

INTEGRAL ESTIMATION IN QUANTUM PHYSICS

by
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The University of Utah
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Mathematical Physics

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The University of Utah
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The University of Utah Graduate School

STATEMENT OF DISSERTATION APPROVAL

The dissertation of Jane Doe
has been approved by the following supervisory committee members:

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the Department/College/School of Mathematics
and by Alice B. Toklas , Dean of The Graduate School.

ABSTRACT

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For my parents, Alice and Bob.

CONTENTS

ABSTRACT	iii
LIST OF FIGURES	vii
LIST OF TABLES	viii
NOTATION AND SYMBOLS	ix
TYPESETTING EXPERIMENTS	x
CHAPTERS	1
1. THE FIRST	1
1.1 The first section	1
1.1.1 The first subsection	2
1.1.2 The second subsection	2
1.1.3 The third subsection	2
1.1.3.1 The first subsubsection	2
1.1.3.2 The second subsubsection	2
1.1.3.2.1 The first numbered paragraph	2
1.1.3.2.2 The second numbered paragraph	2
1.2 The second section	3
1.3 The third section	5
1.4 Free software packages	5
1.5 Resizing figures	9
1.6 Summary and conclusions	14
2. THE SECOND	15
3. THE THIRD	17
4. THE FOURTH	19
4.1 More on the topic	19
4.2 Even more on the topic	19
4.3 Summary and conclusions	20
APPENDICES	21
A. THE FIRST	21
B. THE SECOND	23
C. THE THIRD	25

REFERENCES	27
BINOMIAL NOMENCLATURE INDEX	30
FREE SOFTWARE INDEX	31
TOPIC INDEX	35

LIST OF FIGURES

1.1	The first figure.	8
1.2	The second figure.	8
1.3	The third figure.	8
1.4	The fourth figure (at 50% scale).	11
1.5	The fifth figure (at 75% scale).	11
1.6	The sixth figure (at native size).	11
1.7	The seventh figure (at 125% scale).	11
1.8	The eighth figure (at 175% scale).	11
1.9	The ninth figure (at 50% scale)	12
1.10	The tenth figure (at 75% scale)	12
1.11	Using \LaTeX picture mode	13

LIST OF TABLES

1.1 Lowercase Greek letters.	4
1.2 Uppercase Greek letters.	6

NOTATION AND SYMBOLS

α	fine-structure (dimensionless) constant, approximately $1/137$
α	radiation of doubly-ionized helium ions, He ⁺⁺
β	radiation of electrons
γ	radiation of very high frequency, beyond that of X rays
γ	Euler's constant, approximately 0.577 215 ...
δ	stepsize in numerical integration
$\delta(x)$	Dirac's famous function
ϵ	a tiny number, usually in the context of a limit to zero
$\zeta(x)$	the famous Riemann zeta function
...	...
$\psi(x)$	logarithmic derivative of the gamma function
ω	frequency

TYPESETTING EXPERIMENTS

In this section, we use color in several places. The `\colorbox` command takes two arguments — a named color and text to be in black on a background of that color — and sets the text in a box with a small margin of width `\fboxsep` (set to 3.0pt in this document).

Here, we want a tighter colored box that has a fixed height, and is independent of letter shape. We set the margin to zero inside a group so that the change is purely local, and so that height and depth of the line are not increased over what they would be if the colored box were not used. We prefix a T_EX `\strut` to the user-supplied text, because that command expands to a zero-width box of the height and depth of parentheses, which, in most fonts, delimit the extent of letter shapes.

```
\newcommand {\hilitebox} [1] {\fboxsep = 0pt\colorbox{pink}{\strut #1}}
```

Here is a fragment from the first chapter in another thesis, set in *emphasized text* to distinguish it from the rest of this section:

In light of the known results, the consistency of empirical semivariogram and related estimators is widely considered a settled matter. For example, Lahiri, Lee, and Cressie [22] state:

The simpler and more commonly used nonparametric estimators of the variogram, such as the method of moments estimator of Matheron (1962) and its robustified versions due to Cressie and Hawkins (1980) have many desirable properties like, unbiasedness, consistency, etc. ...

