = \mathbf{a}_i^\top \mathbf{x}_j = a_{ik}x_{kj} = a_{i1}x_{1j} + \cdots + a_{ik}x_{kj} + \cdots + a_{in}x_{nj}$$

39.3 functional

(inner product or dot product) or linear equations

$$\mathbf{a}_i \cdot \mathbf{x} = \mathbf{a}_i^\top \mathbf{x} = a_{ij}x_j = \cdots + a_{ij}x_j + \cdots$$

if finite,

$$\mathbf{a}_i \cdot \mathbf{x} = \mathbf{a}_i^\top \mathbf{x} = a_{ij}x_j = a_{i1}x_1 + \cdots + a_{ij}x_j + \cdots + a_{in}x_n$$

actually, several rows

$$\begin{array}{ccccccc} \vdots & & \vdots & & \vdots & & \vdots \\ \mathbf{a}_i \cdot \mathbf{x} & = & \mathbf{a}_i^\top \mathbf{x} & = & a_{ij}x_j & = & \cdots + a_{ij}x_j + \cdots \\ \vdots & & \vdots & & \vdots & & \vdots \end{array}$$

if finite,

$$\begin{array}{ccccccc} \vdots & & \vdots & & \vdots & & \vdots \\ \mathbf{a}_i \cdot \mathbf{x} & = & \mathbf{a}_i^\top \mathbf{x} & = & a_{ij}x_j & = & a_{i1}x_1 + \cdots + a_{ij}x_j + \cdots + a_{in}x_n \\ \vdots & & \vdots & & \vdots & & \vdots \end{array}$$

in functional aspect,

$$\begin{array}{ccccccc} \vdots & & \vdots & & \vdots & & \vdots \\ f_i(\mathbf{x}) = \mathbf{a}_i \cdot \mathbf{x} = \mathbf{a}_i^\top \mathbf{x} = a_{ij}x_j = \cdots + a_{ij}x_j + \cdots \\ \vdots & & \vdots & & \vdots & & \vdots \end{array}$$

if finite,

$$\begin{array}{ccccccc} \vdots & & \vdots & & \vdots & & \vdots \\ f_i(\mathbf{x}) = \mathbf{a}_i \cdot \mathbf{x} = \mathbf{a}_i^\top \mathbf{x} = a_{ij}x_j = a_{i1}x_1 + \cdots + a_{ij}x_j + \cdots + a_{in}x_n \\ \vdots & & \vdots & & \vdots & & \vdots \end{array}$$

$$\begin{array}{ccccccc} \vdots & & \vdots & & \vdots & & \vdots \\ f_i(\cdots, x_j, \cdots) = f_i(x_j) = f_i(\mathbf{x}) = \mathbf{a}_i \cdot \mathbf{x} = \mathbf{a}_i^\top \mathbf{x} = a_{ij}x_j = \cdots + a_{ij}x_j + \cdots \\ \vdots & & \vdots & & \vdots & & \vdots \end{array}$$

if finite,

$$\begin{array}{ccccccc} \vdots & & \vdots & & \vdots & & \vdots \\ f_i(x_1, \cdots, x_j, \cdots, x_n) = f_i(x_j) = f_i(\mathbf{x}) = \mathbf{a}_i \cdot \mathbf{x} = \mathbf{a}_i^\top \mathbf{x} = a_{ij}x_j = a_{i1}x_1 + \cdots + a_{ij}x_j + \cdots + a_{in}x_n \\ \vdots & & \vdots & & \vdots & & \vdots \end{array}$$

or simply

$$f_i(\cdots, x_j, \cdots) = f_i(x_j) = f_i(\mathbf{x}) = \mathbf{a}_i \cdot \mathbf{x}_j = \mathbf{a}_i^\top \mathbf{x}_j = a_{ik}x_{kj} = \cdots + a_{ij}x_j + \cdots$$

if scalar with complex as the field,

$$f_i : \mathbb{C}^\infty \rightarrow \mathbb{C}$$

if scalar with a field,

$$f_i : \mathbb{F}^\infty \rightarrow \mathbb{F}$$

or more abstract notation,

$$f_i : F^\infty \rightarrow F$$

if scalar with real as the field,

$$f_i : \mathbb{R}^\infty \rightarrow \mathbb{R}$$

if finite,

$$f_i(x_1, \dots, x_j, \dots, x_n) = f_i(x_j) = f_i(\mathbf{x}) = \mathbf{a}_i \cdot \mathbf{x}_j = \mathbf{a}_i^\top \mathbf{x}_j = a_{ij}x_j = a_{i1}x_1 + \dots + a_{ij}x_j + \dots + a_{in}x_n$$

$$\begin{aligned} f_i(x_1, x_2, \dots, x_n) &= f_i(x_1, \dots, x_j, \dots, x_n) = f_i(x_j) = f_i(\mathbf{x}) \\ &= \mathbf{a}_i \cdot \mathbf{x}_j = \mathbf{a}_i^\top \mathbf{x}_j = a_{ij}x_j = a_{i1}x_1 + \dots + a_{ij}x_j + \dots + a_{in}x_n \end{aligned}$$

if scalar with complex as the field,

$$f_i : \mathbb{C}^n \rightarrow \mathbb{C}$$

if scalar with a field,

$$f_i : \mathbb{F}^n \rightarrow \mathbb{F}$$

or more abstract notation,

$$f_i : F^n \rightarrow F$$

if scalar with real as the field,

$$f_i : \mathbb{R}^n \rightarrow \mathbb{R}$$

functionals are a set of functions mapping n -dimensional vectors to scalars.

$$f_i : F^n \rightarrow F$$

$$f = \{f_i | f_i : F^\infty \rightarrow F\} = \left\{ \begin{array}{c} f_i(\dots, x_j, \dots) = f_i(x_j) = f_i(\mathbf{x}) = \mathbf{a}_i \cdot \mathbf{x} = \mathbf{a}_i^\top \mathbf{x} = a_{ij} x_j, \\ \vdots \\ \vdots \end{array} \right\}$$

if finite,

$$\begin{array}{ccccccccc} \vdots & & \vdots & & \vdots & & \vdots & & \vdots \\ f_i(x_1, \dots, x_j, \dots, x_n) & = & f_i(x_j) & = & f_i(\mathbf{x}) & = & \mathbf{a}_i \cdot \mathbf{x} & = & \mathbf{a}_i^\top \mathbf{x} \\ \vdots & & \vdots & & \vdots & & \vdots & & \vdots \end{array}$$

$$f = \{f_i | f_i : F^n \rightarrow F\} = \left\{ \begin{array}{c} \vdots \\ f_i(x_1, x_2, \dots, x_n) = f_i(\mathbf{x}) = a_{i1}x_1 + \dots + a_{ij}x_j + \dots + a_{in}x_n, \\ \vdots \end{array} \right\}$$

linear functionals are a set of functions mapping vectors to scalars linearly

$$f = \{f_i | f_i : F^n \rightarrow F\} = \left\{ \begin{array}{c} \vdots \\ f_i(x_1, x_2, \dots, x_n) = f_i(\mathbf{x}) = a_{i1}x_1 + \dots + a_{ij}x_j + \dots + a_{in}x_n, \\ \vdots \end{array} \right\}$$

39.4 definition of linear functional

functionals generalized to general vector space

$$f = \{f_i | f_i : V \rightarrow F\}$$

linear functionals generalized to general vector space is a linear transformation

$$f = \left\{ f_i \left| \begin{array}{l} f_i : V \rightarrow F \\ \forall \langle \mathbf{x}, \mathbf{y} \rangle \in V^2 [f_i(\mathbf{x} + \mathbf{y}) = f_i(\mathbf{x}) + f_i(\mathbf{y})] \\ \forall \mathbf{x} \in V, c \in F [f_i(c\mathbf{x}) = cf_i(\mathbf{x})] \end{array} \right. \right\}$$

$$f = \left\{ f_i \left| \begin{array}{l} f_i : V \rightarrow F \\ \forall \mathbf{x}, \mathbf{y} \in V [f_i(\mathbf{x} + \mathbf{y}) = f_i(\mathbf{x}) + f_i(\mathbf{y})] \\ \forall \mathbf{x} \in V, c \in F [f_i(c\mathbf{x}) = cf_i(\mathbf{x})] \end{array} \right. \right\}$$

$$\text{if } \begin{cases} F = \mathbb{C} \\ V = \mathbb{C}^n \end{cases},$$

$$f = \left\{ f_i \left| \begin{array}{l} f_i : \mathbb{C}^n \rightarrow \mathbb{C} \\ \forall \langle \mathbf{x}, \mathbf{y} \rangle \in (\mathbb{C}^n)^2 [f_i(\mathbf{x} + \mathbf{y}) = f_i(\mathbf{x}) + f_i(\mathbf{y})] \\ \forall \mathbf{x} \in \mathbb{C}^n, c \in \mathbb{C} [f_i(c\mathbf{x}) = cf_i(\mathbf{x})] \end{array} \right. \right\}$$

$$f = \left\{ f_i \left| \begin{array}{l} f_i : \mathbb{C}^n \rightarrow \mathbb{C} \\ \forall \mathbf{x}, \mathbf{y} \in \mathbb{C}^n [f_i(\mathbf{x} + \mathbf{y}) = f_i(\mathbf{x}) + f_i(\mathbf{y})] \\ \forall \mathbf{x} \in \mathbb{C}^n, c \in \mathbb{C} [f_i(c\mathbf{x}) = cf_i(\mathbf{x})] \end{array} \right. \right\}$$

then

$$f_i(\mathbf{x}) = a_{i1}x_1 + \dots + a_{ij}x_j + \dots + a_{in}x_n$$

satisfying

$$\begin{aligned}
f_i(\mathbf{x} + \mathbf{y}) &= a_{i1}(x+y)_1 + \cdots + a_{ij}(x+y)_j + \cdots + a_{in}(x+y)_n \\
&= a_{i1}(x_1+y_1) + \cdots + a_{ij}(x_j+y_j) + \cdots + a_{in}(x_n+y_n) \\
&= (a_{i1}x_1 + a_{i1}y_1) + \cdots + (a_{ij}x_j + a_{ij}y_j) + \cdots + (a_{in}x_n + a_{in}y_n) \\
&= (a_{i1}x_1 + \cdots + a_{ij}x_j + \cdots + a_{in}x_n) + (a_{i1}y_1 + \cdots + a_{ij}y_j + \cdots + a_{in}y_n) \\
&= f_i(\mathbf{x}) + f_i(\mathbf{y})
\end{aligned}$$

$$\begin{aligned}
f_i(c\mathbf{x}) &= a_{i1}(cx)_1 + \cdots + a_{ij}(cx)_j + \cdots + a_{in}(cx)_n \\
&= a_{i1}(cx_1) + \cdots + a_{ij}(cx_j) + \cdots + a_{in}(cx_n) \\
&= c(a_{i1}x_1) + \cdots + c(a_{ij}x_j) + \cdots + c(a_{in}x_n) \\
&= c(a_{i1}x_1 + \cdots + a_{ij}x_j + \cdots + a_{in}x_n) \\
&= cf_i(\mathbf{x})
\end{aligned}$$

different functional has different a_{ij}

let

$$a_{ij} = f_i(\mathbf{e}_j), \mathbf{e}_j = \left\langle \overbrace{0, \dots, 0}^{j-1}, 1, 0, \dots, 0 \right\rangle = (0 \ \cdots \ 0 \ \ 1 \ \ 0 \ \ \cdots \ \ 0)^T = \begin{pmatrix} 0 \\ \vdots \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix}_{n \times 1} = \begin{pmatrix} 0 \\ \vdots \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix}_{n \times 1}$$

if f_i is a linear functional, then

$$\begin{aligned}
f_i(\mathbf{x}) &= f_i(x_1\mathbf{e}_1 + \cdots + x_j\mathbf{e}_j + \cdots + x_n\mathbf{e}_n) \\
&= f_i(x_1\mathbf{e}_1) + \cdots + f_i(x_j\mathbf{e}_j) + \cdots + f_i(x_n\mathbf{e}_n) \\
&= x_1f_i(\mathbf{e}_1) + \cdots + x_jf_i(\mathbf{e}_j) + \cdots + x_nf_i(\mathbf{e}_n) \\
&= x_1a_{i1} + \cdots + x_ja_{ij} + \cdots + x_na_{in} \\
&= a_{i1}x_1 + \cdots + a_{ij}x_j + \cdots + a_{in}x_n \\
&= f_i(\mathbf{x})
\end{aligned}$$

39.5 set of all linear transformations is a vector space

<https://ccjou.wordpress.com/2011/04/08/%E7%94%A8%E6%88%80%E6%95%99%E7%9A%84%E5%8F%8B%E8%80%85/>

vector space^[40]

<https://math.stackexchange.com/questions/2381942/the-set-of-all-linear-maps-tv-w-is-a-vector-space>

$$T : V \rightarrow W \Leftrightarrow \forall \mathbf{v} \in V, \exists! \mathbf{w} \in W [\mathbf{w} = T(\mathbf{v})]$$

$$\left\{ \begin{array}{l} V, W \text{ are vector spaces} \\ T : V \rightarrow W \\ \left\{ \begin{array}{l} \forall \mathbf{u}, \mathbf{v} \in V [T(\mathbf{u} + \mathbf{v}) = T(\mathbf{u}) + T(\mathbf{v})] \\ \forall \mathbf{v} \in V, c \in F [T(c\mathbf{v}) = cT(\mathbf{v})] \end{array} \right. \end{array} \right. \quad \text{linearity}$$

$\Leftrightarrow T$ is a linear transformation

$$\left\{ \begin{array}{l} V, W \text{ are vector spaces, both over } F \\ T, U : V \rightarrow W \\ \left\{ \begin{array}{l} T : V \rightarrow W \\ U : V \rightarrow W \end{array} \right. \\ T, U \text{ are both linear transformations} \\ \mathbf{v} \in V \\ c \in F \end{array} \right.$$

There is still linearity over linear transformations

(va)

$$\begin{aligned} (T + U)(\mathbf{u} + \mathbf{v}) &= T(\mathbf{u} + \mathbf{v}) + U(\mathbf{u} + \mathbf{v}) \\ &= [T(\mathbf{u}) + T(\mathbf{v})] + [U(\mathbf{u}) + U(\mathbf{v})] \\ &= [T(\mathbf{u}) + U(\mathbf{u})] + [T(\mathbf{v}) + U(\mathbf{v})] \\ &= (T + U)(\mathbf{u}) + (T + U)(\mathbf{v}) \end{aligned}$$

(sm)

$$\begin{aligned} (T + U)(c\mathbf{v}) &= T(c\mathbf{v}) + U(c\mathbf{v}) \\ &= cT(\mathbf{v}) + cU(\mathbf{v}) \\ &= c[T(\mathbf{v}) + U(\mathbf{v})] \\ &= c(T + U)(\mathbf{v}) \end{aligned}$$

so we can define

$$\left\{ \begin{array}{ll} (T + U)(\mathbf{v}) = T(\mathbf{v}) + U(\mathbf{v}) & \text{linear transformation addition} \\ (cT)(\mathbf{v}) = cT(\mathbf{v}) & \text{scalar linear transformation multiplication} \end{array} \right.$$

the set of all linear tranformations is a vector space

\mathcal{T} is the set of all linear tranformations

$$\left\{ \begin{array}{ll}
 F & (f) F \text{ is a field} \\
 \mathcal{T} \neq \emptyset & (ne) \text{ nonempty set} \\
 + : \mathcal{T} \times \mathcal{T} = \mathcal{T}^2 \xrightarrow{\cdot} \mathcal{T} \Leftrightarrow \forall T, U \in \mathcal{T}, \exists S \in \mathcal{T} [S = T + U] & (va) \text{ vector addition} \\
 \cdot : F \times \mathcal{T} \xrightarrow{\cdot} \mathcal{T} \Leftrightarrow \forall c \in F, \forall T \in \mathcal{T}, \exists U \in \mathcal{T} [U = cT = c \cdot T] & (sm) \text{ scalar multiplication} \\
 \left\{ \begin{array}{ll}
 \forall S, T, U \in \mathcal{T} [S + (T + U) = (S + T) + U] & (a) \\
 \forall T, U \in \mathcal{T} [T + U = U + T] & (c) \\
 \exists! O \in \mathcal{T}, \forall T \in \mathcal{T} [O + T = T] & (e) \\
 \forall T \in \mathcal{T}, \exists! -T \in \mathcal{T} [(-T) + T = O] & (i) \\
 \forall b, c \in F, T \in \mathcal{T} [b(cT) = (bc)T] & (a) \\
 \exists! 1 \in F, \forall T \in \mathcal{T} [1T = T] & (e) \\
 \forall c \in F, T, U \in \mathcal{T} [c(T + U) = cT + cU] & (dv) \\
 \forall b, c \in F, T \in \mathcal{T} [(b + c)T = bT + cT] & (ds)
 \end{array} \right. & \begin{array}{l}
 (va) \text{ vector addition axioms} \\
 (sm) \text{ scalar multiplication axioms}
 \end{array}
 \end{array} \right.$$

$\Leftrightarrow \mathcal{T} = \mathcal{T}(F, +, \cdot) = (\mathcal{T}, F, +, \cdot)$ is a vector space over the field F

$\Leftrightarrow \mathcal{T}$ is a vector space

Selected proofs of 8 vector space axioms due to some trivial field and vector space properties:

(va) (a)

$$\begin{aligned}
 (S + (T + U))(\mathbf{v}) &= S(\mathbf{v}) + (T + U)(\mathbf{v}) \\
 &= S(\mathbf{v}) + T(\mathbf{v}) + U(\mathbf{v}) \\
 &= (S + T)(\mathbf{v}) + U(\mathbf{v}) \\
 &= ((S + T) + U)(\mathbf{v})
 \end{aligned}$$

(va) (c)

$$\begin{aligned}
 (T + U)(\mathbf{v}) &= T(\mathbf{v}) + U(\mathbf{v}) \\
 &= U(\mathbf{v}) + T(\mathbf{v}) \\
 &= (U + T)(\mathbf{v})
 \end{aligned}$$

(va) (e)

$$O(\mathbf{v}) = 0\mathbf{w} \in W$$

$$\begin{aligned}
 (O + T)(\mathbf{v}) &= O(\mathbf{v}) + T(\mathbf{v}) \\
 &= 0\mathbf{w} + T(\mathbf{v}) \\
 &= T(\mathbf{v})
 \end{aligned}$$

$$O_1(\mathbf{v}) - O_2(\mathbf{v}) = 0\mathbf{w} - 0\mathbf{w} = 0\mathbf{w} \Rightarrow O_1(\mathbf{v}) = O_2(\mathbf{v})$$

(sm) (dv)

$$\begin{aligned}
 (c(T+U))(\mathbf{v}) &= c(T+U)(\mathbf{v}) \\
 &= c[T(\mathbf{v}) + U(\mathbf{v})] \\
 &= cT(\mathbf{v}) + cU(\mathbf{v}) \\
 &= (cT + cU)(\mathbf{v})
 \end{aligned}$$

The set of all linear transformations \mathcal{T} is a vector space.

□

39.6 definition of dual space

$$V^* = L(V, F)$$

$$= f = \left\{ f_i \left| \begin{array}{l} f_i : V \rightarrow F \\ \forall \mathbf{x}, \mathbf{y} \in V [f_i(\mathbf{x} + \mathbf{y}) = f_i(\mathbf{x}) + f_i(\mathbf{y})] \\ \forall \mathbf{x} \in V, c \in F [f_i(cx) = cf_i(\mathbf{x})] \end{array} \right. \right\} \quad \begin{array}{l} \text{functional mapping vector to field scalar} \\ (L) \text{ linearity} \end{array}$$

$\Leftrightarrow V^*$ is a dual space, a set of linear functionals f_i mapping vectors in the vector space V to scalars in the field F

vector space^[40]

<https://web.math.sinica.edu.tw/mathmedia/HTMLArticle18.jsp?mID=31304>

https://web.math.sinica.edu.tw/mathmedia/author18.jsp?query_filter=%E9%BE%94%E6%98%87

39.7 double dual

double dual = second dual

<https://ccjou.wordpress.com/2014/04/10/%E9%BE%94%E6%98%87/>

Chapter 40

vector space

<https://ccjou.wordpress.com/2010/04/15/%E5%90%8C%E6%9E%9A%E7%9F%A5%E9%97%A8/>

40.1 What is a vector?

What is a vector? or What is an element in a vector space?