Regarding a kernel estimator of the covariance function, Hall and Patil [14] remarked:

It is not difficult to see that if, as n increases, the points t_i become increasingly dense in each bounded subset of \mathbb{R}^d , then the bandwidth h may be chosen so that $\check{\rho}(t) \rightarrow \rho(t)$ as $n \rightarrow \infty$, for each $t \in \mathbb{R}^d$.

However, in order to be true, such statements would need to be qualified by many assumptions on the random field as well as on the observation locations. We will see in §2.3 that even for well-behaved random fields (e.g., ρ^ -mixing Gaussian random fields), it is not enough to assume that the observation locations become increasingly dense in each bounded subset; a stronger assumption*

must be made to ensure that the observation locations do not become denser in one region too much faster than in others.

The text before the previous paragraph contained two quote environments separated by a line of prose. Here are some more tests of both kinds of L^AT_EX environments for showing text written by someone else.

This is a `quote` environment with one short line, following a fairly short paragraph of prose (in this, and following examples, the text is explicitly colored with a command like `\color{purple}` inside the environment before the text):

```
\begin{quote}
  \color{purple}
  14 March 2016 is  $\pi \approx 3.1416$  day in funny notation.
  \hfill \emph{Web news reports}
\end{quote}
```

14 March 2016 is $\pi \approx 3.1416$ day in funny notation. *Web news reports*

This is a `quote` environment with three short lines, each a separate paragraph, following a fairly short paragraph of prose.

```
\begin{quote}
  \color{forestgreen}
  14 March 2016 is  $\pi \approx 3.1416$  day in funny notation.
  \hfill \emph{Web news reports}

  14 March 2016 is  $\pi \approx 3.1416$  day in funny notation.
  \hfill \emph{Web news reports}

  14 March 2016 is  $\pi \approx 3.1416$  day in funny notation.
  \hfill \emph{Web news reports}
\end{quote}
```

14 March 2016 is $\pi \approx 3.1416$ day in funny notation. *Web news reports*

14 March 2016 is $\pi \approx 3.1416$ day in funny notation. *Web news reports*

14 March 2016 is $\pi \approx 3.1416$ day in funny notation. *Web news reports*

Here is another example, this time with separate colors for each paragraph:

```
\begin{quote}
```

```

\color{darkkhaki}
14 March 2016 is $\pi \approx 3.1416$ day in funny notation.
\hfill \emph{Web news reports}

\color{darkmagenta}
14 March 2016 is $\pi \approx 3.1416$ day in funny notation.
\hfill \emph{Web news reports}

\color{darkcyan}
14 March 2016 is $\pi \approx 3.1416$ day in funny notation.
\hfill \emph{Web news reports}

\color{darkorange}
14 March 2016 is $\pi \approx 3.1416$ day in funny notation.
14 March 2016 is $\pi \approx 3.1416$ day in funny notation.
14 March 2016 is $\pi \approx 3.1416$ day in funny notation.
\linebreak
\strut
\hfill \emph{Web news reports}
\end{quote}

14 March 2016 is  $\pi \approx 3.1416$  day in funny notation. Web news reports
14 March 2016 is  $\pi \approx 3.1416$  day in funny notation. Web news reports
14 March 2016 is  $\pi \approx 3.1416$  day in funny notation. Web news reports
14 March 2016 is  $\pi \approx 3.1416$  day in funny notation. 14 March 2016 is  $\pi \approx 3.1416$ 
day in funny notation. 14 March 2016 is  $\pi \approx 3.1416$  day in funny notation.
Web news reports

```

Notice that `quote` paragraphs are *not* indented, but the environment itself *is* indented on the left and right by the value of `\leftmargin` (set to 27.37506pt in this document, which should be identical to 2.5em, where 1em = 11.49739pt).

For debugging purposes, we also have `\leftmarginii` set to 27.37506pt, and we have `\leftmarginiii` set to 24.09003pt.

This is a `quotation` environment with one paragraph, following a fairly short paragraph of prose (notice that the quotation paragraphs *are* indented):

```

\begin{quotation}
\color{blue}
Algebra is concerned with manipulation in
\emph{time}, and geometry is concerned with
\emph{space}. These are two orthogonal aspects
of the world, and they represent two different

```

points of view in mathematics. Thus the argument or dialogue between mathematicians in the past about the relative importance of geometry and algebra represents something very fundamental.

\hfill

\emph{Sir Michael Atiyah}

% Mathematics in the 20th century

% NTM {\bf 10}(1--3) 25--39 (September 2002)

% <http://dx.doi.org/10.1007/BF03033096>

\end{quotation}

Algebra is concerned with manipulation in *time*, and geometry is concerned with *space*. These are two orthogonal aspects of the world, and they represent two different points of view in mathematics. Thus the argument or dialogue between mathematicians in the past about the relative importance of geometry and algebra represents something very fundamental. *Sir Michael Atiyah*

This is a `quotation` environment with three paragraphs, following a fairly short paragraph of prose:

Algebra is concerned with manipulation in *time*, and geometry is concerned with *space*. These are two orthogonal aspects of the world, and they represent two different points of view in mathematics. Thus the argument or dialogue between mathematicians in the past about the relative importance of geometry and algebra represents something very fundamental. Sir Michael Atiyah

Algebra is concerned with manipulation in *time*, and geometry is concerned with *space*. These are two orthogonal aspects of the world, and they represent two different points of view in mathematics. Thus the argument or dialogue between mathematicians in the past about the relative importance of geometry and algebra represents something very fundamental. Sir Michael Atiyah

Algebra is concerned with manipulation in *time*, and geometry is concerned with *space*. These are two orthogonal aspects of the world, and they represent two different points of view in mathematics. Thus the argument or dialogue between mathematicians in the past about the relative importance of geometry and algebra represents something very fundamental. *Sir Michael Atiyah*

[illegible]

and on and on and on

Now all following text should be back in double-spaced mode, and just go on and on
and on and on and on and on and on and on and on and on and on and on and on and on
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1.1.3.2.1 The first numbered paragraph

1.1.3.2.2 The second numbered paragraph

1.2 The second section

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Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

In **Table 1.1** on the next page, we show the 24-character lowercase Greek alphabet.

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

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In **Figure 1.2** on page 8, we have another picture.

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

1.3 The third section

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

In **Table 1.2** on the next page, we show the 24-character uppercase Greek alphabet, 13 of which are identical with Latin letters, because the Romans borrowed several letters from the earlier Greek alphabet. However, the letter sounds do not always carry over: notice in particular the different names of the letter shapes **H** and **P**. In Modern Greek, β is pronounced *veeta*; the letter pair $\mu\pi$ is used to get a *bee* sound;

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1.4 Free software packages

The Free Software Foundation offers almost 300 software packages, most easily portable to many different operating systems and CPU platforms. They include at least these:

`a2ps`, `acct`, `acm`, `adns`, `alive`, `anubis`, `apl`, `archimedes`, `aris`, `aspell`, `auctex`, `autoconf-archive`, `autoconf`, `autogen`, `automake`, `avl`, `ballandpaddle`, `barcode`, `bash`, `bayonne`, `bc`, `binutils`, `bison`, `bool`, `bpel2owfn`, `c-graph`, `ccaudio`, `ccd2cue`, `cctrp`, `ccscript`, `cfengine`, `cflow`, `cgicc`, `chess`, `cim`, `classpath`, `classpathx`, `clisp`, `combine`, `commoncpp`, `complexity`, `config`, `coreutils`, `cpio`, `cpqi`, `cssc`, `cursynth`, `dap`, `datamash`, `ddd`, `ddrescue`, `dejagnu`, `denemo`, `dico`, `diction`, `diffutils`, `dionysus`, `direvent`,

Table 1.2. Uppercase Greek letters. Notice that several have the same letter shapes as Latin letters, and for those, \TeX does not define macro names. For convenience, we supply our own definitions of these macros: `\Alpha`, `\Beta`, `\Epsilon`, `\Zeta`, `\Eta`, `\Iota`, `\Kappa`, `\Mu`, `\Nu`, `\Omicron`, `\Rho`, `\Tau`, and `\Chi`.