Binary operations defined on a vector space satisfying some properties is more important than what is a vector.

ultimate answer: double dual concept^[40.4.1.2]

40.2 vector space definition

<https://tex.stackexchange.com/a/141489> multiline node

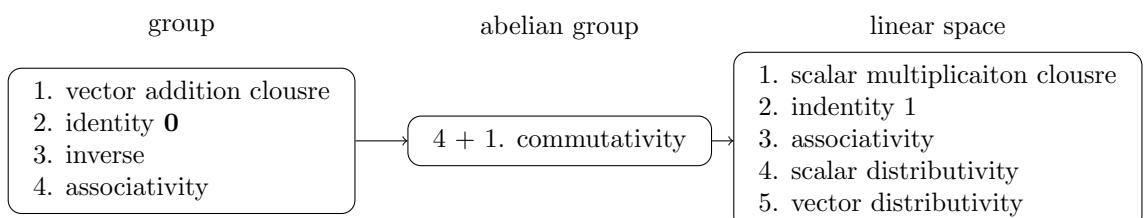


Figure 40.1: vector space construction

$$\left\{ \begin{array}{ll} F \text{ is a field} & (f) \text{ field} \\ V \neq \emptyset & (ne) \text{ nonempty set} \\ + : V \times V = V^2 \xrightarrow{\perp} V \Leftrightarrow \forall \mathbf{u}, \mathbf{v} \in V, \exists! \mathbf{w} \in V [\mathbf{w} = \mathbf{u} + \mathbf{v}] & (va) \text{ vector addition} \\ \cdot : F \times V \rightarrow V \Leftrightarrow \forall s \in F, \forall \mathbf{v} \in V, \exists! \mathbf{u} \in V [\mathbf{u} = s\mathbf{v} = s \cdot \mathbf{v}] & (sm) \text{ scalar multiplication} \\ \left\{ \begin{array}{ll} \exists! \mathbf{0} \in V, \forall \mathbf{v} \in V [\mathbf{0} + \mathbf{v} = \mathbf{v}] & (e) \text{ identity} \\ \forall \mathbf{v} \in V, \exists! -\mathbf{v} \in V [(-\mathbf{v}) + \mathbf{v} = \mathbf{0}] & (i) \text{ inverse} \\ \forall \mathbf{u}, \mathbf{v}, \mathbf{w} \in V [\mathbf{u} + (\mathbf{v} + \mathbf{w}) = (\mathbf{u} + \mathbf{v}) + \mathbf{w}] & (a) \text{ associativity} \\ \forall \mathbf{u}, \mathbf{v} \in V [\mathbf{u} + \mathbf{v} = \mathbf{v} + \mathbf{u}] & (c) \text{ commutativity} \end{array} \right. & (va) \text{ axioms} \\ \left\{ \begin{array}{ll} \exists! 1 \in F, \forall \mathbf{v} \in V [1\mathbf{v} = \mathbf{v}] & (e) \text{ identity} \\ \forall s, t \in F, \mathbf{v} \in V [s(t\mathbf{v}) = (st)\mathbf{v}] & (a) \text{ associativity} \\ \forall s, t \in F, \mathbf{v} \in V [(s+t)\mathbf{v} = s\mathbf{v} + t\mathbf{v}] & (ds) \text{ scalar distributivity} \\ \forall s \in F, \mathbf{u}, \mathbf{v} \in V [s(\mathbf{u} + \mathbf{v}) = s\mathbf{u} + s\mathbf{v}] & (dv) \text{ vector distributivity} \end{array} \right. & (sm) \text{ axioms} \end{array} \right.$$

$\Leftrightarrow V = V(F, +, \cdot) = (V, F, +, \cdot)$ is a vector space over the field F

$\Leftrightarrow V$ is a vector space

40.2.1 commutative group structure of vector space

(va) axioms = vector addition axioms

$V = (V, +)$ is a commutative group $\Leftrightarrow V = (V, +)$ is an abelian group

$$\Leftrightarrow \left\{ \begin{array}{ll} V = (V, +) = (V, +_V) \text{ is a group} & (g) \text{ group} \\ \forall \mathbf{u}, \mathbf{v} \in V [\mathbf{u} + \mathbf{v} = \mathbf{v} + \mathbf{u}] & (c) \text{ commutativity} \end{array} \right.$$

$$\Leftrightarrow \left\{ \begin{array}{ll} + : V \times V = V^2 \xrightarrow{\perp} V \Leftrightarrow \forall \mathbf{u}, \mathbf{v} \in V, \exists! \mathbf{w} \in V [\mathbf{w} = \mathbf{u} + \mathbf{v}] & (cl) \text{ closure} \\ \exists! \mathbf{0} \in V, \forall \mathbf{v} \in V [\mathbf{0} + \mathbf{v} = \mathbf{v}] & (e) \text{ identity} \\ \forall \mathbf{v} \in V, \exists! -\mathbf{v} \in V [(-\mathbf{v}) + \mathbf{v} = \mathbf{0}] & (i) \text{ inverse} \\ \forall \mathbf{u}, \mathbf{v}, \mathbf{w} \in V [\mathbf{u} + (\mathbf{v} + \mathbf{w}) = (\mathbf{u} + \mathbf{v}) + \mathbf{w}] & (a) \text{ associativity} \\ \forall \mathbf{u}, \mathbf{v} \in V [\mathbf{u} + \mathbf{v} = \mathbf{v} + \mathbf{u}] & (c) \end{array} \right. \quad (g) \quad (c)$$

V is a vector space

$\Leftrightarrow V = V(F, +, \cdot) = (V, F, +, \cdot)$ is a vector space over the field F

$$\Leftrightarrow \begin{cases} F \text{ is a field} & (f) \text{ field} \\ V \neq \emptyset & (ne) \text{ nonempty set} \\ V = (V, +) \text{ is a commutative group} \Leftrightarrow V = (V, +) \text{ is an abelian group} & (va) \text{ vector addition} \\ \cdot : F \times V \rightarrow V \Leftrightarrow \forall s \in F, \forall \mathbf{v} \in V, \exists! \mathbf{u} \in V [\mathbf{u} = s\mathbf{v} = s \cdot \mathbf{v}] & (sm) \text{ scalar multiplication} \\ \begin{cases} \exists! 1 \in F, \forall \mathbf{v} \in V [1\mathbf{v} = \mathbf{v}] & (e) \text{ identity} \\ \forall s, t \in F, \mathbf{v} \in V [s(t\mathbf{v}) = (st)\mathbf{v}] & (a) \text{ associativity} \\ \forall s, t \in F, \mathbf{v} \in V [(s+t)\mathbf{v} = s\mathbf{v} + t\mathbf{v}] & (ds) \text{ scalar distributivity} \\ \forall s \in F, \mathbf{u}, \mathbf{v} \in V [s(\mathbf{u} + \mathbf{v}) = s\mathbf{u} + s\mathbf{v}] & (dv) \text{ vector distributivity} \end{cases} & (sm) \text{ axioms} \end{cases}$$

 $\Leftrightarrow \begin{cases} F \text{ is a field} & (f) \text{ field} \\ V \neq \emptyset & (ne) \text{ nonempty set} \\ \begin{cases} V = (V, +) = (V, +_V) \text{ is a group} & (g) \text{ group} \\ \forall \mathbf{u}, \mathbf{v} \in V [\mathbf{u} + \mathbf{v} = \mathbf{v} + \mathbf{u}] & (c) \text{ commutativity} \end{cases} & (va) \text{ vector addition} \\ \cdot = \cdot_{F \times V} : F \times V \rightarrow V \Leftrightarrow \forall s \in F, \forall \mathbf{v} \in V, \exists! \mathbf{u} \in V [\mathbf{u} = s\mathbf{v} = s \cdot \mathbf{v}] & (sm) \text{ scalar multiplication} \\ \begin{cases} \exists! 1 \in F, \forall \mathbf{v} \in V [1\mathbf{v} = \mathbf{v}] & (e) \text{ identity} \\ \forall s, t \in F, \mathbf{v} \in V [s(t\mathbf{v}) = (st)\mathbf{v}] & (a) \text{ associativity} \\ \forall s, t \in F, \mathbf{v} \in V [(s+t)\mathbf{v} = s\mathbf{v} + t\mathbf{v}] & (ds) \text{ scalar distributivity} \\ \forall s \in F, \mathbf{u}, \mathbf{v} \in V [s(\mathbf{u} + \mathbf{v}) = s\mathbf{u} + s\mathbf{v}] & (dv) \text{ vector distributivity} \end{cases} & (sm) \text{ axioms} \end{cases}$

 $\Leftrightarrow \begin{cases} F = F(+_F, \cdot_F) = (F, +_F, \cdot_F) = (F, +, \cdot) \text{ is a field} & (f) \\ V \neq \emptyset & (ne) \\ \begin{cases} + : V \times V = V^2 \xrightarrow{\perp} V \Leftrightarrow \forall \mathbf{u}, \mathbf{v} \in V, \exists! \mathbf{w} \in V [\mathbf{w} = \mathbf{u} + \mathbf{v}] & (cl) \text{ closure} \\ \exists! \mathbf{0} \in V, \forall \mathbf{v} \in V [\mathbf{0} + \mathbf{v} = \mathbf{v}] & (e) \text{ identity} \\ \forall \mathbf{v} \in V, \exists! -\mathbf{v} \in V [(-\mathbf{v}) + \mathbf{v} = \mathbf{0}] & (i) \text{ inverse} \\ \forall \mathbf{u}, \mathbf{v}, \mathbf{w} \in V [\mathbf{u} + (\mathbf{v} + \mathbf{w}) = (\mathbf{u} + \mathbf{v}) + \mathbf{w}] & (a) \text{ associativity} \end{cases} & (va) \\ \forall \mathbf{u}, \mathbf{v} \in V [\mathbf{u} + \mathbf{v} = \mathbf{v} + \mathbf{u}] & (c) \\ \cdot : F \times V \rightarrow V \Leftrightarrow \forall s \in F, \forall \mathbf{v} \in V, \exists! \mathbf{u} \in V [\mathbf{u} = s\mathbf{v} = s \cdot \mathbf{v}] & (cl) \text{ closure} \\ \exists! 1 \in F, \forall \mathbf{v} \in V [1\mathbf{v} = \mathbf{v}] & (e) \text{ identity} \\ \forall s, t \in F, \mathbf{v} \in V [s(t\mathbf{v}) = s \cdot_{F \times V} (t \cdot_{F \times V} \mathbf{v}) = (s \cdot_F t) \cdot_{F \times V} \mathbf{v} = (st)\mathbf{v}] & (a) \text{ associativity} & (sm) \\ \forall s, t \in F, \mathbf{v} \in V [(s+t)\mathbf{v} = (s +_F t)\mathbf{v} = s\mathbf{v} +_V t\mathbf{v} = s\mathbf{v} + t\mathbf{v}] & (ds) \text{ scalar distributivity} \\ \forall s \in F, \mathbf{u}, \mathbf{v} \in V [s(\mathbf{u} + \mathbf{v}) = s\mathbf{u} + s\mathbf{v}] & (dv) \text{ vector distributivity} \end{cases}$

40.2.2 scalar distributivity

(sm) (ds)

$$\forall s, t \in F, \mathbf{v} \in V [(s+t)\mathbf{v} = s\mathbf{v} + t\mathbf{v}]$$

$$\forall s, t \in F, \mathbf{v} \in V [(s +_F t)\mathbf{v} = s\mathbf{v} + t\mathbf{v}]$$

$$\forall s, t \in F, \mathbf{v} \in V [(s +_F t)\mathbf{v} = s\mathbf{v} +_V t\mathbf{v}]$$

40.3 linearity

$$\begin{aligned} & \begin{cases} f(x+y) = f(x) + f(y) & \text{additivity} \\ f(\lambda x) = \lambda f(x) & \text{homogeneity} \end{cases} \\ \Leftrightarrow & f(\lambda x + y) = \lambda f(x) + f(y) \\ \Leftrightarrow & f \text{ is linear} \end{aligned}$$

40.3.1 linear structure of vector space

$$\forall s \in F, \mathbf{u}, \mathbf{v} \in V [\mathbf{u} + s\mathbf{v} \in V]$$

$$\forall s \in F, \forall \mathbf{u}, \mathbf{v} \in V [\mathbf{u} + s\mathbf{v} \in V]$$

$$\forall s \in F, \langle \mathbf{u}, \mathbf{v} \rangle \in V^2 [\mathbf{u} + s\mathbf{v} \in V]$$

$$\begin{aligned} & \begin{cases} \forall \mathbf{u}, \mathbf{v} \in V [\mathbf{u} + \mathbf{v} \in V] & \text{vector addition closure} \\ \forall s \in F, \mathbf{v} \in V [s\mathbf{v} \in V] & \text{scalar multiplication closure} \end{cases} \\ \Leftrightarrow & \begin{cases} \forall \mathbf{u}, \mathbf{v} \in V [\mathbf{u} + \mathbf{v} \in V] & (a) \text{ additivity} \\ \forall s \in F, \mathbf{v} \in V [s\mathbf{v} \in V] & (h) \text{ homogeneity} \end{cases} \\ \Leftrightarrow & \forall s \in F, \mathbf{u}, \mathbf{v} \in V [\mathbf{u} + s\mathbf{v} \in V] \quad (l) \text{ linearity} \end{aligned}$$

40.3.2 linear transformation or linear map

$$\begin{aligned} & \begin{cases} V, W \text{ are vector spaces} \\ T : V \rightarrow W \\ \begin{cases} \forall \mathbf{u}, \mathbf{v} \in V [T(\mathbf{u} + \mathbf{v}) = T(\mathbf{u}) + T(\mathbf{v})] & (a) \text{ additivity} \\ \forall \mathbf{v} \in V, c \in F [T(c\mathbf{v}) = cT(\mathbf{v})] & (h) \text{ homogeneity} \end{cases} \end{cases} \quad (L) \\ \Leftrightarrow & \begin{cases} V, W \text{ are vector spaces} \\ T : V \rightarrow W \\ \forall \mathbf{u}, \mathbf{v} \in V, c \in F [T(\mathbf{u} + c\mathbf{v}) = T(\mathbf{u}) + cT(\mathbf{v})] \quad (l) \text{ linearity} \end{cases} \\ \Leftrightarrow & T \text{ is a linear map from } V \text{ to } W \\ \Leftrightarrow & T \text{ is a linear transformation} \end{aligned}$$

40.4 vector space example

- arrow vector
- number
 - integer
 - real
 - complex
 - quaternion
- function
 - polynomial function
 - continuous function

- matrix
 - real matrix
 - complex matrix
- reciprocal space

applications in different disciplines

- math
 - recursive number series
 - Fourier series
- physics
 - electrical circuit: linear response / [superposition theorem](#) in [linear circuit](#) / linear network
- chemistry
 - [balancing chemical equation](#)

40.4.1 reciprocal space

reciprocal space = 倒易空間

$$\begin{cases} \mathbf{e}_1 = \mathbf{a} & \mathbf{a} \times \mathbf{b} \neq \mathbf{0} \\ \mathbf{e}_2 = \mathbf{b} & \mathbf{b} \times \mathbf{c} \neq \mathbf{0} \\ \mathbf{e}_3 = \mathbf{c} & \mathbf{c} \times \mathbf{a} \neq \mathbf{0} \end{cases} \Rightarrow \begin{cases} \mathbf{e}'_1 = \frac{\mathbf{b} \times \mathbf{c}}{\Omega} \\ \mathbf{e}'_2 = \frac{\mathbf{c} \times \mathbf{a}}{\Omega} \\ \mathbf{e}'_3 = \frac{\mathbf{a} \times \mathbf{b}}{\Omega} \end{cases},$$

$$\Omega = \mathbf{a} \cdot (\mathbf{b} \times \mathbf{c}) = \mathbf{b} \cdot (\mathbf{c} \times \mathbf{a}) = \mathbf{c} \cdot (\mathbf{a} \times \mathbf{b})$$

reciprocal space as dual space and contravariant vector

$$\begin{aligned} \text{span} \{ \mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3 \} &= \text{span} \{ \mathbf{a}, \mathbf{b}, \mathbf{c} \} = V \\ &= \mathbb{R}^3 = \text{span} \{ \mathbf{e}'_1, \mathbf{e}'_2, \mathbf{e}'_3 \} = \text{span} \left\{ \frac{\mathbf{b} \times \mathbf{c}}{\Omega}, \frac{\mathbf{c} \times \mathbf{a}}{\Omega}, \frac{\mathbf{a} \times \mathbf{b}}{\Omega} \right\} \\ &= \text{span} \{ \mathbf{e}^1, \mathbf{e}^2, \mathbf{e}^3 \} = \text{span} \{ \mathbf{e}^* \}_{* \in \{1, 2, 3\}} = V^* \end{aligned}$$

40.4.1.1 Kronecker delta

$$\begin{pmatrix} \mathbf{e}_1 \cdot \mathbf{e}'_1 & \mathbf{e}_1 \cdot \mathbf{e}'_2 & \mathbf{e}_1 \cdot \mathbf{e}'_3 \\ \mathbf{e}_2 \cdot \mathbf{e}'_1 & \mathbf{e}_2 \cdot \mathbf{e}'_2 & \mathbf{e}_2 \cdot \mathbf{e}'_3 \\ \mathbf{e}_3 \cdot \mathbf{e}'_1 & \mathbf{e}_3 \cdot \mathbf{e}'_2 & \mathbf{e}_3 \cdot \mathbf{e}'_3 \end{pmatrix} = [\delta_{ij}] = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} \mathbf{e}^1 \cdot \mathbf{e}_1 & \mathbf{e}^1 \cdot \mathbf{e}_2 & \mathbf{e}^1 \cdot \mathbf{e}_3 \\ \mathbf{e}^2 \cdot \mathbf{e}_1 & \mathbf{e}^2 \cdot \mathbf{e}_2 & \mathbf{e}^2 \cdot \mathbf{e}_3 \\ \mathbf{e}^3 \cdot \mathbf{e}_1 & \mathbf{e}^3 \cdot \mathbf{e}_2 & \mathbf{e}^3 \cdot \mathbf{e}_3 \end{pmatrix}$$

Kronecker delta

$$\mathbf{e}_i \cdot \mathbf{e}'_j = \delta_{ij} = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}$$

Kronecker delta tensor = Kronecker tensor

$$\mathbf{e}^i(\mathbf{e}_j) = \mathbf{e}^i \cdot \mathbf{e}_j = \delta_j^i = \delta^i_j = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}$$

$$\mathbf{v} = v_a \mathbf{a} + v_b \mathbf{b} + v_c \mathbf{c} = v_1 \mathbf{e}_1 + v_2 \mathbf{e}_2 + v_3 \mathbf{e}_3$$

$$\mathbf{e}^1 \cdot \mathbf{v} = \mathbf{v} \cdot \mathbf{e}'_1 = v_1 \mathbf{e}_1 \cdot \mathbf{e}'_1 + v_2 \mathbf{e}_2 \cdot \mathbf{e}'_1 + v_3 \mathbf{e}_3 \cdot \mathbf{e}'_1 = v_1$$

$$\mathbf{e}^2 \cdot \mathbf{v} = \mathbf{v} \cdot \mathbf{e}'_2 = v_1 \mathbf{e}_1 \cdot \mathbf{e}'_2 + v_2 \mathbf{e}_2 \cdot \mathbf{e}'_2 + v_3 \mathbf{e}_3 \cdot \mathbf{e}'_2 = v_2$$

$$\mathbf{e}^3 \cdot \mathbf{v} = \mathbf{v} \cdot \mathbf{e}'_3 = v_1 \mathbf{e}_1 \cdot \mathbf{e}'_3 + v_2 \mathbf{e}_2 \cdot \mathbf{e}'_3 + v_3 \mathbf{e}_3 \cdot \mathbf{e}'_3 = v_3$$

$$\begin{aligned}\mathbf{v} &= v_1 \mathbf{e}_1 + v_2 \mathbf{e}_2 + v_3 \mathbf{e}_3 \\ &= (\mathbf{v} \cdot \mathbf{e}'_1) \mathbf{e}_1 + (\mathbf{v} \cdot \mathbf{e}'_2) \mathbf{e}_2 + (\mathbf{v} \cdot \mathbf{e}'_3) \mathbf{e}_3 \\ &= (\mathbf{e}^1 \cdot \mathbf{v}) \mathbf{e}_1 + (\mathbf{e}^2 \cdot \mathbf{v}) \mathbf{e}_2 + (\mathbf{e}^3 \cdot \mathbf{v}) \mathbf{e}_3 \\ &= \mathbf{e}^1(\mathbf{v}) \mathbf{e}_1 + \mathbf{e}^2(\mathbf{v}) \mathbf{e}_2 + \mathbf{e}^3(\mathbf{v}) \mathbf{e}_3\end{aligned}$$

$$\begin{cases} \mathbf{e}^1(\mathbf{v}) = \mathbf{e}^1 \cdot \mathbf{v} = \mathbf{v} \cdot \mathbf{e}'_1 = v_1 \\ \mathbf{e}^2(\mathbf{v}) = \mathbf{e}^2 \cdot \mathbf{v} = \mathbf{v} \cdot \mathbf{e}'_2 = v_2 \\ \mathbf{e}^3(\mathbf{v}) = \mathbf{e}^3 \cdot \mathbf{v} = \mathbf{v} \cdot \mathbf{e}'_3 = v_3 \end{cases}$$

$$\mathbf{e}^i(\mathbf{e}_j) = \mathbf{e}^i \cdot \mathbf{e}_j = \delta_j^i = \delta_{j,i} = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}$$

reciprocal space is a dual space of its original vector space

$$\begin{aligned}V &= \text{span} \{\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3\} = \{v_1 \mathbf{e}_1 + v_2 \mathbf{e}_2 + v_3 \mathbf{e}_3\} \\ &= \left\{ \sum_{j=1}^3 v_j \mathbf{e}_j \right\} = \left\{ v_j \mathbf{e}_j \middle| \begin{array}{l} v_j \in F \\ \mathbf{e}_j \in F^3 \end{array} \right\} = \{\mathbf{v} | \mathbf{v} \in V\} \\ V^* &= \text{span} \{\mathbf{e}^1, \mathbf{e}^2, \mathbf{e}^3\} = \{v^{*1} \mathbf{e}^1 + v^{*2} \mathbf{e}^2 + v^{*3} \mathbf{e}^3\} \\ &= \left\{ \sum_{i=1}^3 v^{*i} \mathbf{e}^i \right\} = \left\{ v^{*i} \mathbf{e}^i \middle| \begin{array}{l} v^{*i} \in F \\ \mathbf{e}^i \in F^3 \end{array} \right\} = \{\mathbf{v}^* | \mathbf{v}^* \in V^*\} \\ \mathbf{v}^*(\mathbf{v}) &= (v^{*i} \mathbf{e}^i)(\mathbf{v}), \mathbf{v} \in V \\ &= (v^{*1} \mathbf{e}^1 + v^{*2} \mathbf{e}^2 + v^{*3} \mathbf{e}^3)(\mathbf{v}) \\ &= v^{*1} \mathbf{e}^1(\mathbf{v}) + v^{*2} \mathbf{e}^2(\mathbf{v}) + v^{*3} \mathbf{e}^3(\mathbf{v}) \\ &= v^{*1} v_1 + v^{*2} v_2 + v^{*3} v_3 \in F\end{aligned}$$

element in dual space is a functional or mapping from its original vector space to the field

$$\mathbf{v}^* : V \rightarrow F$$

$$V \xrightarrow{\mathbf{v}^*} F$$

$$V^* = \{\mathbf{v}^* | \mathbf{v}^* : V \rightarrow F\}$$

$$\begin{array}{ccccccc}
 & & V & = & \{ & \mathbf{e}_1 & \mathbf{e}_2 & \mathbf{e}_3 & \mathbf{v} & \cdots \} \\
 \mathbf{e}^1 & : & \downarrow & & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\
 V^* = \{ & \mathbf{e}^2 & \} & F & \supseteq & \{ & 1 & 0 & 0 & v_1 & \cdots \} \\
 & \mathbf{e}^3 & V & = & \{ & \mathbf{e}_1 & \mathbf{e}_2 & \mathbf{e}_3 & \mathbf{v} & \cdots \} \\
 \mathbf{v}^* & : & \downarrow & & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\
 \vdots & & F & \supseteq & \{ & v^{*1} & v^{*2} & v^{*3} & v^{*i} v_i & \cdots \}
 \end{array}$$

$$\begin{aligned}
 V^* &= \{\mathbf{v}^* | \mathbf{v}^* \in V^*\} = \{\mathbf{v}^* | \mathbf{v}^* : V \rightarrow F\} \\
 &= \left\{ \mathbf{v}^* \middle| V \xrightarrow{\mathbf{v}^*} F \right\} \\
 &= \{\omega | \omega : V \rightarrow F\} \\
 &= \left\{ \omega^i e^i \middle| \begin{cases} \omega^i \in F \\ e^i \in F^3 \end{cases} \right\}
 \end{aligned}$$

By defining vector addition and scalar multiplication on the dual space

$$\begin{cases}
 + : V^* \times V^* \rightarrow V^* \Leftrightarrow \forall \omega_1, \omega_2 \in V^*, \exists! (\omega_1 + \omega_2) \in V^* [(\omega_1 + \omega_2)(\mathbf{v}) = \omega_1(\mathbf{v}) + \omega_2(\mathbf{v})] \\
 \cdot : F \times V^* \rightarrow V^* \Leftrightarrow \forall k \in F, \forall \omega \in V^*, \exists! (k\omega) \in V^* [(k\omega)(\mathbf{v}) = k \cdot \omega(\mathbf{v})] \\
 \forall \omega \in V^*, \exists! \mathbf{0} \in V^* [(\omega + \mathbf{0})(\mathbf{v}) = \omega(\mathbf{v}) + \mathbf{0}(\mathbf{v}) = \omega(\mathbf{v})]
 \end{cases}$$

the dual space also becomes a vector space.

40.4.1.2 double dual concept

double dual space = second dual space

$$\begin{aligned}
 V^{**} &= (V^*)^* \\
 &= \{\omega^* | \omega^* : V^* \rightarrow F\} \\
 &= \{\omega^* | \omega^* \in V^{**}\}
 \end{aligned}$$

$$\begin{aligned}
 V^{**} &= (V^*)^* = \text{span} \{e^\mu\}_{\mu \in \{1, 2, 3\}}^* \\
 &= \text{span} \{\mathbf{e}^1, \mathbf{e}^2, \mathbf{e}^3\}^* \\
 &= \text{span} \{e^{1*}, e^{2*}, e^{3*}\} \\
 &= \text{span} \{e^{\nu*}\}_{\nu \in \{1, 2, 3\}}
 \end{aligned}$$

$$\begin{aligned}
 \omega^*(\omega) &= (\omega^{*\nu} e^{\nu*})(\omega), \omega \in V^* \\
 &= (\omega^{*1} e^{1*} + \omega^{*2} e^{2*} + \omega^{*3} e^{3*})(\omega) \\
 &= \omega^{*1} e^{1*}(\omega) + \omega^{*2} e^{2*}(\omega) + \omega^{*3} e^{3*}(\omega) \\
 &= \omega^{*1} \omega_1 + \omega^{*2} \omega_2 + \omega^{*3} \omega_3 \in F
 \end{aligned}$$

$$V^{**} = \{\omega^* | \omega^* : V^* \rightarrow F\}$$

$$\begin{array}{ccccccc} & & V^* & = & \{ & e^1 & e^2 & e^3 & \omega & \dots \} \\ V^{**} = \{ & \begin{matrix} e^{1*} \\ e^{2*} \\ e^{3*} \\ \omega^* \\ \vdots \end{matrix} & : & \begin{matrix} \downarrow \\ F \\ V^* \\ \downarrow \\ \vdots \end{matrix} & \supseteq & \{ & 1 & 0 & 0 & \omega^1 & \dots \} \\ & & & & & \{ & e_1 & e_2 & e_3 & v & \dots \} \\ & & & & & & \downarrow & \downarrow & \downarrow & \downarrow \\ & & & & & & \omega^{1*} & \omega^{2*} & \omega^{3*} & \omega^{\mu*} \omega^\mu & \dots \} \end{array}$$

$$\begin{cases} e^{1*}(\omega) = e^{1*} \cdot \omega = \omega \cdot e^{1*} = \omega(e^{1*}) \\ e^{2*}(\omega) = e^{2*} \cdot \omega = \omega \cdot e^{2*} = \omega(e^{2*}) \\ e^{3*}(\omega) = e^{3*} \cdot \omega = \omega \cdot e^{3*} = \omega(e^{3*}) \end{cases}$$

$$\omega^*(\omega) = \omega^* \cdot \omega = \omega \cdot \omega^* = \omega(\omega^*)$$

i.e. f acts on x equivalent to x acts on f

$$x(f) = x \cdot f = f \cdot x = f(x)$$

$$e^\mu(e_\nu) = e^\mu \cdot e_\nu = \delta_\nu^\mu = \delta^\mu_\nu = \begin{cases} 1 & \mu = \nu \\ 0 & \mu \neq \nu \end{cases}$$

$$\begin{array}{c} e^{\nu*}(e^\mu) \stackrel{\text{def.}}{=} e_\nu \cdot e^\mu = e^\mu \cdot e_\nu = e^\mu(e_\nu) \\ \Downarrow \\ V^{**} = \text{span}\{e^{\nu*}\}_{\nu \in \{1, 2, 3\}} \cong \text{span}\{e_\nu\}_{\nu \in \{1, 2, 3\}} = V \\ V^{**} \cong V \\ \Downarrow \begin{cases} V^{**} \cong V & V, V^{**} \text{ are isomorphism} \\ & \text{independent of choice of bases} \\ V, V^{**} \text{ are naturally isomorphism} \end{cases} \end{array}$$

$$V^{**} = \{\omega^* | \omega^* : V^* \rightarrow F\} \cong V = \{v | v : V^* \rightarrow F\}$$

$$\begin{array}{ccccccc} & & V^* & = & \{ & e^1 & e^2 & e^3 & \omega & \dots \} \\ V^{**} = \{ & \begin{matrix} e^{1*} \\ e^{2*} \\ e^{3*} \\ \omega^* \\ \vdots \end{matrix} & : & \begin{matrix} \downarrow \\ F \\ V^* \\ \downarrow \\ \vdots \end{matrix} & \supseteq & \{ & 1 & 0 & 0 & \omega^1 & \dots \} \\ & & & & & \{ & e^1 & e^2 & e^3 & v^* & \dots \} \\ & & & & & & \downarrow & \downarrow & \downarrow & \downarrow \\ & & & & & & \omega^{1*} & \omega^{2*} & \omega^{3*} & \omega^{\mu*} \omega^\mu & \dots \} \\ & & & & & & \{ & e^1 & e^2 & e^3 & v^* & \dots \} \\ & & & & & & \cong V = \{ & 1 & 0 & 0 & v^{*1} & \dots \} \\ & & & & & & \{ & e^1 & e^2 & e^3 & v^* & \dots \} \\ & & & & & & \{ & v_1 & v_2 & v_3 & v_\mu v^{*\mu} & \dots \} \\ & & & & & & \{ & v_1 & v_2 & v_3 & v_\mu v^{*\mu} & \dots \} \end{array}$$

$$V \cong V^{**}$$

$$V \cong V^{**} = \{\omega^* | \omega^* : V^* \rightarrow F\}$$

$$V = \{v | v : V^* \rightarrow F\}$$

i.e. **vector space is a set of functionals or mappings from its dual space to the field**, answering **What is a vector?**^[40.1], and satifying Fig: 40.1.

40.5 field

https://web.math.sinica.edu.tw/math_media/d312/31202.pdf

40.6 module

<https://web.math.sinica.edu.tw/mathmedia/HTMLArticle18.jsp?mID=31304>

40.7 subspace

Chapter 41

$\mathrm{d}f$

41.1 $\mathrm{d}f$ decomposed with partials as a set of basis in vector space

$$f = \{f_i\} = \{f_1, f_2, \dots\} = \{f, g, \dots\}$$

$$\mathbf{v} : f \rightarrow F$$

$$\mathbf{v}(af + bg) = a\mathbf{v}(f) + b\mathbf{v}(g)$$

$$\mathbf{v}(fg) = f|_P \mathbf{v}(g) + \mathbf{v}(f) g|_P$$

$$\frac{\mathrm{d}}{\mathrm{d}x} [f(x)g(x)]|_{x=x_0} = f(x_0) \frac{\mathrm{d}}{\mathrm{d}x} g(x)|_{x=x_0} + \frac{\mathrm{d}}{\mathrm{d}x} f(x)|_{x=x_0} g(x_0)$$

$$V = \{\mathbf{v} | \mathbf{v} : f \rightarrow F\}$$

$$\begin{aligned} f &= f(\mathbf{x}) \\ &= f(x_1, \dots, x_j, \dots, x_n) \\ &= f(x^1, \dots, x^j, \dots, x^n) \end{aligned}$$

$$\mathbf{x} = \langle x^1, \dots, x^j, \dots, x^n \rangle$$

$$\mathbf{x}(t) = \langle x^1(t), \dots, x^j(t), \dots, x^n(t) \rangle$$

$$\begin{aligned} \frac{\mathrm{d}f}{\mathrm{d}t} &= \frac{\mathrm{d}x^1}{\mathrm{d}t} \frac{\partial f}{\partial x^1} + \dots + \frac{\mathrm{d}x^j}{\mathrm{d}t} \frac{\partial f}{\partial x^j} + \dots + \frac{\mathrm{d}x^n}{\mathrm{d}t} \frac{\partial f}{\partial x^n} \\ &= \dots + \frac{\mathrm{d}x^j}{\mathrm{d}t} \frac{\partial f}{\partial x^j} + \dots = \frac{\mathrm{d}x^j}{\mathrm{d}t} \frac{\partial f}{\partial x^j} = \frac{\mathrm{d}x^j}{\mathrm{d}t} \partial_j f \end{aligned}$$

$$\begin{aligned}
V &= \text{span} \{ \mathbf{e}_1, \dots, \mathbf{e}_j, \dots, \mathbf{e}_n \} \\
&= \text{span} \left\{ \frac{\partial}{\partial x^1}|_P, \dots, \frac{\partial}{\partial x^j}|_P, \dots, \frac{\partial}{\partial x^n}|_P \right\} \\
&= \text{span} \{ \boldsymbol{\partial}_1, \dots, \boldsymbol{\partial}_j, \dots, \boldsymbol{\partial}_n \} \\
&= \left\{ \boldsymbol{\partial}_t \left| \boldsymbol{\partial}_t = a_j \mathbf{e}_j = a_j \boldsymbol{\partial}_j = a_j \frac{\partial}{\partial x^j}|_P \right. \right\} \\
&= \left\{ \frac{\partial}{\partial t}|_P \left| \frac{\partial}{\partial t}|_P = a_1 \frac{\partial}{\partial x^1}|_P + \dots + a_j \frac{\partial}{\partial x^j}|_P + \dots + a_n \frac{\partial}{\partial x^n}|_P \right. \right\}
\end{aligned}$$

41.2 dual space of span of partials

$$V^* = \{ \omega_f | \omega_f : V \rightarrow F \}$$

$$\omega_f(\mathbf{e}_j) = \omega_f(\boldsymbol{\partial}_j) = \omega_f \left(\frac{\partial}{\partial x^j}|_P \right) = \frac{\partial f}{\partial x^j}|_P \in F$$

$$\begin{aligned}
\omega_{fg}(\boldsymbol{\partial}_j) &= \frac{\partial fg}{\partial x^j}|_P = f|_P \frac{\partial g}{\partial x^j}|_P + \frac{\partial f}{\partial x^j}|_P g|_P \\
&= f|_P \omega_g(\boldsymbol{\partial}_j) + \omega_f(\boldsymbol{\partial}_j) g|_P
\end{aligned}$$

$$\omega_{x^i}(\boldsymbol{\partial}_j) = \omega_{x^i} \left(\frac{\partial}{\partial x^j}|_P \right) = \frac{\partial x^i}{\partial x^j}|_P = \delta_{ij} = \begin{cases} 1 & i=j \\ 0 & i \neq j \end{cases}$$

$$V^* = \{ \omega_f | \omega_f : V \rightarrow F \} = \left\{ \omega_f \left| \begin{array}{l} \omega_f(\mathbf{e}_j) = \omega_f(\boldsymbol{\partial}_j) = \omega_f \left(\frac{\partial}{\partial x^j}|_P \right) = \frac{\partial f}{\partial x^j}|_P \in F \\ \omega_{fg}(\boldsymbol{\partial}_j) = f|_P \omega_g(\boldsymbol{\partial}_j) + \omega_f(\boldsymbol{\partial}_j) g|_P \\ \omega_{x^i}(\boldsymbol{\partial}_j) = \omega_{x^i} \left(\frac{\partial}{\partial x^j}|_P \right) = \frac{\partial x^i}{\partial x^j}|_P = \delta_{ij} = \begin{cases} 1 & i=j \\ 0 & i \neq j \end{cases} \end{array} \right. \right\}$$

$$\{ df | df : V \rightarrow F \} = \left\{ df \left| \begin{array}{l} df(\mathbf{e}_j) = df(\boldsymbol{\partial}_j) = df \left(\frac{\partial}{\partial x^j}|_P \right) = \frac{\partial f}{\partial x^j}|_P \in F \\ dfg(\boldsymbol{\partial}_j) = f|_P (dg) + (df) g|_P \\ dx^i(\boldsymbol{\partial}_j) = dx^i \left(\frac{\partial}{\partial x^j}|_P \right) = \frac{\partial x^i}{\partial x^j}|_P = \delta_{ij} = \begin{cases} 1 & i=j \\ 0 & i \neq j \end{cases} \end{array} \right. \right\}$$

$$dx^i \left(\frac{\partial}{\partial x^j}|_P \right) = \delta_{ij} = \mathbf{e}^i \cdot \mathbf{e}_j \Rightarrow \begin{cases} \mathbf{e}^i = dx^i \\ \mathbf{e}_j = \frac{\partial}{\partial x^j}|_P \end{cases}$$

$$V^* = \{ df | df : V \rightarrow F \} = \left\{ df \left| \begin{array}{l} df(\mathbf{e}_j) = df(\boldsymbol{\partial}_j) = df \left(\frac{\partial}{\partial x^j}|_P \right) = \frac{\partial f}{\partial x^j}|_P \in F \\ dfg(\boldsymbol{\partial}_j) = f|_P (dg) + (df) g|_P \\ dx^i(\boldsymbol{\partial}_j) = dx^i \left(\frac{\partial}{\partial x^j}|_P \right) = \frac{\partial x^i}{\partial x^j}|_P = \delta_{ij} = \begin{cases} 1 & i=j \\ 0 & i \neq j \end{cases} \end{array} \right. \right\}$$

$$= \text{span} \{ dx^1, \dots, dx^i, \dots, dx^n \} = \text{span} \{ \mathbf{e}^1, \dots, \mathbf{e}^j, \dots, \mathbf{e}^n \}$$

41.3 directional derivative

$$\begin{aligned}
 df(\mathbf{v}) &= df(v_j \mathbf{e}_j) = v_j df(\mathbf{e}_j) \\
 &= v_j df(\partial_j) = v_j \frac{\partial f}{\partial x^j}|_P \\
 &= v_1 \frac{\partial f}{\partial x^1}|_P + v_2 \frac{\partial f}{\partial x^2}|_P + \cdots + v_n \frac{\partial f}{\partial x^n}|_P \\
 &= (v_1 \quad \cdots \quad v_j \quad \cdots \quad v_n) \nabla f
 \end{aligned}$$

$$\widehat{PQ} = C(t) - C(0) = Q - P$$

$$\mathbf{v} = \frac{\partial}{\partial t}|_P$$

$$\begin{aligned}
 df(s\mathbf{v}) &= df\left(s \frac{\partial}{\partial t}|_P\right) = s \frac{\partial f}{\partial t}|_P \\
 &= s\mathbf{v}(f) = s \cdot \lim_{t \rightarrow 0} \frac{f(C(t)) - f(C(0))}{t} \\
 &\approx s \cdot \frac{f(Q) - f(P)}{s} = f(Q) - f(P) = \Delta f
 \end{aligned}$$