A	Alpha
B	Beta
Γ	Gamma
Δ	Delta
E	Epsilon
Z	Zeta
H	Eta
Θ	Theta
I	Iota
K	Kappa
Λ	Lambda
M	Mu
N	Nu
Ξ	Xi
O	Omicron
Π	Pi
P	Rho
Σ	Sigma
T	Tau
Y	Upsilon
Φ	Phi
X	Chi
Ψ	Psi
Ω	Omega

dismal, dominion, easejs, ed, edma, electric, emacs, emms, enscript, fdisk, ferret, findutils, fisicalab, flex, fontutils, freedink, freefont, freeipmi, gama, garpd, gawk, gcal, gcc, gcide, gcl, gcompris, gdb, gdbm, gengen, gengetopt, gettext, gforth, ggradebook, ghostscript, gift, gleem, glibc, global, glpk, gmp, gnash, gnats, gnatsweb, gnu-c-manual, gnu-crypto, gnu-pw-mgr, gnubatch, gnubik, gnuca, gnuobol, gnudos, gnue, gnugo, gnuit, gnujump, gnukart, gnumach, gnun, gnunet, gnupod, gnuprologjava, gnuradio, gnurobots, gnuschool, gnushogi, gnusound, gnuspeech, gnuspool, gnustep, gnutls, gnutrution, gnuzilla, goptical, gperf, gprolog, greg, grep, groff, grub, gsasl, gsegrafx, gsl, gslip, gsrc, gss, gtypist, guile-gnome, guile-gtk, guile-ncurses, guile-opengl, guile-rpc, guile-sdl, guile, gv, gvpe,



This is Figure 1

Figure 1.1. The first figure.



This is Figure 2

Figure 1.2. The second figure.



This is Figure 3

Figure 1.3. The third figure. This one has both short and long captions. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah. Blah blah blah blah blah.

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1.5 Resizing figures

In **Figure 1.4** on page 11 through **Figure 1.8** on page 11, we show how graphics files can be rescaled to convenient sizes.

```
\begin{figure}[p]
  \centerline{\includegraphics[scale = 0.5]{fig1}}
  \caption{The fourth figure (at 50\% scale).}%
```




This is Figure 1

Figure 1.4. The fourth figure (at 50% scale).



This is Figure 1

Figure 1.5. The fifth figure (at 75% scale).



This is Figure 1

Figure 1.6. The sixth figure (at native size).



This is Figure 1

Figure 1.7. The seventh figure (at 125% scale).



This is Figure 1

Figure 1.8. The eighth figure (at 175% scale).

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Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

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As a final example in this chapter, **Figure 1.11** on the next page shows how you can use \LaTeX picture mode for annotating and positioning graphics images prepared outside \LaTeX . The input that produced that figure looks like this:

```
\begin{figure}[b]
  %% The original image is 216bp wide by 72bp high, but we
  %% rescale it to 150 picture units divided by \unitlength:
  %% 150 / 0.75 = 112.5 mm
  \newcommand {\myfig} {\includegraphics[width = 112.5mm]{fig1}}

  \begin{center}
    %% The \unitlength is chosen to make the complete picture fit
    %% within the page margins

    \setlength{\unitlength}{0.75mm}

    %%%      insert (width,height)(lower-left-x,lower-left-y)
    \begin{picture}(170,70)(10,10)
      %% Place the included image FIRST!
      \put(10,10) {\myfig}
    \end{picture}
  \end{center}
\end{figure}
```



This is Figure 1

Figure 1.9. The ninth figure (at 50% scale), boxed with the tenth figure.



This is Figure 1

Figure 1.10. The tenth figure (at 75% scale), boxed with the ninth figure.

```

%% Everything that follows OVERLAYS the original image!

\graphpaper[10](0,0)(170,70)

%% Mark the image center and corners by centered bullets
\newcommand{\thedot}{\makebox(0,0){$\bullet$}}
\put(85,35){\thedot}
\put(10,10){\thedot}
\put(10,60){\thedot}
\put(160,10){\thedot}
\put(160,60){\thedot}

\put(10,10){\makebox(0,0)[r]{lower-left}}
\put(160,10){\makebox(0,0)[l]{lower-right}}
\put(10,60){\makebox(0,0)[r]{upper-left}}
\put(160,60){\makebox(0,0)[l]{upper-right}}
\end{picture}
\end{center}

\vspace{2\baselineskip}

\caption[Using \LaTeX{} \texttt{picture} mode]
{Using \LaTeX{} \texttt{picture} mode for figure labeling
and positioning.}
\figlabel{picture-mode}
\end{figure}