41.4 coefficient of linear combination for vector space and dual space

$$\begin{aligned}
 V &= \{\mathbf{v} | \mathbf{v} : f \rightarrow F\} \\
 &= \text{span}\{\mathbf{e}_1, \dots, \mathbf{e}_j, \dots, \mathbf{e}_n\} \\
 &= \text{span}\left\{\frac{\partial}{\partial x^1}|_P, \dots, \frac{\partial}{\partial x^j}|_P, \dots, \frac{\partial}{\partial x^n}|_P\right\} = \text{span}\{\partial_1, \dots, \partial_j, \dots, \partial_n\} \\
 &= \left\{\partial_t \middle| \partial_t = a_j \mathbf{e}_j = a_j \partial_j = a_j \frac{\partial}{\partial x^j}|_P\right\} \\
 &= \left\{\frac{\partial}{\partial t}|_P \middle| \frac{\partial}{\partial t}|_P = a_1 \frac{\partial}{\partial x^1}|_P + \cdots + a_j \frac{\partial}{\partial x^j}|_P + \cdots + a_n \frac{\partial}{\partial x^n}|_P\right\}
 \end{aligned}$$

$$\begin{aligned}
 V^* &= \{df|df : V \rightarrow F\} \\
 &= \text{span}\{\mathbf{e}^1, \dots, \mathbf{e}^i, \dots, \mathbf{e}^n\} \\
 &= \text{span}\{dx^1, \dots, dx^i, \dots, dx^n\} \\
 &= \{df|df = b^i \mathbf{e}^i = b^i dx^i\} \\
 &= \{df|df = b^1 dx^1 + \cdots + b^i dx^i + \cdots + b^n dx^n\}
 \end{aligned}$$

or more simply to be comparison

$$\begin{array}{lll}
 V &= \text{span}\{ & \mathbf{e}_j = \partial_j \quad \} = \{ & \mathbf{v} = \partial_t|_P = a_j \mathbf{e}_j = a_j \partial_j|_P : f \rightarrow F \quad \} \\
 V^* &= \text{span}\{ & \mathbf{e}^i = dx^i \quad \} = \{ & \omega = df = b^i \mathbf{e}^i = b^i dx^i : V \rightarrow F \quad \}
 \end{array}$$

$$\begin{aligned}
& \left\{ \begin{array}{l} dx^i(\partial_j) = dx^i\left(\frac{\partial}{\partial x^j}|_P\right) = \frac{\partial x^i}{\partial x^j}|_P = \delta_{ij} = \begin{cases} 1 & i=j \\ 0 & i \neq j \end{cases} \\ \partial_t = a_j e_j = a_j \partial_j \Leftrightarrow \frac{\partial}{\partial t}|_P = a_1 \frac{\partial}{\partial x^1}|_P + \cdots + a_j \frac{\partial}{\partial x^j}|_P + \cdots + a_n \frac{\partial}{\partial x^n}|_P \end{array} \right. \\
& \Rightarrow \left\{ \begin{array}{l} dx^i(\partial_t) = dx^i\left(\frac{\partial}{\partial t}|_P\right) = \frac{\partial x^i}{\partial t}|_P \\ dx^i(\partial_t) = dx^i(a_j \partial_j) = a_j dx^i(\partial_j) = a_j \delta_{ij} = a_i \end{array} \right. \Rightarrow a_i = dx^i(\partial_t) = \frac{\partial x^i}{\partial t}|_P \\
& \Rightarrow a_i = \frac{\partial x^i}{\partial t}|_P \Rightarrow a_j = \frac{\partial x^j}{\partial t}|_P = \partial_t x^j|_P \\
& \Rightarrow \frac{\partial}{\partial t}|_P = a_i \frac{\partial}{\partial x^i}|_P = \frac{\partial x^i}{\partial t}|_P \frac{\partial}{\partial x^i}|_P = \frac{\partial x^i}{\partial t} \frac{\partial}{\partial x^i}|_P \Rightarrow \frac{\partial}{\partial t} = \frac{\partial x^i}{\partial t} \frac{\partial}{\partial x^i} \\
& \Rightarrow \partial_t|_P = \frac{\partial x^j}{\partial t} \partial_j|_P \Leftrightarrow \partial_t|_P = \partial_t x^j \partial_j|_P
\end{aligned}$$

$$\begin{aligned}
df &= b^i e^i = b^i dx^i \\
\frac{\partial f}{\partial x^j} &= df(\partial_j) = df(e_j) = b^i e^i \cdot e_j = b^i \delta_{ij} = b^j \\
b^j &= \frac{\partial f}{\partial x^j} \\
b^i &= \frac{\partial f}{\partial x^i} = \partial_i f \\
df &= b^i e^i = b^i dx^i = \frac{\partial f}{\partial x^i} dx^i \\
df &= \frac{\partial f}{\partial x^i} dx^i \\
df &= \partial_i f dx^i
\end{aligned}$$

$$\begin{array}{lll}
V &= \text{span}\{ & e_j = \partial_j \} = \{ & v = \partial_t|_P = a_j e_j = \partial_t x^j \partial_j|_P : f \rightarrow F \} \\
V^* &= \text{span}\{ & e^i = dx^i \} = \{ & \omega = df = b^i e^i = \partial_i f dx^i : V \rightarrow F \}
\end{array}$$

41.5 change of basis / change of coordinate

$$\frac{\partial}{\partial t} = \frac{\partial x^i}{\partial t} \frac{\partial}{\partial x^i} \stackrel{t=x'^j}{\Rightarrow} \frac{\partial}{\partial x'^j} = \frac{\partial x^i}{\partial x'^j} \frac{\partial}{\partial x^i} = \frac{\partial x^1}{\partial x'^j} \frac{\partial}{\partial x^1} + \frac{\partial x^2}{\partial x'^j} \frac{\partial}{\partial x^2} + \frac{\partial x^3}{\partial x'^j} \frac{\partial}{\partial x^3}$$

$$\begin{aligned}
df &= \frac{\partial f}{\partial x^i} dx^i \\
f &= x'^j \Downarrow \\
dx'^j &= \frac{\partial x'^j}{\partial x^i} dx^i
\end{aligned}$$

$$\begin{cases} \frac{\partial}{\partial x'^j} = \frac{\partial x^i}{\partial x'^j} \frac{\partial}{\partial x^i} = \sum_i \frac{\partial x^i}{\partial x'^j} \frac{\partial}{\partial x^i} \\ dx'^j = \frac{\partial x'^j}{\partial x^i} dx^i = \sum_i \frac{\partial x'^j}{\partial x^i} dx^i \end{cases}$$

Chapter 42

determinant

42.1 induction of determinant axioms

42.2 determinant axioms

determinant axioms

$$\left\{ \begin{array}{l} \det(\mathbf{u}, \mathbf{v}) = \det(\mathbf{u} + s\mathbf{v}, \mathbf{v}) \\ \det(\mathbf{u}, \mathbf{v}) = \det(\mathbf{u}, \mathbf{v} + s\mathbf{u}) \end{array} \right. \quad \begin{array}{l} \text{translation invariance} \\ \text{scaling} \end{array}$$
$$\left\{ \begin{array}{l} \det(s\mathbf{u}, \mathbf{v}) = s \det(\mathbf{u}, \mathbf{v}) \\ \det(\mathbf{u}, s\mathbf{v}) = s \det(\mathbf{u}, \mathbf{v}) \end{array} \right. \quad \text{decomposition}$$
$$\Leftrightarrow \left\{ \begin{array}{l} \det(\mathbf{u}, \mathbf{v}) = \det(\mathbf{u} + s\mathbf{v}, \mathbf{v}) \\ \det(\mathbf{u}, \mathbf{v}) = \det(\mathbf{u}, \mathbf{v} + s\mathbf{u}) \end{array} \right. \quad \begin{array}{l} \text{translation invariance} \\ \text{linearity} \end{array}$$
$$\left\{ \begin{array}{l} \det(\mathbf{u}_1 + \mathbf{u}_2, \mathbf{v}) = \det(\mathbf{u}_1, \mathbf{v}) + \det(\mathbf{u}_2, \mathbf{v}) \\ \det(\mathbf{u}, \mathbf{v}_1 + \mathbf{v}_2) = \det(\mathbf{u}, \mathbf{v}_1) + \det(\mathbf{u}, \mathbf{v}_2) \end{array} \right.$$

42.3 determinant theorems or properties

42.4 ellipse area

42.5 Cramer rule geometry perspective

Chapter 43

hypergeometric function

43.1 linear space of function

43.2 beta function

43.3 gamma function

43.4 recursion

43.5 mean and variance of discrete probability distributions

Chapter 44

Feynman method

44.1 Feynman method of derivative

44.2 Feynman method of integral

44.3 path integral

<https://www.youtube.com/watch?v=Sp5SvdDh2u8>

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

<https://www.youtube.com/watch?v=7yjv-gLHFqg>

Chapter 45

Hilbert space

45.1 Taylor expansion or Taylor series

Lemma 45.1. Newton-Leibniz formula = N-LF, equivalent to first mean value theorem for derivatives / Lagrange mean value theorem = MVTdL / MVTd1

牛頓-萊布尼茨公式 Newton-Leibniz formula = N-LF, equivalent to 第一微分均值定理 / 拉格朗日均值定理 first mean value theorem for derivatives / Lagrange mean value theorem = MVTdL / MVTd1 ??

$$\int_a^b f'(x) dx = f(b) - f(a) \quad (45.1)$$

$$\left\{ \begin{array}{ll} f : [a, b] \rightarrow \mathbb{R} & (0) \\ f \text{ continuous on } [a, b] & (1) \\ f \text{ differentiable on } (a, b) & (2) \\ f' : [a, b] \rightarrow \mathbb{R} & (4) \\ f' \text{ continuous on } [a, b] & (5) \end{array} \right. \quad a < b \quad (3) \Rightarrow \exists c \in (a, b) \left(f'(c) = \frac{\int_a^b f'(x) dx}{b-a} \right) \quad \text{MVTi1 ??}$$

$$\exists c \in (a, b) \{ f'(c)(b-a) = f(b) - f(a) \} \quad 45.1$$

$$\Rightarrow \quad \Updownarrow \quad \int_a^b f'(x) dx = f(b) - f(a) \quad 45.1$$

(↓):

$$\left\{ \begin{array}{ll} f : [a, b] \rightarrow \mathbb{R} & (0) \\ f \text{ continuous on } [a, b] & (1) \\ f \text{ differentiable on } (a, b) & (2) \\ [a, b] = [x_0, x_n] = [x_0, x_1] \cup [x_0, x_2] \cup \dots \cup [x_{n-1}, x_n] & \end{array} \right. \quad \stackrel{??}{\Rightarrow} \quad \exists c \in (a, b) \{ f'(c)(b-a) = f(b) - f(a) \} \quad \text{MVTd1 ??}$$

$$\stackrel{??}{\Rightarrow} \quad \int_a^b f'(x) dx = f(b) - f(a) \quad 45.2$$

(↑):

$$\left\{
 \begin{array}{l}
 \left\{
 \begin{array}{ll}
 f : [a, b] \rightarrow \mathbb{R} & (0) \\
 f \text{ continuous on } [a, b] & (1) \xrightarrow{\text{??}} \int_a^b f'(x) dx = f(b) - f(a)
 \end{array}
 \right. \quad \text{N-LF 45.1} \\
 \left\{
 \begin{array}{ll}
 f \text{ differentiable on } (a, b) & (2) \\
 f' : [a, b] \rightarrow \mathbb{R} & (4) \\
 f' \text{ continuous on } [a, b] & (5) \quad a < b \quad (3) \Rightarrow \exists c \in (a, b) \left(f'(c) = \frac{\int_a^b f'(x) dx}{b-a} \right) \quad \text{MVTi1 ??}
 \end{array}
 \right.
 \end{array}
 \right.$$

$\Rightarrow \exists c \in (a, b) \{f'(c)(b-a) = f(b) - f(a)\}$

Proof: (\Downarrow)

重疊端點分割 $[a, b]$ 成 n 部分聯集 ($n \in \mathbb{N}$)

$$[a, b] = [x_0, x_n] = [x_0, x_1] \cup [x_0, x_2] \cup \cdots \cup [x_{n-1}, x_n] \quad (45.2)$$

$$\left\{ \begin{array}{ll} f : [a, b] \rightarrow \mathbb{R} & (0) \\ f \text{ continuous on } [a, b] & (1) \xrightarrow{\text{??}} \exists c \in (a, b) \{ f'(c)(b-a) = f(b) - f(a) \} \quad \text{MVTd1 ??} \\ f \text{ differentiable on } (a, b) & (2) \\ [a, b] = [x_0, x_n] = [x_0, x_1] \cup [x_0, x_2] \cup \dots \cup [x_{n-1}, x_n] & \end{array} \right. \quad 45.2$$

$$\Rightarrow \left\{ \begin{array}{l} (f : [x_0, x_n] \rightarrow \mathbb{R}) = (f : [x_0, x_1] \cup [x_0, x_2] \cup \dots \cup [x_{n-1}, x_n] \rightarrow \mathbb{R}) \Leftarrow (0) \\ f \text{ continuous on } [x_0, x_1] \cup [x_0, x_2] \cup \dots \cup [x_{n-1}, x_n] \Leftarrow (1) \\ f \text{ differentiable on } (x_0, x_1) \cup [x_0, x_2] \cup \dots \cup [x_{n-1}, x_n] \Leftarrow (2) \end{array} \right.$$

$$\Rightarrow \left\{ \begin{array}{l} f : [x_0, x_1] \rightarrow \mathbb{R}, f : [x_0, x_2] \rightarrow \mathbb{R}, \dots, f : [x_{n-1}, x_n] \rightarrow \mathbb{R} \\ f \text{ continuous on } [x_0, x_1], [x_0, x_2], \dots, [x_{n-1}, x_n] \\ f \text{ differentiable on } (x_0, x_1), [x_0, x_2], \dots, [x_{n-1}, x_n] \Rightarrow f \text{ differentiable on } (x_0, x_1), (x_0, x_2), \dots, (x_{n-1}, x_n) \end{array} \right.$$

$$\xrightarrow{\text{??}} \left\{ \begin{array}{l} \exists c_1 \in (x_0, x_1) \{ f'(c_1)(x_1 - x_0) = f(x_1) - f(x_0) \} \\ \exists c_2 \in (x_1, x_2) \{ f'(c_2)(x_2 - x_1) = f(x_2) - f(x_1) \} \\ \vdots \\ \exists c_k \in (x_{k-1}, x_k) \{ f'(c_k)(x_k - x_{k-1}) = f(x_k) - f(x_{k-1}) \} \quad \forall k \in \mathbb{N} \cap [1, n] \\ \vdots \\ \exists c_n \in (x_{n-1}, x_n) \{ f'(c_n)(x_n - x_{n-1}) = f(x_n) - f(x_{n-1}) \} \end{array} \right.$$

$$\Rightarrow f'(c_k)(x_k - x_{k-1}) = f(x_k) - f(x_{k-1})$$

$$\Rightarrow \sum_k f'(c_k)(x_k - x_{k-1}) = \sum_k f(x_k) - f(x_{k-1})$$

$$\Rightarrow \sum_{k=1}^n f'(c_k)(x_k - x_{k-1}) = \sum_{k=1}^n f(x_k) - f(x_{k-1}) = [f(x_1) - f(x_0)] + [f(x_2) - f(x_1)] + \dots + [f(x_n) - f(x_{n-1})]$$

$$= f(x_n) - f(x_0) = f(b) - f(a) \Rightarrow \sum_{k=1}^n f'(c_k)(x_k - x_{k-1}) = f(b) - f(a) \xrightarrow{\Delta x_k = x_k - x_{k-1}} \sum_{k=1}^n f'(c_k) \Delta x_k = j$$

$$\Rightarrow \lim_{n \rightarrow \infty} \lim_{\Delta x_k = \frac{x_n - x_0}{n}} \sum_{k=1}^n f'(c_k) \Delta x_k = \lim_{n \rightarrow \infty} \lim_{\Delta x_k = \frac{b-a}{n} \rightarrow 0} f(b) - f(a) = f(b) - f(a)$$

$$\Rightarrow \int_a^b f'(x) dx = \int_{x_0}^{x_n} f'(x) dx = f(b) - f(a)$$

$$\Rightarrow \int_a^b f'(x) dx = f(b) - f(a)$$

$$\int_a^b f'(x) dx = f(b) - f(a)$$

得到 牛頓-萊布尼茨公式 Newton-Leibniz formula = N-LF [eq:N-LF]

□

Proof: (↑):

$$\begin{aligned}
& \left\{ \begin{array}{ll} f : [a, b] \rightarrow \mathbb{R} & (0) \\ f \text{ continuous on } [a, b] & (1) \end{array} \right. \xrightarrow[??]{??} \int_a^b f'(x) dx = f(b) - f(a) \quad \text{N-LF 45.1} \\
& \left\{ \begin{array}{ll} f \text{ differentiable on } (a, b) & (2) \end{array} \right. \\
& \left\{ \begin{array}{ll} f : [a, b] \rightarrow \mathbb{R} & a < b \ (3) \\ f \text{ continuous on } [a, b] & (1) \end{array} \right. \Rightarrow \exists c \in (a, b) \left(f(c) = \frac{\int_a^b f(x) dx}{b-a} \right) \quad \text{MVTi1 ??} \\
\Rightarrow & \left\{ \begin{array}{ll} f : [a, b] \rightarrow \mathbb{R} & (0) \\ f \text{ continuous on } [a, b] & (1) \end{array} \right. \xrightarrow[??]{??} \int_a^b f'(x) dx = f(b) - f(a) \quad \text{N-LF 45.1} \\
& \left\{ \begin{array}{ll} f \text{ differentiable on } (a, b) & (2) \end{array} \right. \\
& \left\{ \begin{array}{ll} f : [a, b] \rightarrow \mathbb{R} & a < b \ (3) \\ f \text{ continuous on } [a, b] & (1) \end{array} \right. \Rightarrow \exists c \in (a, b) \left\{ f(c)(b-a) = \int_a^b f(x) dx \right\} \quad \text{MVTi1 ??} \\
\Rightarrow & \left\{ \begin{array}{ll} f : [a, b] \rightarrow \mathbb{R} & (0) \\ f \text{ continuous on } [a, b] & (1) \end{array} \right. \xrightarrow[??]{??} \int_a^b f'(x) dx = f(b) - f(a) \quad \text{N-LF 45.1} \\
& \left\{ \begin{array}{ll} f \text{ differentiable on } (a, b) & (2) \end{array} \right. \\
& \left\{ \begin{array}{ll} \text{if } f' : [a, b] \rightarrow \mathbb{R} & (4) \\ \text{if } f' \text{ continuous on } [a, b] & (5) \end{array} \right. \Rightarrow \exists c \in (a, b) \left\{ f'(c)(b-a) = \int_a^b f'(x) dx \right\} \quad \text{MVTi1 ??} \\
\Rightarrow & \exists c \in (a, b) \left\{ f'(c)(b-a) = \int_a^b f'(x) dx = f(b) - f(a) \right\} \\
\Rightarrow & \exists c \in (a, b) \{ f'(c)(b-a) = f(b) - f(a) \} \\
\\
& \exists c \in (a, b) [f'(c)(b-a) = f(b) - f(a)]
\end{aligned}$$

得到 第一微分均值定理 / 拉格朗日均值定理 first mean value theorem for derivatives / Lagrange mean value theorem = MVTdL / MVTd1 [thm:MVTd1]

□

Lemma 45.2. *univariable product rule*

$$d(uv) = (du)v + u dv = v du + u dv$$

$$\frac{d(uv)}{dt} = v \frac{du}{dt} + u \frac{dv}{dt}$$

Lemma 45.3. *integration by parts*

$$\begin{aligned} \int \frac{d(uv)}{dt} dt &= \int v \frac{du}{dt} + u \frac{dv}{dt} dt \\ \int d(uv) &= \int v \frac{du}{dt} dt + \int u \frac{dv}{dt} dt \\ uv &= \int v du + \int u dv \\ \int u \frac{dv}{dt} dt &= uv - \int v \frac{du}{dt} dt \text{ "switching derivatives"} \end{aligned} \tag{45.3}$$

$$\int u dv = uv - \int v du \text{ "switching differentials"} \tag{45.4}$$

Theorem 45.1. *univariable Taylor theorem with the remainder in integral form*

$$f(x) = \sum_{k=0}^n \frac{f^{(k)}(a)}{k!} (x-a)^k + \int_a^x f^{(n+1)}(t) \frac{(t-x)^n}{n!} dt$$