```

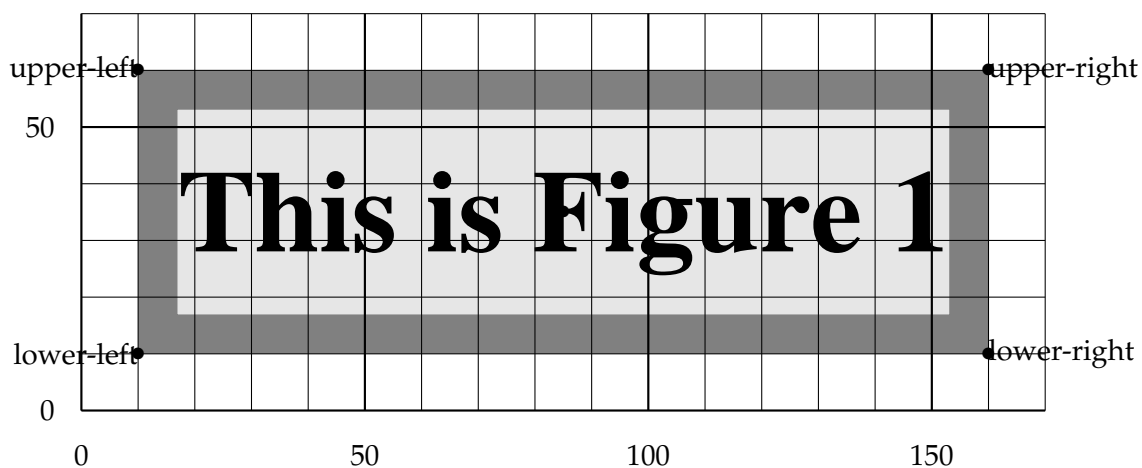


Figure 1.11. Using \LaTeX picture mode for figure labeling and positioning.

1.6 Summary and conclusions

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

Chapter 2

THE SECOND

This is a chapter.

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Chapter 3

THE THIRD

This is a chapter.

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah
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Chapter 4

THE FOURTH

This is a chapter.

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

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4.1 More on the topic

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

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4.2 Even more on the topic

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

Appendix A

THE FIRST

This is an appendix. Notice that the `\LaTeX` markup for an appendix is, surprisingly, `\chapter`. The `\appendix` command does not produce a heading; instead, it just changes the numbering style from numeric to alphabetic, and it changes the heading prefix from **CHAPTER** to **APPENDIX**.

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Appendix B

THE SECOND

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BINOMIAL NOMENCLATURE INDEX

A

Alces alces 14, 15, 17, 20
Antilocapra americana 14, 15, 17, 20

B

bobcat (*Lynx rufus*) 17, 20
bongo (*Tragelaphus eurycerus*) 17, 20
Bos taurus indicus 14, 20

C

Cervus canadensis 14, 17, 20
Connochaetes gnou 14, 21, 23, 26
Puma concolor 17, 20

E

E. coli bacterium 14, 21, 23, 26
elk (*Cervus canadensis*) 17, 20

J

jaguar (*Panthera onca*) 17, 20

L

Lama glama 14, 17, 20
llama (*Lama glama*) 17, 20
lynx (*Lynx canadensis*) 17, 20
Lynx canadensis 17, 20
Lynx rufus 20

M

manatee (*Trichechus inunguis*) 15, 17, 20
margay (*Leopardus wiedii*) 15, 17, 20
marmot (*Marmota marmota*) 15, 17, 20
Marmota marmota 15, 17, 20
Marmota monax 14, 20
moose (*Alces alces*) 15, 17, 20