Proof:

$$\frac{f(x) - f(a)}{\int_a^x f'(t) dt} = \int_a^x f'(t) \frac{d(t-x)}{dt} dt \stackrel{45.3}{=} [f'(t)(t-x)]_{t=a}^x - \int_a^x (t-x) \frac{df'(t)}{dt} dt \quad (45.5)$$

$$\stackrel{45.1}{=} \int_a^x f'(t) dt = \int_a^x f'(t) \frac{d(t-x)}{dt} dt \stackrel{45.3}{=} [f'(t)(t-x)]_{t=a}^x - \int_a^x (t-x) \frac{df'(t)}{dt} dt \quad (45.6)$$

$$= [-f'(a)(a-x)] - \int_a^x f''(t)(t-x) dt = f'(t)(x-a) - \int_a^x f''(t) \frac{d(t-x)^2}{dt} dt \quad (45.7)$$

$$= f'(a)(x-a) - \left(\left[f''(t) \frac{(t-x)^2}{2} \right]_{t=a}^x - \int_a^x \frac{(t-x)^2}{2} \frac{df''(t)}{dt} dt \right) \quad (45.8)$$

$$= f'(a)(x-a) - \left(\left[-f''(a) \frac{(x-a)^2}{2} \right] - \int_a^x f'''(t) \frac{(t-x)^2}{2} dt \right) \quad (45.9)$$

$$= f'(a)(x-a) + f''(a) \frac{(x-a)^2}{2} + \int_a^x f'''(t) \frac{(t-x)^2}{2} dt \quad (45.10)$$

$$= f'(a)(x-a) + f''(a) \frac{(x-a)^2}{2} + \int_a^x f'''(t) \frac{d\frac{(t-x)^3}{2 \cdot 3}}{dt} dt \quad (45.11)$$

$$= f'(a)(x-a) + f''(a) \frac{(x-a)^2}{2} + \left(\left[f'''(t) \frac{(t-x)^3}{2 \cdot 3} \right]_{t=a}^x - \int_a^x \frac{(t-x)^3}{2 \cdot 3} \frac{df'''(t)}{dt} dt \right) \quad (45.12)$$

$$= f'(a)(x-a) + f''(a) \frac{(x-a)^2}{2} + \left(\left[f'''(a) \frac{(x-a)^3}{2 \cdot 3} \right] - \int_a^x f^{(4)}(t) \frac{(t-x)^3}{2 \cdot 3} dt \right) \quad (45.13)$$

$$= f'(a)(x-a) + f''(a) \frac{(x-a)^2}{2} + f'''(t) \frac{(x-a)^3}{2 \cdot 3} - \int_a^x f^{(4)}(t) \frac{(t-x)^3}{2 \cdot 3} dt \quad (45.14)$$

$$= f'(a)(x-a) + f''(a) \frac{(x-a)^2}{2} + f'''(t) \frac{(x-a)^3}{2 \cdot 3} - \int_a^x f^{(4)}(t) \frac{d\frac{(t-x)^4}{2 \cdot 3 \cdot 4}}{dt} dt \quad (45.15)$$

$$= f'(a)(x-a) + f''(a) \frac{(x-a)^2}{2} + f'''(t) \frac{(x-a)^3}{2 \cdot 3} \quad (45.16)$$

$$- \left(\left[f^{(4)}(t) \frac{(t-x)^4}{2 \cdot 3 \cdot 4} \right]_{t=a}^x - \int_a^x \frac{(t-x)^4}{2 \cdot 3 \cdot 4} \frac{df^{(4)}(t)}{dt} dt \right) \quad (45.17)$$

$$= f'(t)(x-a) + f''(a) \frac{(x-a)^2}{2} + f'''(t) \frac{(x-a)^3}{2 \cdot 3} \quad (45.18)$$

$$- \left(\left[-f^{(4)}(a) \frac{(x-a)^4}{2 \cdot 3 \cdot 4} \right] - \int_a^x f^{(5)}(t) \frac{(t-x)^4}{2 \cdot 3 \cdot 4} dt \right) \quad (45.19)$$

$$= f'(t)(x-a) + f''(a) \frac{(x-a)^2}{2} + f'''(a) \frac{(x-a)^3}{2 \cdot 3} + f^{(4)}(a) \frac{(x-a)^4}{2 \cdot 3 \cdot 4} \quad (45.20)$$

$$\vdots + \int_a^x f^{(5)}(t) \frac{(t-x)^4}{2 \cdot 3 \cdot 4} dt \quad (45.21)$$

$$= \sum_{k=1}^n \frac{f^{(k)}(a)}{k!} (x-a)^k + \int_a^x f^{(n+1)}(t) \frac{(t-x)^n}{n!} dt \text{ remainder in integral form} \quad (45.22)$$

□

Theorem 45.2. univariable Taylor theorem with the remainder in Lagrange form

$$f(x) = \sum_{k=0}^n \frac{f^{(k)}(a)}{k!} (x-a)^k + \frac{f^{(n+1)}(\xi)}{(n+1)!} (x-a)^{n+1}$$

Proof:

by 連續函數 極值定理 / 最大最小值定理 / 最小最大值定理 continuous function extreme value theorem
 = CFEVT / extreme value theorem = EVT ?? and 連續函數 介值定理 / 中間值定理 continuous function intermediate value theorem = CFIVT / intermediate value theorem = IVT ??

$$\text{let } f(x) = \sum_{k=0}^n \frac{f^{(k)}(a)}{k!} (x-a)^k + r_n(x) \quad (45.23)$$

$$r_n(x) = \int_a^x f^{(n+1)}(t) \frac{(t-x)^n}{n!} dt \quad (45.24)$$

$$\text{let } n \in \{2k-1 | k \in \mathbb{N}\} \quad (45.25)$$

$$\text{let } f(t) \stackrel{??}{\in} [m, M] \subseteq f((a, x)) \text{ when } a < x \quad (45.26)$$

$$\int_a^x m \frac{(t-x)^n}{n!} dt \leq r_n(x) \leq \int_a^x M \frac{(t-x)^n}{n!} dt \quad (45.27)$$

$$m \int_a^x \frac{(t-x)^n}{n!} dt = M \int_a^x \frac{(t-x)^n}{n!} dt \quad (45.28)$$

$$m \left[\frac{(t-x)^{n+1}}{(n+1)!} \right]_{t=a}^x = M \left[\frac{(t-x)^{n+1}}{(n+1)!} \right]_{t=a}^x \quad (45.29)$$

$$m \frac{(x-a)^{n+1}}{(n+1)!} = M \frac{(x-a)^{n+1}}{(n+1)!} \quad (45.30)$$

$$\Downarrow \quad ?? \quad (45.31)$$

$$r_n(x) \stackrel{\exists \xi \in (a, x)}{=} f^{(n+1)}(\xi) \frac{(x-a)^{n+1}}{(n+1)!} \quad (45.32)$$

$$f(x) = \sum_{k=0}^n \frac{f^{(k)}(a)}{k!} (x-a)^k + f^{(n+1)}(\xi) \frac{(x-a)^{n+1}}{(n+1)!} \quad (45.33)$$

$$= \sum_{k=0}^n \frac{f^{(k)}(a)}{k!} (x-a)^k + \frac{f^{(n+1)}(\xi)}{(n+1)!} (x-a)^{n+1} \quad (45.34)$$

□

Theorem 45.3. univariable Taylor theorem with the remainder in big O form

$$f(a+h) = \sum_{k=0}^n \frac{f^{(k)}(a)}{k!} h^k + O(h^{n+1})$$

Proof:

$$\text{if } |f^{(n+1)}(t)| \leq K \forall t \in (a, x) \quad (45.35)$$

$$|r_n(x)| = \left| \frac{f^{(n+1)}(\xi)}{(n+1)!} (x-a)^{n+1} \right| \leq \frac{K}{(n+1)!} |x-a|^{n+1} \quad (45.36)$$

$$r_n(x) \in O((x-a)^{n+1}) \quad (45.37)$$

$$\text{let } R_n(h) = r_n(a+h) \quad (45.38)$$

$$R_n(h) \in O(h^{n+1}) \quad (45.39)$$

$$f(a+h) = \sum_{k=0}^n \frac{f^{(k)}(a)}{k!} h^k + \frac{f^{(n+1)}(\xi)}{(n+1)!} h^{n+1} \quad (45.40)$$

$$= \sum_{k=0}^n \frac{f^{(k)}(a)}{k!} h^k + O(h^{n+1}) \quad (45.41)$$

□

45.1.1 Elliot Schneider

<https://www.youtube.com/watch?v=HQsZG8Yxb7w>

<https://www.youtube.com/watch?v=HQsZG8Yxb7w&t=12m25s>

$$f(x) = \sum_{k=0}^n \frac{f^{(k)}(x_0)}{k!} (x-x_0)^k + \frac{f^{(n+1)}(\xi)}{(n+1)!} (x-x_0)^{n+1}$$

$$f(x_0 + \epsilon) = \sum_{k=0}^n \frac{f^{(k)}(x_0)}{k!} \epsilon^k + O(\epsilon^{n+1}), \epsilon = x - x_0$$

$$f(x + \epsilon) = \sum_{n=0}^{\infty} \frac{f^{(n)}(x)}{n!} \epsilon^n$$

$$\begin{aligned} f(x + \epsilon) &= \sum_{n=0}^{\infty} \frac{f^{(n)}(x)}{n!} \epsilon^n = \sum_{n=0}^{\infty} \frac{\frac{d^n}{dx^n} f(x)}{n!} \epsilon^n = \sum_{n=0}^{\infty} \frac{\left(\frac{d}{dx}\right)^n f(x)}{n!} \epsilon^n \\ &= \sum_{n=0}^{\infty} \frac{\left(\epsilon \frac{d}{dx}\right)^n f(x)}{n!} = \left(\sum_{n=0}^{\infty} \frac{\left(\epsilon \frac{d}{dx}\right)^n}{n!} \right) f(x) = e^{\epsilon \frac{d}{dx}} f(x) \end{aligned}$$

univariable Taylor operator

$$f(x + \epsilon) = e^{\epsilon \frac{d}{dx}} f(x)$$

$$e^{\epsilon \frac{d}{dx}} = \sum_{n=0}^{\infty} \frac{\left(\epsilon \frac{d}{dx}\right)^n}{n!} = 1 + \epsilon \frac{d}{dx} + \frac{1}{2} \epsilon^2 \frac{d^2}{dx^2} + \dots$$

$$f(x) = mx + b,$$

$$\begin{aligned} e^{\epsilon \frac{d}{dx}} f(x) &= \left(1 + \epsilon \frac{d}{dx} + \frac{1}{2} \epsilon^2 \frac{d^2}{dx^2} + \dots\right) (mx + b) \\ &= 1(mx + b) + \epsilon \frac{d}{dx}(mx + b) + \frac{1}{2} \epsilon^2 \frac{d^2}{dx^2}(mx + b) + \dots \\ &= (mx + b) + (\epsilon m) + \left(\frac{1}{2} \epsilon^2 0\right) + (0 + 0 + \dots) \\ &= (mx + b) + (\epsilon m) + (0 + 0 + \dots) \\ &= (mx + b) + (\epsilon m) + 0 \\ &= mx + b + m\epsilon = m(x + \epsilon) + b = f(x + \epsilon) \end{aligned}$$

<https://www.youtube.com/watch?v=HQsZG8Yxb7w&t=15m34s>

multivariable ...

$$\begin{aligned} f(x + \epsilon) &= e^{\epsilon \frac{d}{dx}} f(x) \\ f(x + \epsilon_x, y + \epsilon_y, z + \epsilon_z) &= f(x, y + \epsilon_y, z + \epsilon_z) \\ &\quad + \epsilon \frac{\partial}{\partial x} f(x, y + \epsilon_y, z + \epsilon_z) \\ &\quad + \frac{1}{2} \epsilon^2 \frac{\partial^2}{\partial x^2} f(x, y + \epsilon_y, z + \epsilon_z) \\ &\quad + \dots \end{aligned}$$

$$\begin{aligned} f(x + \epsilon) &= e^{\epsilon \frac{d}{dx}} f(x) \\ f(x + \epsilon_x, y + \epsilon_y, z + \epsilon_z) &= f(\mathbf{r} + \boldsymbol{\epsilon}) = e^{\boldsymbol{\epsilon} \cdot \nabla} f(\mathbf{r}), \quad \begin{cases} \mathbf{r} = (x, y, z) \\ \boldsymbol{\epsilon} = (\epsilon_x, \epsilon_y, \epsilon_z) \\ \nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right) \end{cases} \end{aligned}$$

$$\boldsymbol{\epsilon} \cdot \nabla = (\epsilon_x, \epsilon_y, \epsilon_z) \cdot \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right) = \epsilon_x \frac{\partial}{\partial x} + \epsilon_y \frac{\partial}{\partial y} + \epsilon_z \frac{\partial}{\partial z}$$

multivariable Taylor operator

$$f(\mathbf{r} + \boldsymbol{\epsilon}) = e^{\boldsymbol{\epsilon} \cdot \nabla} f(\mathbf{r})$$

<https://www.youtube.com/watch?v=HQsZG8Yxb7w&t=17m36s>

physics

45.1.1.1 making complicated equation simple

linearize

simple pendulum

$\sin(x)$ to x linearization

potential energy

$$f(x_0 + \epsilon) = \sum_{k=0}^n \frac{f^{(k)}(x_0)}{k!} \epsilon^k + O(\epsilon^{n+1})$$

$$U(x_0 + \epsilon) = \sum_{k=0}^n \frac{U^{(k)}(x_0)}{k!} \epsilon^k + O(\epsilon^{n+1}) = U(x_0) + U'(x_0)x + \frac{1}{2}U''(x_0)x^2 + \dots$$

$$F = \frac{-dU}{dx} = -U'(x_0) - U''(x_0)x - \dots \stackrel{\text{if } U'(x_0)=0}{=} -U''(x_0)x = -kx, k = U''(x_0)$$

45.1.1.2 non-relativistic limit

<https://www.youtube.com/watch?v=HQsZG8Yxb7w&t=22m32s>

$$\begin{aligned} E &= \sqrt{(mc^2)^2 + (pc)^2} = \sqrt{m^2c^4 + p^2c^2} \\ &= mc^2 \sqrt{1 + \left(\frac{pc}{mc^2}\right)^2} = mc^2 \sqrt{1 + \left(\frac{p}{mc}\right)^2} = mc^2 \left(1 + \left(\frac{p}{mc}\right)^2\right)^{\frac{1}{2}} \\ &= mc^2 \left[\frac{1}{0!} + \frac{1}{1!} \left(\frac{1}{2}\right) \left(\left(\frac{p}{mc}\right)^2\right)^1 + \frac{1}{2!} \left(\frac{1}{2}\right) \left(\frac{1}{2} - 1\right) \left(\left(\frac{p}{mc}\right)^2\right)^2 + \dots \right] \\ &= mc^2 \left[1 + \frac{1}{2} \left(\frac{p}{mc}\right)^2 - \frac{1}{8} \left(\frac{p}{mc}\right)^4 + \dots \right] = mc^2 \left[1 + \frac{1}{2} \frac{p^2}{m^2c^2} - \frac{1}{8} \frac{p^4}{m^4c^4} + \dots \right] \\ &= mc^2 + \frac{1}{2} \frac{p^2}{m} - \frac{1}{8} \frac{p^4}{m^3c^2} + \dots = mc^2 + \frac{p^2}{2m} - \frac{p^4}{8m^3c^2} + \dots \\ &= E_0 + \frac{p^2}{2m} - \frac{p^4}{8m^3c^2} + \dots, \quad \begin{cases} E_0 = mc^2 \\ \frac{p^2}{2m} = \frac{(mv)^2}{2m} = \frac{mv^2}{2} = \frac{1}{2}mv^2 \end{cases} \end{aligned}$$

slappy here $p = \gamma mv$ <https://www.youtube.com/watch?v=HQsZG8Yxb7w&t=24m50s>

leading relativistic correction

$$-\frac{p^4}{8m^3c^2}$$

binding energy of hydrogen atom

<https://www.youtube.com/watch?v=HQsZG8Yxb7w&t=25m40s>

fine-structure constant

45.1.1.3 quantum momentum operator

<https://www.youtube.com/watch?v=HQsZG8Yxb7w&t=29m13s>

45.2 Dirac delta function

45.3 Fourier expansion or Fourier series

45.4 Hilbert space

45.5 Dirac bracket

45.6 quantum operator

45.7 Gram-Schmidt algorithm to find orthonormal basis

45.8 Hermite polynomials and Legendre polynomials

Chapter 46

Lagrange inversion

Lagrange inversion theorem

拉格朗日反演

Chapter 47

quantum color dynamics

Chapter 48

Lagrangian

- Elliot Schneider: Physics with Elliot
 - Lagrangian fundamentals
 - Lagrangian mechanics

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<https://courses.physicswithelliot.com/products/fundamentals-of-lagrangian-mechanics/categories/2150492681/posts/2161912460>

<https://courses.physicswithelliot.com/products/fundamentals-of-lagrangian-mechanics/categories/2150492681/posts/2161912464>

Chapter 49

Hamiltonian

- Elliot Schneider: Physics with Elliot
 - Hamiltonian mechanics

Chapter 50

Fourier analysis

50.1 Simon Xu

50.1.1 DFT = discrete Fourier transform

50.1.2 FFT = fast Fourier transform

50.1.3 wavelet

Chapter 51

axiom of choice

51.1 Zorn lemma

Chapter 52

linear algebra

52.1 CCJou

https://www.youtube.com/playlist?list=PLP-JUp2VR1LsFtHT-i_vZ3oNFIAc3t_Ju

52.2 Chi, Chen-Yu

<https://www.youtube.com/playlist?list=PLJWAeYEa8SXBej3kuQMz8vV41VabZUILb>

Chapter 53

analysis

53.1 Chi, Chen-Yu

<https://www.youtube.com/playlist?list=PLVJXJebpO4PhAc21JW-cYbzT3sq4s7Qg8>

<https://www.youtube.com/playlist?list=PLil-R4o6jmGihq7XzdNzb0d5hHqEJbr6L>

https://www.youtube.com/playlist?list=PLil-R4o6jmGhUqtKbZf0LIFKd-xN_g_M

https://www.youtube.com/playlist?list=PLil-R4o6jmGhkuZPmKL_A5Y7N4HOsa1nX

53.2 Chen, Jin-Tzu

<https://www.youtube.com/playlist?list=PLil-R4o6jmGjoxAWZurHXAY0q9yxwXv5F>

Chapter 54

matrix calculus

13

$$\mathbf{x} = \langle x_1, x_2, \dots, x_n \rangle = [x_1 \ x_2 \ \dots \ x_n]^\top = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$$

$$f(x_1, x_2, \dots, x_n) = f(\langle x_1, x_2, \dots, x_n \rangle) = f(\mathbf{x})$$
$$\mathbf{y} = \langle y_1, y_2, \dots, y_m \rangle = [y_1 \ y_2 \ \dots \ y_m]^\top = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix}$$

54.1 vector-by-scalar

$$\frac{\partial \mathbf{y}}{\partial x} = \begin{bmatrix} \frac{\partial y_1}{\partial x} \\ \frac{\partial y_2}{\partial x} \\ \vdots \\ \frac{\partial y_m}{\partial x} \end{bmatrix}$$

54.2 scalar-by-vector

$$\nabla f = \frac{\partial}{\partial \mathbf{x}} f = \frac{\partial f}{\partial \mathbf{x}} = \left\langle \frac{\partial f}{\partial x_1}, \frac{\partial f}{\partial x_2}, \dots, \frac{\partial f}{\partial x_n} \right\rangle = \begin{bmatrix} \frac{\partial f}{\partial x_1} & \frac{\partial f}{\partial x_2} & \dots & \frac{\partial f}{\partial x_n} \end{bmatrix}^\top = \begin{bmatrix} \frac{\partial f}{\partial x_1} \\ \frac{\partial f}{\partial x_2} \\ \vdots \\ \frac{\partial f}{\partial x_n} \end{bmatrix}$$

$$f_i = f_i(x_1, x_2, \dots, x_n) = f_i(\mathbf{x})$$

$$\mathbf{f} = \langle f_1, f_2, \dots, f_m \rangle = [f_1 \ f_2 \ \dots \ f_m]^\top = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_m \end{bmatrix}$$