O

ocelot (*Leopardus pardalis*) 15, 17, 20
Odocoileus virginianus 14, 20

P

Panthera onca 17, 20

Panthera tigris 14, 20
pronghorn (*Antilocapra americana*) 15, 17, 20

T

Panthera tigris) 14, 20
Tragelaphus eurycerus 17, 20

V

Vicugna vicugna 14, 20
vicuña (*Vicugna vicugna*) 14, 20

W

wapiti (*Cervus canadensis*) 14
white-tailed deer (*Odocoileus virginianus*)
14, 20
woodchuck (*Marmota monax*) 14, 20

Z

zebu (cattle) (*Bos taurus indicus*) 14

FREE SOFTWARE INDEX

A

a2ps 5
acct 5
acm 5
adns 5
alive 5
anubis 5
apl 5
archimedes 5
aris 5
aspell 5
auctex 5
autoconf 5
autoconf-archive 5
autogen 5
automake 5
avl 5

B

ballandpaddle 5
barcode 5
bash 5
bayonne 5
bc 5
binutils 5
bison 5
bool 5
bpel2owfn 5

C

c-graph 5
ccaudio 5
ccd2cue 5
ccrtp 5
ccscript 5
cfengine 5
cflow 5
cgicc 5
chess 5
cim 5
classpath 5

classpathx 5
clisp 5
combine 5
commoncpp 5
complexity 5
config 5
coreutils 5
cpio 5
cppl 5
cssc 5
cursynth 5

D

dap 5
datamash 5
ddd 5
ddrescue 5
dejagnu 5
denemo 5
dico 5
diction 5
diffutils 5
dionysus 5
direvent 5
dismal 6
dominion 6

E

easejs 6
ed 6
edma 6
electric 6
emacs 6
emms 6
enscript 6

F

fdisk 6
ferret 6
findutils 6
fisicalab 6

flex 6
fontutils 6
freedink 6
freefont 6
freeipmi 6

G

gama 6
garpd 6
gawk 6
gcal 6
gcc 6
gcide 6
gcl 6
gcompris 6
gdb 6
gdbm 6
gengen 6
gengetopt 6
gettext 6
gforth 6
ggradebook 6
ghostscript 6
gift 6
gleem 6
glibc 6
global 6
glpk 6
gmp 6
gnash 6
gnats 6
gnatsweb 6
gnu-c-manual 6
gnu-crypto 6
gnu-pw-mgr 6
gnubatch 6
gnubik 6
gnucap 6
gnucobol 6
gnudos 6
gnue 6
gnugo 6
gnuit 6
gnujump 6
gnukart 6
gnumach 6
gnun 6
gnunet 6

gnupod 6
gnuprologjava 6
gnuradio 6
gnurobots 6
gnuschool 6
gnushogi 6
gnusound 6
gnuspeech 6
gnuspool 6
gnustep 6
gnutls 6
gnutrition 6
gnuzilla 6
goptical 6
gperf 6
gprolog 6
greg 6
grep 6
groff 6
grub 6
gsasl 6
gsegrafx 6
gsl 6
gslip 6
gsrc 6
gss 6
gtypist 6
guile 6
guile-gnome 6
guile-gtk 6
guile-ncurses 6
guile-opengl 6
guile-rpc 6
guile-sdl 6
gv 6
gvpe 6
gxmessage 7
gzip 7

H

halifax 7
health 7
hello 7
help2man 7
hp2xx 7
httptunnel 7
hurd 7
hyperbole 7

I

idutils 7
ignuit 7
indent 7
inetutils 7
intlfonts 7

J

jacal 7
jel 7
jwhois 7

K

kawa 7

L

less 7
libcdio 7
libextractor 7
libffcall 7
libiconv 7
libidn 7
libmatheval 7
libmicrohttpd 7
librejs 7
libsigsegv 7
libtasn1 7
libtool 7
libunistring 7
libxmi 7
lightning 7
lilypond 7
liquidwar6 7
lsh 7

M

m4 7
macchanger 7
mailman 7
mailutils 7
make 7
marst 7
maverik 7
mc 7
mcron 7
mcsim 7
mdk 7
metahtml 7

mifluz 7
mig 7
miscfiles 7
mit-scheme 7
moe 7
motti 7
mpc 7
mpfr 7
mpria 7
mtools 7
myserver 7