54.3 vector-by-vector

54.3.1 numerator-layout notation

分子布局

$$\frac{\partial \mathbf{y}}{\partial \mathbf{x}} = \begin{bmatrix} \frac{\partial y_1}{\partial \mathbf{x}} \\ \frac{\partial y_2}{\partial \mathbf{x}} \\ \vdots \\ \frac{\partial y_p}{\partial \mathbf{x}} \end{bmatrix} = \begin{bmatrix} \frac{\partial \mathbf{y}}{\partial x_1} & \frac{\partial \mathbf{y}}{\partial x_2} & \dots & \frac{\partial \mathbf{y}}{\partial x_n} \end{bmatrix} = \begin{bmatrix} \frac{\partial y_1}{\partial x_1} & \frac{\partial y_1}{\partial x_2} & \dots & \frac{\partial y_1}{\partial x_n} \\ \frac{\partial y_2}{\partial x_1} & \frac{\partial y_2}{\partial x_2} & \dots & \frac{\partial y_2}{\partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial y_m}{\partial x_1} & \frac{\partial y_m}{\partial x_2} & \dots & \frac{\partial y_m}{\partial x_n} \end{bmatrix} = \left[\frac{\partial y_i}{\partial x_j} \right]_{m \times n}$$

54.3.2 denominator-layout notation

分母布局

$$\frac{\partial \mathbf{y}}{\partial \mathbf{x}} = \begin{bmatrix} \frac{\partial \mathbf{y}}{\partial x_1} \\ \frac{\partial \mathbf{y}}{\partial x_2} \\ \vdots \\ \frac{\partial \mathbf{y}}{\partial x_n} \end{bmatrix} = \begin{bmatrix} \frac{\partial y_1}{\partial \mathbf{x}} & \frac{\partial y_2}{\partial \mathbf{x}} & \dots & \frac{\partial y_m}{\partial \mathbf{x}} \end{bmatrix} = \begin{bmatrix} \frac{\partial y_1}{\partial x_1} & \frac{\partial y_2}{\partial x_1} & \dots & \frac{\partial y_m}{\partial x_1} \\ \frac{\partial y_1}{\partial x_2} & \frac{\partial y_2}{\partial x_2} & \dots & \frac{\partial y_m}{\partial x_2} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial y_1}{\partial x_n} & \frac{\partial y_2}{\partial x_n} & \dots & \frac{\partial y_m}{\partial x_n} \end{bmatrix} = \left[\frac{\partial y_j}{\partial x_i} \right]_{n \times m}$$

Chapter 55

genetics

55.1 term

- chromosome
- locus (sl.) loci (pl.)
- marker
- allele
- haplotype
- genotype
- phenotype / trait
 - endophenotype

55.2 marker

- large marker: STRP = short tandem repeat polymorphism, STRs = short tandem repeats
 - linkage analysis
 - paternity testing
 - taxonomy
- small marker: SNP = single-nucleotide polymorphism
 - association analysis
 - disease diagnosis
 - pharmacodynamics? drug design / pharmacogenomics = custom drug
- RFLP = restriction fragment length polymorphism
- platform
 - customized: MALDI-TOF MS(= mass spectrometry)
 - whole-genome gene chip
 - * Affymetrix
 - Taiwan BioBank: TWB2.0
 - * Illumina
 - NGS = next-generation sequencing

55.3 genome project

- HGP = Human Genome Project
 - 20~25K genes

- 3 billion bps(base pairs)
- ELSI = ethical, legal, and social issues
- 99.9% bps are exactly the same in all people
- germline mutation
 - * male : female = 2 : 1
- HapMap = International HapMap Project
 - SNP, haplotype, tag SNP
 - * haplotypes are combination of SNPs
 - * tag SNPs can identify unique haplotypes
 - HapMap 1 & 2
 - * between-ancestry SNP: 1 common SNP per 5 Kb to 1 common SNP per 1 Kb
 - African
 - European
 - East Asian
 - Han Chinese
 - Japanese
 - HapMap 3: more ancestries
 - 1000 Genomes Project
 - NGS
 - identify 95% genetic variants with frequencies at least 1%
 - final phase 77M SNPs
 - browser
 - * Ensembl GRCh37
 - * Ensembl GRCh38 http://asia.ensembl.org/Homo_sapiens/Info/Index
 - TWB = Taiwan BioBank
 - browser: TaiwanView <https://taiwanview.twbiobank.org.tw/index>
 - pricing: https://www.biobank.org.tw/about_price.php
 - TPMI = Taiwan Precision Medicine Initiative <https://tpmi.ibms.sinica.edu.tw/www/precision-medicine/>

55.4 linkage analysis

- Mendel 1st & 2nd laws
 - law of segregation ~ 3 : 1
 - law of assortment ~ 9 : 3 : 3 : 1
- phenotypic model by R.A. Fisher
 -

$$P = G + E$$

- * G is the genotypic component
- * E is the environmental component

$$P = G + E + G \cdot E$$

- * $G \cdot E$ is the interaction between the genotypic component and environmental component
- linkage = co-segregation = cosegregation
 - θ = recombination fraction: 1% recombination = 1 crossover per 100 meioses = 1 cM(centiMorgan) on genetic map
- statistical hypothesis testing for linkage mapping
 - statistical hypothesis testing for categorical trait in linkage mapping: PLA = parametric linkage analysis
 - * H_0 : no linkage $\theta = 0.5$
 - * H_1 : linkage $\theta < 0.5$

- statistical hypothesis testing for quantitative trait in linkage mapping: VCLA = variance component linkage analysis
 - * H_0 : no linkage $\sigma_q^2 = 0$
 - * H_1 : linkage $\sigma_q^2 > 0$
- study design
 - case control
 - trio
 - affected / discordant sib-pair
 - extended pedigree
- data format: linkage format
 - family-based
 - * PID = pedigree Id
 - * IID = individual Id
 - * FID = father Id
 - * MID = mother Id
 - * gender
 - * affection
 - * marker
 - M1 = marker 1
 - M2 = marker 2
 - ...
- single major locus model
 - a two-allele A and a locus influences a dichotomous trait
 - allele frequency
 - * $p = P(A)$
 - * $q = P(a) = 1 - p$
 - penetrance
 - * $f_{AA} = P(\text{affected} \mid AA)$
 - * $f_{Aa} = P(\text{affected} \mid Aa) = f_{aA}$
 - * $f_{aa} = P(\text{affected} \mid aa)$
 - disease mode of inheritance
 - * dominant model
 - $\begin{cases} f_{AA} = 1 \\ f_{Aa} = 1 \\ f_{aa} = 0 \end{cases}$
 - * recessive model
 - $\begin{cases} f_{AA} = 0 \\ f_{Aa} = 0 \\ f_{aa} = 1 \end{cases}$
 - * additive model
 - $\begin{cases} f_{AA} = 1 \\ f_{Aa} = \frac{1}{2} \\ f_{aa} = 0 \end{cases}$
 - * phenocopy model
 - $f_{aa} > 0$ perhaps due to environmental cause
 - * liability model
 - e.g. f_{AA}, f_{Aa}, f_{aa} are age-dependent

55.4.1 PLA = parametric linkage analysis

- LOD score

55.4.2 VCLA = variance component linkage analysis

- allele-sharing: IBS and IBD
 - IBS = identity-by-state
 - IBD = identity-by-descent

55.5 association analysis

- LD = linkage disequilibrium
- genotype & allele frequency
 - diallelic marker
 - * p_{AA}
 - * p_{Aa}
 - * p_{aA}
 - * p_{aa}
 - * p_A
 - * p_a
- HWC = Hardy-Weinberg condition
 - HWE = Hardy-Weinberg equilibrium
 - HWD = Hardy-Weinberg disequilibrium
- gametic or haplotype frequency
 - LE = linkage equilibrium
 - LD = linkage disequilibrium

Chapter 56

multivariate normal distribution

Definition 56.1. probability density function (PDF) of normal distribution (= Gaussian distribution)

$$\mathcal{N}(x | \mu, \sigma^2) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\}$$

If a continuous random variable X follows a normal distribution with mean 0 and variance σ^2

$$\begin{aligned} X &\sim n(\mu, \sigma^2) = \mathcal{N}(\mu, \sigma^2) \\ \Leftrightarrow f_X(x) &= \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} = \frac{e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}}{\sigma\sqrt{2\pi}} = n(x | \mu, \sigma^2) \\ &= \frac{1}{\sqrt{2\pi}\sigma} \exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\} = \mathcal{N}(x | \mu, \sigma^2) \end{aligned}$$

A random variable X can be standardized by subtracting the mean μ and dividing by the standard deviation σ , resulting in the standardized random variable Z

$$Z = \frac{X - \mu}{\sigma} \text{ or } z = \frac{x - \mu}{\sigma}$$

The standardized random variable Z follows the standard normal distribution

$$\begin{aligned} Z &\sim n(0, 1^2) = \mathcal{N}(0, 1^2) \\ \Leftrightarrow f_Z(z) &= \frac{e^{-\frac{1}{2}\left(\frac{z-0}{1}\right)^2}}{1 \cdot \sqrt{2\pi}} = \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{z^2}{2}\right\} \\ &= n(z | 0, 1^2) = \mathcal{N}(z | 0, 1^2) \end{aligned}$$

To generalize from univariate random variables to multivariate random vectors, a random vector¹⁴

$$\mathbf{Z} = \langle Z_1, Z_2, \dots, Z_p \rangle = [Z_1 \ Z_2 \ \dots \ Z_p]^\top = \begin{bmatrix} Z_1 \\ Z_2 \\ \vdots \\ Z_p \end{bmatrix}$$

with p random variable components is said to follow the standard multivariate normal distribution if and only if its joint PDF is given by

$$f_{\mathbf{Z}}(\mathbf{z}) = \frac{1}{(2\pi)^{p/2}} \exp \left\{ -\frac{\mathbf{z}^T \mathbf{z}}{2} \right\} = \frac{1}{(2\pi)^{p/2}} \exp \left\{ -\frac{\mathbf{z} \cdot \mathbf{z}}{2} \right\} \quad (56.1)$$

(56.1) can be rewritten as the following

$$\begin{aligned} f_{\mathbf{Z}}(\mathbf{z}) &= \underbrace{\frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{2\pi}} \cdots \frac{1}{\sqrt{2\pi}}}_{p \text{ times}} \exp \left\{ -\frac{z_1^2}{2} - \frac{z_2^2}{2} - \cdots - \frac{z_p^2}{2} \right\} \\ &= \frac{1}{\sqrt{2\pi}} \exp \left\{ -\frac{z_1^2}{2} \right\} \frac{1}{\sqrt{2\pi}} \exp \left\{ -\frac{z_2^2}{2} \right\} \cdots \frac{1}{\sqrt{2\pi}} \exp \left\{ -\frac{z_p^2}{2} \right\} \\ &= f(z_1) f(z_2) \cdots f(z_p) \end{aligned}$$

where

$$f_{Z_i}(z_i) = \frac{1}{\sqrt{2\pi}} \exp \left\{ -\frac{z_i^2}{2} \right\} = f(z_i) \Rightarrow Z_i \sim \mathcal{N}(0, 1^2) = \text{n}(0, 1^2) \quad (56.2)$$

$$\begin{aligned} f_{Z_i}(z_i) &= \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} f_{\mathbf{Z}}(z_1, \dots, z_{i-1}, z_i, z_{i+1}, \dots, z_p) dz_1 \cdots dz_{i-1} dz_{i+1} \cdots dz_p \\ &= \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} f(z_1) \cdots f(z_{i-1}) f(z_i) f(z_{i+1}) \cdots f(z_p) dz_1 \cdots dz_{i-1} dz_{i+1} \cdots dz_p \\ &= f(z_i) \int_{-\infty}^{\infty} f(z_1) dz_1 \cdots \int_{-\infty}^{\infty} f(z_{i-1}) dz_{i-1} \int_{-\infty}^{\infty} f(z_{i+1}) dz_{i+1} \cdots \int_{-\infty}^{\infty} f(z_p) dz_p \\ &= f(z_i) \stackrel{(56.2)}{=} \frac{1}{\sqrt{2\pi}} \exp \left\{ -\frac{z_i^2}{2} \right\} \end{aligned}$$

Definition 56.2. covariance matrix of a random vector⁸

$$\text{C}[\mathbf{X}] = \text{Cov}[\mathbf{X}] = \text{V}[\mathbf{X}] = \mathbb{E}[(\mathbf{X} - \mathbb{E}(\mathbf{X}))(\mathbf{X} - \mathbb{E}(\mathbf{X}))^T]$$

$$\mathbf{X} = \langle X_1, X_2, \dots, X_p \rangle = [X_1 \ X_2 \ \cdots \ X_p]^T = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_p \end{bmatrix}$$

$$\mathbb{E}[\mathbf{X}] = \langle \mathbb{E}[X_1], \mathbb{E}[X_2], \dots, \mathbb{E}[X_p] \rangle = [\mathbb{E}[X_1] \ \mathbb{E}[X_2] \ \cdots \ \mathbb{E}[X_p]]^T = \begin{bmatrix} \mathbb{E}[X_1] \\ \mathbb{E}[X_2] \\ \vdots \\ \mathbb{E}[X_p] \end{bmatrix}$$

$$\mathbf{X} - \mathbb{E}[\mathbf{X}] = \begin{bmatrix} X_1 - \mathbb{E}[X_1] \\ X_2 - \mathbb{E}[X_2] \\ \vdots \\ X_p - \mathbb{E}[X_p] \end{bmatrix}$$

$$\begin{aligned}
& [\mathbf{X} - \mathbb{E}(\mathbf{X})] [\mathbf{X} - \mathbb{E}(\mathbf{X})]^\top \\
&= \begin{bmatrix} X_1 - \mathbb{E}[X_1] \\ X_2 - \mathbb{E}[X_2] \\ \vdots \\ X_p - \mathbb{E}[X_p] \end{bmatrix} \begin{bmatrix} X_1 - \mathbb{E}[X_1] & X_2 - \mathbb{E}[X_2] & \cdots & X_p - \mathbb{E}[X_p] \end{bmatrix} \\
&= \begin{bmatrix} (X_1 - \mathbb{E}[X_1])(X_1 - \mathbb{E}[X_1]) & (X_1 - \mathbb{E}[X_1])(X_2 - \mathbb{E}[X_2]) & \cdots & (X_1 - \mathbb{E}[X_1])(X_p - \mathbb{E}[X_p]) \\ (X_2 - \mathbb{E}[X_2])(X_1 - \mathbb{E}[X_1]) & (X_2 - \mathbb{E}[X_2])(X_2 - \mathbb{E}[X_2]) & \cdots & (X_2 - \mathbb{E}[X_2])(X_p - \mathbb{E}[X_p]) \\ \vdots & \vdots & \ddots & \vdots \\ (X_p - \mathbb{E}[X_p])(X_1 - \mathbb{E}[X_1]) & (X_p - \mathbb{E}[X_p])(X_2 - \mathbb{E}[X_2]) & \cdots & (X_p - \mathbb{E}[X_p])(X_p - \mathbb{E}[X_p]) \end{bmatrix} \\
&= \begin{bmatrix} (X_1 - \mathbb{E}[X_1])^2 & \cdots & (X_1 - \mathbb{E}[X_1])(X_p - \mathbb{E}[X_p]) \\ \vdots & \ddots & \vdots \\ (X_p - \mathbb{E}[X_p])(X_1 - \mathbb{E}[X_1]) & \cdots & (X_p - \mathbb{E}[X_p])^2 \end{bmatrix}
\end{aligned}$$

$$\mathbb{E} [[\mathbf{X} - \mathbb{E}(\mathbf{X})][\mathbf{X} - \mathbb{E}(\mathbf{X})]^T] \quad (56.3)$$

$$= \mathbb{E} \begin{bmatrix} (X_1 - \mathbb{E}[X_1])^2 & \cdots & (X_1 - \mathbb{E}[X_1])(X_p - \mathbb{E}[X_p]) \\ \vdots & \ddots & \vdots \\ (X_p - \mathbb{E}[X_p])(X_1 - \mathbb{E}[X_1]) & \cdots & (X_p - \mathbb{E}[X_p])^2 \end{bmatrix} \quad (56.4)$$

$$= \begin{bmatrix} \mathbb{E}[(X_1 - \mathbb{E}[X_1])^2] & \cdots & \mathbb{E}[(X_1 - \mathbb{E}[X_1])(X_p - \mathbb{E}[X_p])] \\ \vdots & \ddots & \vdots \\ \mathbb{E}[(X_p - \mathbb{E}[X_p])(X_1 - \mathbb{E}[X_1])] & \cdots & \mathbb{E}[(X_p - \mathbb{E}[X_p])^2] \end{bmatrix} \quad (56.5)$$

$$= \begin{bmatrix} V(X_1, X_1) & \cdots & V(X_1, X_p) \\ \vdots & \ddots & \vdots \\ V(X_p, X_1) & \cdots & V(X_p, X_p) \end{bmatrix} = \begin{bmatrix} V(X_1, X_1) & V(X_1, X_2) & \cdots & V(X_1, X_p) \\ V(X_2, X_1) & V(X_2, X_2) & \cdots & V(X_2, X_p) \\ \vdots & \vdots & \ddots & \vdots \\ V(X_p, X_1) & V(X_p, X_2) & \cdots & V(X_p, X_p) \end{bmatrix} \quad (56.6)$$

$$= \begin{bmatrix} V(X_1) & \cdots & V(X_1, X_p) \\ \vdots & \ddots & \vdots \\ V(X_p, X_1) & \cdots & V(X_p) \end{bmatrix} = \begin{bmatrix} V(X_1) & V(X_1, X_2) & \cdots & V(X_1, X_p) \\ V(X_2, X_1) & V(X_2) & \cdots & V(X_2, X_p) \\ \vdots & \vdots & \ddots & \vdots \\ V(X_p, X_1) & V(X_p, X_2) & \cdots & V(X_p) \end{bmatrix} \quad (56.7)$$

$$= \begin{bmatrix} V(X_1) & \cdots & C(X_1, X_p) \\ \vdots & \ddots & \vdots \\ C(X_p, X_1) & \cdots & V(X_p) \end{bmatrix} = \begin{bmatrix} V(X_1) & C(X_1, X_2) & \cdots & C(X_1, X_p) \\ C(X_2, X_1) & V(X_2) & \cdots & C(X_2, X_p) \\ \vdots & \vdots & \ddots & \vdots \\ C(X_p, X_1) & C(X_p, X_2) & \cdots & V(X_p) \end{bmatrix} \quad (56.8)$$

$$= \begin{bmatrix} \sigma_1^2 & \cdots & \sigma_{1p} \\ \sigma_{21} & \sigma_2^2 & \cdots & \sigma_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{p1} & \cdots & \sigma_p^2 \end{bmatrix} = \begin{bmatrix} \sigma_1^2 & \sigma_{12} & \cdots & \sigma_{1p} \\ \sigma_{21} & \sigma_2^2 & \cdots & \sigma_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{p1} & \sigma_{p2} & \cdots & \sigma_{pp} \end{bmatrix} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \cdots & \sigma_{1p} \\ \sigma_{21} & \sigma_{22} & \cdots & \sigma_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{p1} & \sigma_{p2} & \cdots & \sigma_{pp} \end{bmatrix} = [\sigma_{ij}]_{p \times p} = \Sigma \quad (56.9)$$

$$\mathbf{X} \sim \mathcal{D}(\boldsymbol{\mu}, \Sigma) = d(\boldsymbol{\mu}_{\mathbf{X}}, \Sigma_{\mathbf{X}}) = d(\mathbb{E}[\mathbf{X}], \mathbb{C}[\mathbf{X}]) = d(\mathbb{E}[\mathbf{X}], \mathbb{V}[\mathbf{X}])$$

$$\mathbf{Z} \sim \mathcal{N}(\boldsymbol{\mu}_{\mathbf{Z}}, \Sigma_{\mathbf{Z}}) = n(\mathbb{E}[\mathbf{Z}], \mathbb{V}[\mathbf{Z}])$$

$$\mathbb{E}[\mathbf{Z}] = \begin{bmatrix} \mathbb{E}[Z_1] \\ \mathbb{E}[Z_2] \\ \vdots \\ \mathbb{E}[Z_p] \end{bmatrix} = [\mathbb{E}[Z_i]]_{p \times 1}$$

$$\Rightarrow \mathbb{E}[Z_i] = \int_{-\infty}^{\infty} z_i f_{Z_i}(z_i) dz_i \stackrel{(56.2)}{=} \int_{-\infty}^{\infty} z_i \frac{e^{-\frac{1}{2}z_i^2}}{\sqrt{2\pi}} dz_i = 0$$

$$\Rightarrow \mathbb{E}[\mathbf{Z}] = \mathbf{0}$$

$$\Rightarrow \mathbf{Z} \sim \mathcal{N}(\boldsymbol{\mu}_{\mathbf{Z}} = \mathbf{0}, \Sigma_{\mathbf{Z}}) = n(\mathbf{0}, \mathbb{V}[\mathbf{Z}])$$