N

nano 7
ncurses 7
nettle 7
non-gnu 7

O

ocrad 7
octave 7
oleo 7
orgadoc 7
osip 7

P

paperclips 7
parallel 7
parted 7
patch 7
pem 7
pexec 7
phantom 7
pies 7
plotutils 7
proxyknife 7
pspp 7
psychosynth 7
pth 7
pyconfigure 7

R

radius 7
rcs 7
readline 7
recutils 7
reftex 7
remotecontrol 7

rottlog 7
rpge 7
rush 7

S

sather 7
sauce 7
savannah 7
scm 7
screen 7
sed 7
serveez 7
sharutils 7
shishi 7
shmm 7
shtool 7
sipwitch 7
slib 7
smalltalk 7
solfege 7
spacechart 7
spell 7
sqltutor 7
src-highlite 7
stow 7
superopt 7
swbis 7

T

tar 7
termcap 7
termutils 7
teseq 7
teximpatient 7
texinfo 7
thales 7
time 7
tramp 7
trueprint 7

U

unifont 7
units 7
unrtf 7
userv 7
uucp 7

V

vc-dwim 7

vcdimager 7
vera 7

W

wb 7
wdiff 7
websocket4j 7
wget 7
which 7
windows 7

X

xaos 7
xboard 7
xhippo 7
xlogmaster 7
xnee 7
xorriso 7

Z

zile 7

TOPIC INDEX

A

aardvark 17, 20
aardwolf 17, 20
addax 17, 20
African ungulate *see* gnu
Alces alces 14, *see* moose, 15, 17, 20
antelope 17, 20
Antilocapra americana 14, *see* pronghorn, 15, 17, 20
aoudad 17, 20
azymous (unleavened) 17, 20

B

Babbage, Charles (1791–1871) 25
beaver 17, 20
bison 17, 20
bobcat (*Lynx rufus*) 17, 20
bongo (*Tragelaphus eurycerus*) 17, 20
Bos taurus indicus 14, 20

C

caribou 17, 20
Cervus canadensis 14, *see* elk, *see* wapiti, 17, 20
cheetah 17, 20
Connochaetes gnou 14, *see* gnu, 21, 23, 26
Puma concolor) 17, 20
coyote 17, 20
crocodile 17, 20

D

DCT *see* discrete cosine transform
deer 17, 20
DWT *see* discrete wavelet transform

E

E. coli bacterium 14, 21, 23, 26
elephant 17, 20
elk (*Cervus canadensis*) 17, 20
Encapsulated PostScript (EPS) 1
Escherichia coli *see* *E. coli*

F

ferret 17, 20
fox 17, 20
free software *see also* GNU Project

G

gazelle 17, 20
gecko 17, 20
gila monster 17, 20
giraffe 17, 20
gnu 14, 15, 17, 20, 21, 23, 26
 diet 14, 15, 17, 23, 26
 dry season 14, 15, 17, 23, 26
 wet season 14, 15, 17, 23, 26
hair 14, 21, 26
 color 14, 21, 26
 DNA analysis 14, 21, 26
 texture 14, 21, 26
 thickness 14, 21, 26
nonpredators
 aardvarks 20
 blesbok 20
 elephants 20
 gazelles 20
 giraffes 20
 zebras 20
predators 14, 17, 20, 23, 26
 crocodiles 14, 17, 20, 23, 26
 hyenas 14, 17, 20, 23, 26
 lions 14, 17, 20, 23, 26
gnu hair 14, 21, 23, 26
GNU Project 14, 21, 23, 26

H

hartebeest 17, 20
hippopotamus 17, 20
hyena 17, 20

I

ibex 17, 20
impala 17, 20

J

jackal 17, 20
 jackass 17, 20
 jackrabbit 17, 20
 jaguar (*Panthera onca*) 17, 20
 jerboa 17, 20