$$\mathbb{V}(Z_i) = \int_{-\infty}^{\infty} (z_i - \mu_{Z_i})^2 f_{Z_i}(z_i) dz_i \stackrel{(56.2)}{=} \int_{-\infty}^{\infty} (z_i - 0)^2 \frac{e^{-\frac{1}{2}z_i^2}}{\sqrt{2\pi}} dz_i = 1$$

$$\text{V}(Z_i, Z_j) \stackrel{i \neq j \Rightarrow Z_i, Z_j \text{ are independent}}{=} 0 \quad (56.10)$$

$$\begin{aligned} \text{V}[\mathbf{Z}] &= \begin{bmatrix} \text{V}(Z_1) & \text{V}(Z_1, Z_2) & \cdots & \text{V}(Z_1, Z_p) \\ \text{V}(Z_2, Z_1) & \text{V}(Z_2) & \cdots & \text{V}(Z_2, Z_p) \\ \vdots & \vdots & \ddots & \vdots \\ \text{V}(Z_p, Z_1) & \text{V}(Z_p, Z_2) & \cdots & \text{V}(Z_p) \end{bmatrix} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \cdots & \sigma_{1p} \\ \sigma_{21} & \sigma_{22} & \cdots & \sigma_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{p1} & \sigma_{p2} & \cdots & \sigma_{pp} \end{bmatrix} \\ &= \begin{bmatrix} \sigma_1^2 & \sigma_{12} & \cdots & \sigma_{1p} \\ \sigma_{21} & \sigma_2^2 & \cdots & \sigma_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{p1} & \sigma_{p2} & \cdots & \sigma_p^2 \end{bmatrix} \stackrel{56.10}{=} \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix} = I_{p \times p} = I_p = I \end{aligned}$$

$$\mathbf{Z} \sim \mathcal{N}(\boldsymbol{\mu}_{\mathbf{Z}}, \Sigma_{\mathbf{Z}}) = \text{n}(\text{E}[\mathbf{Z}], \text{V}[\mathbf{Z}]) = \mathcal{N}(\mathbf{0}, I) \Leftrightarrow \begin{cases} \boldsymbol{\mu}_{\mathbf{Z}} = \text{E}[\mathbf{Z}] = \mathbf{0} = [0]_p = [0]_{p \times 1} \\ \Sigma_{\mathbf{Z}} = \text{V}[\mathbf{Z}] = I = I_p = I_{p \times p} \end{cases}$$

$$\begin{aligned} \mathbf{Z} &= \begin{bmatrix} Z_1 \\ Z_2 \\ \vdots \\ Z_p \end{bmatrix} = \begin{bmatrix} \frac{X_1 - \mu_1}{\sigma_1} \\ \frac{X_2 - \mu_2}{\sigma_2} \\ \vdots \\ \frac{X_p - \mu_p}{\sigma_p} \end{bmatrix} = \begin{bmatrix} \frac{1}{\sigma_1} & 0 & \cdots & 0 \\ 0 & \frac{1}{\sigma_2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \frac{1}{\sigma_p} \end{bmatrix} \begin{bmatrix} X_1 - \mu_1 \\ X_2 - \mu_2 \\ \vdots \\ X_p - \mu_p \end{bmatrix} \\ &= \begin{bmatrix} \frac{1}{\sigma_1} & 0 & \cdots & 0 \\ 0 & \frac{1}{\sigma_2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \frac{1}{\sigma_p} \end{bmatrix} \left(\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_p \end{bmatrix} - \begin{bmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_p \end{bmatrix} \right) = B^{-1}(\mathbf{X} - \boldsymbol{\mu}) \end{aligned}$$

$$\Rightarrow \mathbf{X} = B\mathbf{Z} + \boldsymbol{\mu}$$

$$\mathbf{X} = B\mathbf{Z} + \boldsymbol{\mu} = T(\mathbf{Z})$$

by $\text{V}[A\mathbf{X} + \mathbf{b}] = A\text{V}[\mathbf{X}]A^{\top}$

$$\Sigma = \Sigma_{\mathbf{X}} = \text{V}[\mathbf{X}] = \text{V}[B\mathbf{Z} + \boldsymbol{\mu}] = B\text{V}[\mathbf{Z}]B^{\top} = BIB^{\top} = BB^{\top} \quad (56.11)$$

Consider two infinitesimal volumes of p -dimensional parallelepipeds in the different \mathbb{R}^p spaces¹⁵

$$V_{\mathbf{x}} = [x_1, x_1 + dx_1] \times [x_2, x_2 + dx_2] \times \cdots \times [x_p, x_p + dx_p]$$

and

$$V_{\mathbf{z}} = [z_1, z_1 + dz_1] \times [z_2, z_2 + dz_2] \times \cdots \times [z_p, z_p + dz_p]$$

Their relationship under linear transformation is

$$\begin{aligned} V_{\mathbf{x}} = T(V_{\mathbf{z}}) &= [T(z_1), T(z_1) + T(dz_1)] \\ &\quad \times [T(z_2), T(z_2) + T(dz_2)] \\ &\quad \times \dots \\ &\quad \times [T(z_p), T(z_p) + T(dz_p)] \end{aligned}$$

and

$$dx_i = \sum_j \frac{\partial x_i}{\partial z_j} dz_j$$

For examples in 2 dimension,

$$\begin{bmatrix} dx_1 \\ dx_2 \end{bmatrix} = \begin{bmatrix} \frac{\partial x_1}{\partial z_1} & \frac{\partial x_1}{\partial z_2} \\ \frac{\partial x_2}{\partial z_1} & \frac{\partial x_2}{\partial z_2} \end{bmatrix} \begin{bmatrix} dz_1 \\ dz_2 \end{bmatrix}$$

Two element infinitesimal one-directional vectors of \mathbf{Z} transformed into another space of \mathbf{X} are

$$T(dz_1) = \begin{bmatrix} \frac{\partial x_1}{\partial z_1} & \frac{\partial x_1}{\partial z_2} \\ \frac{\partial x_2}{\partial z_1} & \frac{\partial x_2}{\partial z_2} \end{bmatrix} \begin{bmatrix} dz_1 \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{\partial x_1}{\partial z_1} dz_1 \\ \frac{\partial x_2}{\partial z_1} dz_1 \end{bmatrix}$$

and

$$T(dz_2) = \begin{bmatrix} \frac{\partial x_1}{\partial z_1} & \frac{\partial x_1}{\partial z_2} \\ \frac{\partial x_2}{\partial z_2} & \frac{\partial x_2}{\partial z_2} \end{bmatrix} \begin{bmatrix} 0 \\ dz_2 \end{bmatrix} = \begin{bmatrix} \frac{\partial x_1}{\partial z_2} dz_2 \\ \frac{\partial x_2}{\partial z_2} dz_2 \end{bmatrix}$$

Their corresponding area(volume) in the space of \mathbf{X} is

$$\begin{aligned} \int_{A_{\mathbf{x}}} dA_{\mathbf{x}} &= \int_{A_{\mathbf{x}}} dx_1 dx_2 = \int_{T(A_{\mathbf{z}})} dx_1 dx_2 \\ &= \int_{A_{\mathbf{z}}} |[T(dz_1) \quad T(dz_2)]| = \int_{A_{\mathbf{z}}} \left| \begin{array}{cc} \frac{\partial x_1}{\partial z_1} dz_1 & \frac{\partial x_1}{\partial z_2} dz_2 \\ \frac{\partial x_2}{\partial z_1} dz_1 & \frac{\partial x_2}{\partial z_2} dz_2 \end{array} \right| \\ &= \int_{A_{\mathbf{z}}} \left| \begin{array}{cc} \frac{\partial x_1}{\partial z_1} & \frac{\partial x_1}{\partial z_2} \\ \frac{\partial x_2}{\partial z_1} & \frac{\partial x_2}{\partial z_2} \end{array} \right| dz_1 dz_2 = \int_{A_{\mathbf{z}}} |J| dA_{\mathbf{z}} \end{aligned}$$

To generalize for volumes in p dimension,

$$\begin{aligned}
\int_{V_x} dV_x &= \int_{V_x} dx_1 dx_2 \cdots dx_p = \int_{T(V_z)} dx_1 dx_2 \cdots dx_p \\
&= \int_{A_z} \left| \begin{bmatrix} T(dx_1) & T(dx_2) & \cdots & T(dx_p) \end{bmatrix} \right| = \int_{V_z} \left| \begin{bmatrix} \frac{\partial x_i}{\partial z_j} dz_j \end{bmatrix}_{p \times p} \right| \\
&= \int_{V_z} \left| \begin{bmatrix} \frac{\partial x_i}{\partial z_j} \end{bmatrix}_{p \times p} \right| dz_1 dz_2 \cdots dz_p = \int_{V_z} |J| dV_z
\end{aligned}$$

i.e.

$$\int_{V_x} dV_x = \int_{V_z} |J| dV_z \quad (56.12)$$

where J is a Jacobian matrix

$$J = \left[\frac{\partial x_i}{\partial z_j} \right]_{p \times p} = \frac{\partial \mathbf{x}}{\partial \mathbf{z}}$$

or $|J|$ is a Jacobian determinant or simply Jacobian

$$|J| = \left| \frac{\partial x_i}{\partial z_j} \right|_{p \times p} = \left| \frac{\partial \mathbf{x}}{\partial \mathbf{z}} \right|$$

The probability of the same event should be invariant under transformation.

$$\begin{aligned}
\int_{V_x} f_{\mathbf{X}}(\mathbf{x}) dV_x &= \int_{V_x} f_{\mathbf{X}}(\mathbf{x}) dx_1 dx_2 \cdots dx_p \\
&= \int_{T(V_z)} f_{\mathbf{X}}(\mathbf{x}) dx_1 dx_2 \cdots dx_p \\
&= \int_{V_z} f_{\mathbf{Z}}(\mathbf{z}) dV_z = \int_{V_z} f_{\mathbf{Z}}(\mathbf{z}) dz_1 dz_2 \cdots dz_p
\end{aligned}$$

i.e.

$$\int_{V_x} f_{\mathbf{X}}(\mathbf{x}) dV_x = \int_{V_z} f_{\mathbf{Z}}(\mathbf{z}) dV_z \quad (56.13)$$

$$\begin{cases} \int_{V_x} f_{\mathbf{X}}(\mathbf{x}) dV_x = \int_{V_z} f_{\mathbf{Z}}(\mathbf{z}) dV_z & 56.13 \\ \int_{V_x} dV_x = \int_{V_z} |J| dV_z & 56.12 \end{cases}$$

$$\mathbf{Z} = B^{-1}(\mathbf{X} - \boldsymbol{\mu}) \quad (56.14)$$

$$\mathbf{z} = B^{-1}(\mathbf{x} - \boldsymbol{\mu})$$

$$\mathbf{X} = B\mathbf{Z} + \boldsymbol{\mu}$$

$$\mathbf{x} = B\mathbf{z} + \boldsymbol{\mu}$$

$$J = \left[\frac{\partial x_i}{\partial z_j} \right]_{p \times p} = \frac{\partial \mathbf{x}}{\partial \mathbf{z}} = B \quad (56.15)$$

$$|J| = \left| \frac{\partial x_i}{\partial z_j} \right|_{p \times p} = \left| \frac{\partial \mathbf{x}}{\partial \mathbf{z}} \right| = |B|$$

$$\begin{aligned} & \int_{V_z} f_{\mathbf{Z}}(\mathbf{z}) dV_z \stackrel{56.13}{=} \int_{V_x} f_{\mathbf{X}}(\mathbf{x}) dV_x = \int_{V_x} dV_x f_{\mathbf{X}}(\mathbf{x}) \\ & \stackrel{56.12}{=} \int_{V_z} |J| dV_z f_{\mathbf{X}}(\mathbf{x}(\mathbf{z})) = \int_{V_z} f_{\mathbf{X}}(\mathbf{x}(\mathbf{z})) |J| dV_z \\ & f_{\mathbf{Z}}(\mathbf{z}) \stackrel{\Downarrow}{=} f_{\mathbf{X}}(\mathbf{x}(\mathbf{z})) |J| \\ & f_{\mathbf{X}}(\mathbf{x}(\mathbf{z})) \stackrel{\Downarrow}{=} |J|^{-1} f_{\mathbf{Z}}(\mathbf{z}) \stackrel{56.1}{=} |J|^{-1} \frac{1}{(2\pi)^{p/2}} \exp \left\{ \frac{-\mathbf{z}^\top \mathbf{z}}{2} \right\} \\ & f_{\mathbf{X}}(\mathbf{x}) \stackrel{\Downarrow}{=} |J|^{-1} f_{\mathbf{Z}}(\mathbf{z}(\mathbf{x})) \stackrel{56.15, 56.14}{=} |B|^{-1} f_{\mathbf{Z}}(B^{-1}(\mathbf{x} - \boldsymbol{\mu})) \\ & = |B|^{-1} (2\pi)^{-p/2} \exp \left\{ \frac{-1}{2} [B^{-1}(\mathbf{x} - \boldsymbol{\mu})]^\top [B^{-1}(\mathbf{x} - \boldsymbol{\mu})] \right\} \\ & = |B|^{-1/2} |B|^{-1/2} (2\pi)^{-p/2} \exp \left\{ \frac{-1}{2} (\mathbf{x} - \boldsymbol{\mu})^\top (B^{-1})^\top B^{-1} (\mathbf{x} - \boldsymbol{\mu}) \right\} \\ & = |B|^{-1/2} |B^\top|^{-1/2} (2\pi)^{-p/2} \exp \left\{ \frac{-1}{2} (\mathbf{x} - \boldsymbol{\mu})^\top (B^\top)^{-1} B^{-1} (\mathbf{x} - \boldsymbol{\mu}) \right\} \\ & = |BB^\top|^{-1/2} (2\pi)^{-p/2} \exp \left\{ \frac{-1}{2} (\mathbf{x} - \boldsymbol{\mu})^\top (BB^\top)^{-1} (\mathbf{x} - \boldsymbol{\mu}) \right\} \\ & \stackrel{56.11}{=} |\Sigma|^{-1/2} (2\pi)^{-p/2} \exp \left\{ \frac{-1}{2} (\mathbf{x} - \boldsymbol{\mu})^\top \Sigma^{-1} (\mathbf{x} - \boldsymbol{\mu}) \right\} \\ & = (|\Sigma| (2\pi)^p)^{-1/2} \exp \left\{ \frac{-1}{2} (\mathbf{x} - \boldsymbol{\mu})^\top \Sigma^{-1} (\mathbf{x} - \boldsymbol{\mu}) \right\} \end{aligned}$$

Definition 56.3. probability density function (PDF) of multivariate normal distribution (= multivariate Gaussian distribution)

$$\mathcal{N}(\mathbf{x} | \boldsymbol{\mu}, \Sigma) = f_{\mathbf{X}}(\mathbf{x}) = (|\Sigma| (2\pi)^p)^{-1/2} \exp \left\{ \frac{-1}{2} (\mathbf{x} - \boldsymbol{\mu})^\top \Sigma^{-1} (\mathbf{x} - \boldsymbol{\mu}) \right\}$$

Definition 56.4. correlation coefficient

$$\rho_{ij} = \frac{\sigma_{ij}}{\sqrt{\sigma_{ii}} \sqrt{\sigma_{jj}}} = \frac{\sigma_{ij}}{\sqrt{\sigma_i^2} \sqrt{\sigma_j^2}} = \frac{\sigma_{ij}}{\sigma_i \sigma_j} = \frac{\text{V}(X_i, X_j)}{\sqrt{\text{V}(X_i)} \sqrt{\text{V}(X_j)}} = \text{R}(X_i, X_j)$$

56.1 bivariate normal distribution

$p = 2$ is the case of bivariate normal distribution

$$\Sigma = [\sigma_{ij}]_{2 \times 2} = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{bmatrix} = \begin{bmatrix} \sigma_1^2 & \sigma_{12} \\ \sigma_{21} & \sigma_2^2 \end{bmatrix} = \begin{bmatrix} \sigma_1^2 & \sigma_1\sigma_2\rho_{12} \\ \sigma_2\sigma_1\rho_{21} & \sigma_2^2 \end{bmatrix} = \begin{bmatrix} \sigma_1^2 & \sigma_1\sigma_2\rho \\ \sigma_2\sigma_1\rho & \sigma_2^2 \end{bmatrix}$$

$$\rho_{12} = \rho = \rho_{21}$$

$$|\Sigma| = \begin{vmatrix} \sigma_1^2 & \sigma_1\sigma_2\rho_{12} \\ \sigma_2\sigma_1\rho_{21} & \sigma_2^2 \end{vmatrix} = \sigma_1^2\sigma_2^2(1 - \rho_{12}\rho_{21}) = \sigma_1^2\sigma_2^2(1 - \rho^2)$$

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix}^{-1} = \frac{1}{|a - b|} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix}$$

$$\begin{aligned} \Sigma^{-1} &= \frac{1}{|\Sigma|} \begin{bmatrix} \sigma_2^2 & -\sigma_1\sigma_2\rho \\ -\sigma_2\sigma_1\rho & \sigma_1^2 \end{bmatrix} \\ &= \frac{1}{\sigma_1^2\sigma_2^2(1 - \rho^2)} \begin{bmatrix} \sigma_2^2 & -\sigma_1\sigma_2\rho \\ -\sigma_2\sigma_1\rho & \sigma_1^2 \end{bmatrix} \\ &= \frac{1}{(1 - \rho^2)} \begin{bmatrix} \frac{1}{\sigma_2^2} & \frac{-\rho}{\sigma_1\sigma_2} \\ \frac{-\rho}{\sigma_2\sigma_1} & \frac{1}{\sigma_2^2} \end{bmatrix} \end{aligned}$$

$$\begin{aligned} \mathcal{N} \left(\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \middle| \boldsymbol{\mu} = \begin{bmatrix} \mu_1 \\ \mu_2 \end{bmatrix}, \Sigma = \begin{bmatrix} \sigma_1^2 & \sigma_1\sigma_2\rho \\ \sigma_2\sigma_1\rho & \sigma_2^2 \end{bmatrix} \right) \\ = \left(|\Sigma| (2\pi)^{p=2} \right)^{-1/2} \exp \left\{ \frac{-1}{2} (\mathbf{x} - \boldsymbol{\mu})^\top \Sigma^{-1} (\mathbf{x} - \boldsymbol{\mu}) \right\} \\ = \left(\sigma_1^2\sigma_2^2(1 - \rho^2)(2\pi)^2 \right)^{-1/2} \exp \left\{ \frac{-1}{2} \begin{bmatrix} x_1 - \mu_1 \\ x_2 - \mu_2 \end{bmatrix}^\top \Sigma^{-1} \begin{bmatrix} x_1 - \mu_1 \\ x_2 - \mu_2 \end{bmatrix} \right\} \\ = \frac{1}{2\pi\sigma_1\sigma_2\sqrt{1 - \rho^2}} \exp \left\{ \frac{-1}{2} \begin{bmatrix} x_1 - \mu_1 \\ x_2 - \mu_2 \end{bmatrix}^\top \frac{1}{(1 - \rho^2)} \begin{bmatrix} \frac{1}{\sigma_2^2} & \frac{-\rho}{\sigma_1\sigma_2} \\ \frac{-\rho}{\sigma_2\sigma_1} & \frac{1}{\sigma_2^2} \end{bmatrix} \begin{bmatrix} x_1 - \mu_1 \\ x_2 - \mu_2 \end{bmatrix} \right\} \\ = \frac{1}{2\pi\sigma_1\sigma_2\sqrt{1 - \rho^2}} \exp \left\{ \frac{-1}{2(1 - \rho^2)} \begin{bmatrix} x_1 - \mu_1 \\ x_2 - \mu_2 \end{bmatrix}^\top \begin{bmatrix} \frac{1}{\sigma_1^2} & \frac{-\rho}{\sigma_1\sigma_2} \\ \frac{-\rho}{\sigma_2\sigma_1} & \frac{1}{\sigma_2^2} \end{bmatrix} \begin{bmatrix} x_1 - \mu_1 \\ x_2 - \mu_2 \end{bmatrix} \right\} \\ = \frac{1}{2\pi\sigma_1\sigma_2\sqrt{1 - \rho^2}} \exp \left\{ \frac{-1}{2(1 - \rho^2)} \left[\left(\frac{x_1 - \mu_1}{\sigma_1} \right)^2 - 2\rho \left(\frac{x_1 - \mu_1}{\sigma_1} \right) \left(\frac{x_2 - \mu_2}{\sigma_2} \right) + \left(\frac{x_2 - \mu_2}{\sigma_2} \right)^2 \right] \right\} \end{aligned}$$

Definition 56.5. probability density function (PDF) of bivariate normal distribution (= bivariate Gaussian distribution)

$$\begin{aligned}\mathcal{N} \left(\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \middle| \begin{bmatrix} \mu_1 \\ \mu_2 \end{bmatrix}, \begin{bmatrix} \sigma_1^2 & \sigma_1\sigma_2\rho \\ \sigma_2\sigma_1\rho & \sigma_2^2 \end{bmatrix} \right) \\ = \frac{1}{2\pi\sigma_1\sigma_2\sqrt{1-\rho^2}} \exp \left\{ \frac{-1}{2(1-\rho^2)} \left[\left(\frac{x_1 - \mu_1}{\sigma_1} \right)^2 - 2\rho \left(\frac{x_1 - \mu_1}{\sigma_1} \right) \left(\frac{x_2 - \mu_2}{\sigma_2} \right) + \left(\frac{x_2 - \mu_2}{\sigma_2} \right)^2 \right] \right\}\end{aligned}$$

Chapter 57

logic

57.1 Shai Ben-David

<https://www.youtube.com/playlist?list=PLPW2keNyw-utXOOzLR-Wp1p0eE5LEtv3N>

Chapter 58

algorithm

58.1 Chen, Vivian

<https://www.youtube.com/playlist?list=PLTpF-A8hKVUMcBaEuGyWbBXBn21seO3vA>

58.2 The Bubble Sort Curve

https://www.youtube.com/watch?v=Gm8v_MR7TGk

<https://linesthatconnect.github.io/blog/a-rigorous-derivation-of-the-bubble-sort-curve/>

Chapter 59

computer graphics

59.1 Cem Yuksel

https://www.youtube.com/playlist?list=PLplnkTzzqsZTfYh4UbhLGpI5kGd5oW_Hh

<https://www.youtube.com/playlist?list=PLplnkTzzqsZS3R5DjmCQsqupu43oS9CFN>

Chapter 60

autoregression in time series

張翔老師. 2015. “ARMA Part1.” <https://www.youtube.com/watch?v=G-0dR57W-fo>.

張翔老師. 2015. “ARMA Part2.” <https://www.youtube.com/watch?v=fQaZzO7E6FE>.

張翔老師. 2015. “ARMA Part3.” <https://www.youtube.com/watch?v=Ocw4NXoO8Xo>.
time series [data]

$$\dots, Y_{t-2}, Y_{t-1}, Y_t, Y_{t+1}, Y_{t+2}, \dots$$

- lag
 - 1st lag = lag 1

$$Y_{t-1}$$

- k^{th} lag = lag k

$$Y_{t-k}$$

1st difference

$$\Delta Y_t = Y_t - Y_{t-1}$$

approximation for RoR = rate of return

$$\begin{aligned}\Delta \ln Y_t &= \ln Y_t - \ln Y_{t-1} = \ln \frac{Y_t}{Y_{t-1}} = \ln \left(1 + \frac{Y_t - Y_{t-1}}{Y_{t-1}} \right) \\ &= \frac{Y_t - Y_{t-1}}{Y_{t-1}} + O\left(\left(\frac{Y_t - Y_{t-1}}{Y_{t-1}}\right)^2\right) \\ &\approx \frac{Y_t - Y_{t-1}}{Y_{t-1}} = \text{RoR}\end{aligned}$$

$$\begin{cases} \ln(1+x) = \sum_{n=1}^{\infty} (-1)^{n+1} \frac{x^n}{n} = x - \frac{x^2}{2} + \frac{x^3}{3} - \dots \\ \ln(1-x) = - \sum_{n=1}^{\infty} \frac{x^n}{n} = -x - \frac{x^2}{2} - \frac{x^3}{3} - \dots \end{cases}$$

$$\begin{aligned}\frac{1}{1+t} &= 1 - t + t^2 - t^3 + \dots \\ \ln(1+x) &= \int_0^x \frac{1}{1+t} dt \\ &= x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \dots\end{aligned}$$

Definition 60.1. autocorrelation = serial correlation

$$\exists t_1 \neq t_2 [V(Y_{t_1}, Y_{t_2}) \neq 0]$$

$$\begin{cases} E(Y_t) \triangleq \mu_t \\ V(Y_t) \triangleq \sigma_t^2 \end{cases}$$

Definition 60.2. k^{th} order autocovariance

$$V(Y_t, Y_{t-k}) \triangleq \gamma(t, k)$$

$$\sigma_t^2 \triangleq V(Y_t) = V(Y_t, Y_t) = V(Y_t, Y_{t-0}) = \gamma(t, k=0) = \gamma(t, 0)$$

Definition 60.3. k^{th} order autocorrelation

$$\rho_{t,t-k} = \frac{\sigma_{t,t-k}}{\sqrt{\sigma_{tt}}\sqrt{\sigma_{t-k,t-k}}} = \frac{\sigma_{t,t-k}}{\sqrt{\sigma_t^2}\sqrt{\sigma_{t-k}^2}} = \frac{\sigma_{t,t-k}}{\sigma_t \sigma_{t-k}} = \frac{V(Y_t, Y_{t-k})}{\sqrt{V(Y_t)}\sqrt{V(Y_{t-k})}} \triangleq R(Y_t, Y_{t-k}) \triangleq \rho(t, k)$$

Definition 60.4. stationary time series

$$\begin{cases} E(Y_t) \triangleq \mu_t = \mu & (1) \text{ independent of } t \\ V(Y_t) \triangleq \sigma_t^2 = \sigma^2 < \infty & (2) \text{ independent of } t \\ V(Y_t, Y_{t-k}) \triangleq \gamma(t, k) = \gamma(k) & (3) \text{ independent of } t \end{cases}$$

properties

$$\begin{cases} V(Y_t) \triangleq \sigma_t^2 = \gamma(t, k=0) = \gamma(k=0) \stackrel{(3)}{=} \gamma(0) \stackrel{(2)}{=} \sigma^2 & (4) \Rightarrow V(Y_{t-k}) = \gamma(0) \\ R(Y_t, Y_{t-k}) \triangleq \rho(t, k) \triangleq \frac{V(Y_t, Y_{t-k})}{\sqrt{V(Y_t)}\sqrt{V(Y_{t-k})}} \\ = \frac{\gamma(t, k)}{\sqrt{\gamma(0)}\sqrt{\gamma(0)}} \stackrel{(3)}{=} \frac{\gamma(k)}{\gamma(0)} \stackrel{(4)}{=} \frac{\gamma_k}{\gamma_0} \triangleq \rho(k) \triangleq \rho_k & (5) \\ \gamma(k) = \gamma(-k) & (6) \Rightarrow \rho(k) = \rho(-k) \end{cases}$$

$$\gamma(k) \stackrel{(3)}{=} V(Y_t, Y_{t-k}) = V(Y_{t-k}, Y_t) = V(Y_{t'}, Y_{t'+k}) = V(Y_{t'}, Y_{t'-(k)}) \stackrel{(3)}{=} \gamma(-k) \Rightarrow (6)$$

point estimation

$$\left\{ \begin{array}{l} \widehat{\mathbb{E}}(Y_t) \triangleq \bar{Y} \triangleq \widehat{\mu} = \frac{1}{T} \sum_{t=1}^T Y_t \\ \widehat{\text{V}}(Y_t) \triangleq \widehat{\gamma}_0 = \frac{1}{T} \sum_{t=1}^T (Y_t - \bar{Y})^2 \\ \widehat{\text{V}}(Y_t, Y_{t-k}) \triangleq \widehat{\gamma}_k \\ = \frac{1}{T} \sum_{t=k+1}^T (Y_t - \bar{Y})(Y_{t-k} - \bar{Y}) = \frac{1}{T} \sum_{t=1}^{T-k} (Y_t - \bar{Y})(Y_{t+k} - \bar{Y}) \rightarrow \text{V}(Y_t, Y_{t-k}) = \gamma_k \\ \frac{\widehat{\text{V}}(Y_t, Y_{t-k})}{\sqrt{\widehat{\text{V}}(Y_t)} \sqrt{\widehat{\text{V}}(Y_{t-k})}} \triangleq \widehat{\rho}_k = \frac{\widehat{\gamma}_k}{\widehat{\gamma}_0} = \frac{\frac{1}{T} \sum_{t=k+1}^T (Y_t - \bar{Y})(Y_{t-k} - \bar{Y})}{\frac{1}{T} \sum_{t=1}^T (Y_t - \bar{Y})^2} \rightarrow R(Y_t, Y_{t-k}) = \rho_k \end{array} \right.$$

$$Y_1 Y_{1+k} + Y_2 Y_{2+k} + \cdots + Y_t Y_{t+k} + \cdots + Y_{T-k} Y_T$$

1^{st} -order autocorrelation estimation

$$\widehat{\rho}_1 = \frac{\widehat{\gamma}_1}{\widehat{\gamma}_0} = \frac{\frac{1}{T} \sum_{t=1+1=2}^T (Y_t - \bar{Y})(Y_{t-1} - \bar{Y})}{\frac{1}{T} \sum_{t=1}^T (Y_t - \bar{Y})^2}$$

60.1 AR(1) = 1^{st} -order autoregressive model = first-order autoregressive model

張翔老師. 2015. “ARMA Part3.” <https://www.youtube.com/watch?v=Ocw4NXoO8Xo>.

Definition 60.5. $AR(1) = 1^{st}$ -order autoregressive model\$

$$Y_t = \beta_0 + \beta_1 Y_{t-1} + \varepsilon_t$$

$$\varepsilon_t \sim \mathcal{N}(0, \sigma_\varepsilon^2)$$

$$\begin{aligned} Y_t &= \beta_0 + \beta_1 Y_{t-1} + \varepsilon_t \\ &= \beta_0 + \beta_1 (\beta_0 + \beta_1 Y_{t-2} + \varepsilon_{t-1}) + \varepsilon_t \\ &= \beta_0 (1 + \beta_1) + \beta_1^2 Y_{t-2} + \varepsilon_t + \beta_1 \varepsilon_{t-1} \\ &= \beta_0 (1 + \beta_1) + \beta_1^2 (\beta_0 + \beta_1 Y_{t-3} + \varepsilon_{t-2}) + \varepsilon_t + \beta_1 \varepsilon_{t-1} \\ &= \beta_0 (1 + \beta_1 + \beta_1^2) + \beta_1^3 Y_{t-3} + \varepsilon_t + \beta_1 \varepsilon_{t-1} + \beta_1^2 \varepsilon_{t-2} \\ &\quad \vdots \\ &= \beta_0 (1 + \beta_1 + \beta_1^2 + \cdots) + \varepsilon_t + \beta_1 \varepsilon_{t-1} + \beta_1^2 \varepsilon_{t-2} + \cdots \\ &\stackrel{|\beta_1| < 1}{=} \frac{\beta_0}{1 - \beta_1} + \sum_{k=0}^{\infty} \beta_1^k \varepsilon_{t-k} \end{aligned}$$

$$\left\{ \begin{array}{l} \mu = E(Y_t) = E\left(\frac{\beta_0}{1-\beta_1} + \sum_{i=0}^{\infty} \beta_1^i \mathcal{E}_{t-i}\right) \\ = \frac{\beta_0}{1-\beta_1} + \sum_{i=0}^{\infty} \beta_1^i E(\mathcal{E}_{t-i}) \stackrel{\mathcal{E}_t \sim \mathcal{N}(0, \sigma_{\mathcal{E}}^2)}{=} \frac{\beta_0}{1-\beta_1} \quad \mu = \frac{\beta_0}{1-\beta_1} \\ \gamma_0 = \sigma^2 = V(Y_t) = V\left(\mu + \sum_{i=0}^{\infty} \beta_1^i \mathcal{E}_{t-i}\right) = V\left(\sum_{i=0}^{\infty} \beta_1^i \mathcal{E}_{t-i}\right) \\ = \sum_{i=0}^{\infty} (\beta_1^i)^2 V(\mathcal{E}_{t-i}) \stackrel{\mathcal{E}_t \sim \mathcal{N}(0, \sigma_{\mathcal{E}}^2)}{=} \sum_{i=0}^{\infty} (\beta_1^2)^i \sigma_{\mathcal{E}}^2 = \frac{\sigma_{\mathcal{E}}^2}{1-\beta_1^2} \quad \gamma_0 = \sigma^2 = \frac{\sigma_{\mathcal{E}}^2}{1-\beta_1^2} \\ \gamma_k = V(Y_t, Y_{t-k}) = V\left(\mu + \sum_{i=0}^{\infty} \beta_1^i \mathcal{E}_{t-i}, \mu + \sum_{i=0}^{\infty} \beta_1^i \mathcal{E}_{t-k-i}\right) \\ = V\left(\sum_{i=0}^{\infty} \beta_1^i \mathcal{E}_{t-i}, \sum_{i=0}^{\infty} \beta_1^i \mathcal{E}_{t-k-i}\right) = \dots \quad \gamma_k = \frac{\beta_1^k \sigma_{\mathcal{E}}^2}{1-\beta_1^2} \\ \rho_k = R(Y_t, Y_{t-k}) = \frac{\gamma_k}{\gamma_0} = \frac{\frac{\beta_1^k \sigma_{\mathcal{E}}^2}{1-\beta_1^2}}{\sigma_{\mathcal{E}}^2} = \beta_1^k \quad \rho_k = \frac{\gamma_k}{\gamma_0} = \beta_1^k \end{array} \right.$$

$$\rho_1 = \frac{\gamma_1}{\gamma_0} = \beta_1^1 = \beta_1$$

$$\begin{aligned} \gamma_k &= V(Y_t, Y_{t-k}) = V\left(\mu + \sum_{i=0}^{\infty} \beta_1^i \mathcal{E}_{t-i}, \mu + \sum_{i=0}^{\infty} \beta_1^i \mathcal{E}_{t-k-i}\right) \\ &= V\left(\sum_{i=0}^{\infty} \beta_1^i \mathcal{E}_{t-i}, \sum_{i=0}^{\infty} \beta_1^i \mathcal{E}_{t-k-i}\right) = \dots \end{aligned}$$

$$\mathbf{Y} = \langle Y_1, Y_2, \dots, Y_T \rangle = \begin{bmatrix} Y_1 & Y_2 & \dots & Y_T \end{bmatrix}^T = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_T \end{bmatrix}$$

AR(1) covariance matrix

by (56.3)

$$\begin{aligned}
 V(\mathbf{Y}) &= E \left[[\mathbf{Y} - E(\mathbf{Y})] [\mathbf{Y} - E(\mathbf{Y})]^T \right] \\
 &= \begin{bmatrix} \sigma_1^2 & \sigma_{12} & \cdots & \sigma_{1T} \\ \sigma_{21} & \sigma_2^2 & \cdots & \sigma_{2T} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{T1} & \sigma_{T2} & \cdots & \sigma_T^2 \end{bmatrix} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \cdots & \sigma_{1T} \\ \sigma_{21} & \sigma_{22} & \cdots & \sigma_{2T} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{T1} & \sigma_{T2} & \cdots & \sigma_{TT} \end{bmatrix} = [\sigma_{ij}]_{T \times T} = \Sigma \\
 &= \begin{bmatrix} \gamma_0 & \gamma_1 & \cdots & \gamma_{T-1} \\ \gamma_1 & \gamma_0 & \cdots & \gamma_{T-2} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{T-1} & \gamma_{T-2} & \cdots & \gamma_0 \end{bmatrix} = \begin{bmatrix} \frac{\sigma_{\varepsilon}^2}{1-\beta_1^2} & \frac{\beta_1^1 \sigma_{\varepsilon}^2}{1-\beta_1^2} & \cdots & \frac{\beta_1^{T-1} \sigma_{\varepsilon}^2}{1-\beta_1^2} \\ \frac{\beta_1^1 \sigma_{\varepsilon}^2}{1-\beta_1^2} & \frac{\sigma_{\varepsilon}^2}{1-\beta_1^2} & \cdots & \frac{\beta_1^{T-2} \sigma_{\varepsilon}^2}{1-\beta_1^2} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\beta_1^{T-1} \sigma_{\varepsilon}^2}{1-\beta_1^2} & \frac{\beta_1^{T-2} \sigma_{\varepsilon}^2}{1-\beta_1^2} & \cdots & \frac{\sigma_{\varepsilon}^2}{1-\beta_1^2} \end{bmatrix} \\
 &= \frac{\sigma_{\varepsilon}^2}{1-\beta_1^2} \begin{bmatrix} 1 & \beta_1 & \cdots & \beta_1^{T-1} \\ \beta_1 & 1 & \cdots & \beta_1^{T-2} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_1^{T-1} & \beta_1^{T-2} & \cdots & 1 \end{bmatrix} = \sigma^2 \begin{bmatrix} 1 & \beta_1 & \beta_1^2 & \cdots & \beta_1^{T-1} \\ \beta_1 & 1 & \beta_1 & \cdots & \beta_1^{T-2} \\ \beta_1^2 & \beta_1 & 1 & \cdots & \beta_1^{T-3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \beta_1^{T-1} & \beta_1^{T-2} & \beta_1^{T-3} & \cdots & 1 \end{bmatrix} \\
 &= \sigma^2 \begin{bmatrix} 1 & \rho_1 & \rho_2 & \cdots & \rho_{T-1} \\ \rho_1 & 1 & \rho_1 & \cdots & \rho_{T-2} \\ \rho_2 & \rho_1 & 1 & \cdots & \rho_{T-3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_{T-1} & \rho_{T-2} & \rho_{T-3} & \cdots & 1 \end{bmatrix} = \sigma^2 \begin{bmatrix} 1 & \rho & \rho^2 & \cdots & \rho^{T-1} \\ \rho & 1 & \rho & \cdots & \rho^{T-2} \\ \rho^2 & \rho & 1 & \cdots & \rho^{T-3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho^{T-1} & \rho^{T-2} & \rho^{T-3} & \cdots & 1 \end{bmatrix}
 \end{aligned}$$

$$\mathbf{Y} \sim \mathcal{D}(\boldsymbol{\mu}, \Sigma) = d(\boldsymbol{\mu}_{\mathbf{Y}}, \Sigma_{\mathbf{Y}}) = d(E[\mathbf{Y}], V[\mathbf{Y}])$$

where

$$\Sigma = \begin{bmatrix} \gamma_0 & \gamma_1 & \cdots & \gamma_{T-1} \\ \gamma_1 & \gamma_0 & \cdots & \gamma_{T-2} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{T-1} & \gamma_{T-2} & \cdots & \gamma_0 \end{bmatrix} = \sigma^2 \begin{bmatrix} 1 & \rho & \rho^2 & \cdots & \rho^{T-1} \\ \rho & 1 & \rho & \cdots & \rho^{T-2} \\ \rho^2 & \rho & 1 & \cdots & \rho^{T-3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho^{T-1} & \rho^{T-2} & \rho^{T-3} & \cdots & 1 \end{bmatrix}$$

60.2 $AR(2) = 2^{\text{nd}}\text{-order autoregressive model} = \text{second-order autoregressive model}$

Definition 60.6. $AR(2) = 2^{\text{nd}}$ -order autoregressive model

$$Y_t = \beta_0 + \beta_1 Y_{t-1} + \beta_2 Y_{t-2} + \varepsilon_t$$

$$\varepsilon_t \sim \mathcal{N}(0, \sigma_{\varepsilon}^2)$$

60.3 AR(p) = p^{th} -order autoregressive model

$$Y_t = \beta_0 + \sum_{i=1}^p \beta_i Y_{t-i} + \varepsilon_t$$

60.4 MA(q) = q^{th} -order moving-average model

$$Y_t = \mu + \varepsilon_t + \sum_{i=1}^q \alpha_i \varepsilon_{t-i}$$

60.5 ARMA(p,q) = $p^{\text{th}}, q^{\text{th}}$ -order autoregressive-moving-average model

$$Y_t = \varepsilon_t + \sum_{i=1}^q \alpha_i \varepsilon_{t-i} + \sum_{i=1}^p \beta_i Y_{t-i}$$

Chapter 61

conductivity

61.1 resistance

https://www.bilibili.com/video/BV1tN41147SK/?spm_id_from=333.999.section.playall&vd_source=2b462dd516a0bbcdcb7d97d0fc60b38

61.2 semiconductor

<https://www.youtube.com/watch?v=-lHXZk5M6cI>

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