K

kangaroo 17, 20
 koala 17, 20
 kudu 17, 20

L

Lama glama 14, *see* llama, 17, 20
 lemming 17, 20
 lemur 17, 20
 leopard 17, 20
Leopardus pardalis *see* ocelot
Leopardus wiedii *see* margay
 lion 17, 20
 llama (*Lama glama*) 17, 20
 Lovelace, Lady Augusta Ada (1815–1852)
 25
 lynx (*Lynx canadensis*) 17, 20
Lynx canadensis *see* lynx, 17, 20
Lynx rufus *see* bobcat, 20

M

mammoth 15, 17, 20
 manatee (*Trichechus inunguis*) 15, 17, 20
 margay (*Leopardus wiedii*) 15, 17, 20
 marmot (*Marmota marmota*) 15, 17, 20
Marmota marmota 15, 17, 20
Marmota monax 14, *see* woodchuck, 20
 mastiff 15, 17, 20
 mastodon 15, 17, 20
 moose (*Alces alces*) 15, 17, 20
 μ (mu) *see* Borel measure
 musk ox 15, 17, 20
 muskrat 15, 17, 20

N

narwhal 15, 17, 20
 nautilus 15, 17, 20
 Neanderthal 15, 17, 20
 nilgai 15, 17, 20

O

ocelot (*Leopardus pardalis*) 15, 17, 20
 octopus 15, 17, 20
Odocoileus virginianus 14, 20
 okapi 15, 17, 20
 opossum 15, 17, 20

P

pachyderm *see* elephant, *see*
 hippopotamus, *see* rhinoceros
 panda 15, 17, 20
 panther 15, 17, 20
Panthera onca *see* jaguar, 17, 20
Panthera tigris 14, *see* tiger, 20
 peccary 15, 17, 20
 Portable Document Format (PDF) 1
 pronghorn (*Antilocapra americana*) 15, 17, 20
 pterodactyl 15, 17, 20
 puffin 15, 17, 20
 puma *see* cougar
Puma concolor *see* cougar

Q

quagga 15, 17, 20
 quail 15, 17, 20
 Queensland viper 15, 17, 20

R

raccoon 15, 17, 20
 rat 15, 17, 20
 rhea 15, 17, 20
 Rhine berry 15, 17, 20
 Rhinegrave 15, 17, 20
 Rhineland 15, 17, 20
 rhinestone 15, 17, 20
 rhino *see* rhinoceros
 rhinocerite 15, 17, 20
 rhinoceros 15, 17, 20
 rhinoceros horn 15, 17, 20
 rhinodon 15, 17, 20
 rhinodont 15, 17, 20

S

saber-toothed cat 14, 20
 salamander 14, 20
 sapajou 14, 20
 skink 14, 20
 skunk 14, 20

sunfish 14, 20
 suslik 14, 20
 swordfish 14, 20

T

tangun 14, 20
 tapir 14, 20
Panthera tigris) 14, 20
 toucan 14, 20
Tragelaphus eurycerus see bongo, 17, 20
 transform 25, see also Discrete DCT
 Transform, see also Fast Fourier
 Transform
Trichechus inunguis see manatee
 tuna 14, 20
 turbot 14, 20

U

ungulate see gnu, see impala, see kudu, see
 springbok
 unicorn 14, 20

V

vampire bat 14, 20
Vicugna vicugna 14, see vicuña, 20
 vicuña (*Vicugna vicugna*) 14, 20
 vulture 14, 20

W

wallaby 14, 20
 walrus 14, 20
 wanderoo 14, 20
 wapiti 20
 wapiti (*Cervus canadensis*) 14
 wart hog 14, 20
 water buffalo 14, 20
 weasel 14, 20
 whale 14, 20
 whippet 14, 20
 white-tailed deer (*Odocoileus virginianus*)
 14, 20
 wildebeest see gnu
 wolf 14, 20
 wolverine 14, 20
 woodchuck (*Marmota monax*) 14, 20

X

X ray 14, 20

X-radiation 14, 20
 xenon (noble gas) 14, 20
 xylem (woody tissue of a plant) 14, 20
 xylophone 14, 20

Y

yak 14, 20
 yucca 14, 20

Z

zebra 14, 20
 zebu (cattle) 20
 zebu (cattle) (*Bos taurus indicus*) 14
 zoetrope 14, 20
 zythum (ancient Egyptian malt beverage)
 14, 20