## Subject Index

adaptive MCMC, 308
adding parameters to a model, 185-186
adequate summary, 217, 232
adolescent smoking survey, 148-150
AECM algorithm, 324, 348
airline fatalities, 59, 82
Akaike information criterion (AIC), 172, 177
discussion, 182
educational testing example, 179
Alcoholics Anonymous survey, 213-214
aliasing, 89, 521, 524, 533
all-at-once Gibbs sampler for hierarchical regression, 393
alternating conditional sampling, see Gibbs sampler
analysis of variance (Anova), 114, 395398, 402, 403
finite-population and superpopulation models, 396-397
fixed and random effects, 396-397
for hierarchical logistic regression, 423
internet example, 398
notation, 395
ancillary test statistic, 151
approximate Bayesian computation (ABC), 344
approximate inference, 263
approximations based on posterior modes, 311-330
asymptotic theorems, 87-88, 206, 215216, 232
counterexamples, 89-91
proofs, 585-588
Australia, adolescent smoking survey in, 148-150, 162, 211-212
auxiliary variables for computation, 297299, 309
basis functions, 487-499
Gaussian, 487
multivariate, 495-498
selection and shrinkage, 490-494
splines, 488-490
Bayes factor, 182-184, 193
Bayes' rule, 6, 20
discrete examples, 8-11, 245
original example, 30
Bayesian data analysis, three steps of, 3
Bayesian filtering and smoothing, 516
Behrens-Fisher problem, 80
belief functions, 98
Bernoulli distribution, 584
Bernoulli trials, 29, 147
beta distribution, 30, 34, 60, 578, 582
beta-binomial distribution, 578,584
as overdispersed alternative to binomial, 438
beta-blockers, example of meta-analysis, 124-128
betting and probability, $13-16$
bias, 94, 99
compared to miscalibration, 128
difficulties with the notion, 94
prediction vs. estimation, 94, 401
'biased-coin' design, 235
BIC ('Bayesian' information criterion), 175
bicycle traffic, 81, 136
binned residual plots, 157-158
binomial distribution, 578, 583
binomial model, 29, 37, 80
posterior predictive check, 147-148
bioassay experiment, 74-79, 82
normal approximation, 86
birthdays, example of Gaussian process modeling, 505-510
births, proportion girls, 37-39
blockwise Gibbs sampler for hierarchical regression, 392
bootstrap, 96
Box-Cox transformation, 188-191, 194195
bridge sampling, 347, 348
Bugs, see software
burn-in for MCMC, why we prefer the term warm-up, 282
business school grades, hierarchical multivariate regression, 391-392
calibration, 128
calibration of probability estimates, 16 19
cancer maps, 47-51
capture-recapture sampling, 233

Cauchy model, 59, 437
causal inference, 4, 214, 223-224
instrumental variables, 224
observational studies, 220
incumbency example, 358-364
principal stratification, 223-224
randomized experiments, 214, 231
using regression models, 365
cavity distribution in expectation propagation, 339
censored data, 61, 224-228
Census, 422, 466
record linkage, 16-19
central composite design integration (CCD), 344
chess competition, example of paired comparisons, 427
$\chi^{2}$ distribution, 576, 581
Chinese restaurant process, 550
Chloride example, 489, 492, 494
Cholesky factor (matrix square root), 356, 580
classical methods
confidence intervals, 92, 95
frequency evaluations, 91
hypothesis testing, 145, 150
maximum likelihood, 93
multiple comparisons, 96
nonparametric inference, 96
normal-theory inference, 83
point estimation, 85, 91
standard errors, 85
unbiased estimates, 94
Wilcoxon rank test, 97
cluster sampling, 210-212, 232
coarse data, 230
cockroach allergen data, 472
coefficient of variation (CV), 6
coherence, 13
coin tossing, 12, 26
collinearity, 365
colochos, xiv
complementary log-log link, 407
complete data, 199
complete-data likelihood, 200
completely randomized experiments, 214216
computation, see posterior simulation computer programs, see software
conditional maximization, see posterior modes
conditional posterior distribution, 122, 325
confidence intervals, 3, 92, 95
conjugacy, see prior distribution
conjugate gradient optimization, 313
consistency, 88,91
contingency tables, 428-431
with missing data, 462
continuous models for discrete data, 458
contour plots, 76, 111, 112
and normal approximation, 85
control variable, 353
convergence of iterative simulation, 281286
covariance matrix, 20, 71
for a Gaussian process, 501
for a sum of Gaussian processes, 506
inverse-Wishart distribution, 72-74, 390, 576, 582
literature on models for, 401
LKJ distribution, 576, 582
scaled inverse-Wishart model, 74, 390
Wishart distribution, 576, 582
covariates, see regression models, explanatory variables
cow feed experiment, 217-218, 379
cross-validation, 175-177
discussion, 182
educational testing example, 179
crude estimation, 76, 263
bioassay example, 76
educational testing example, 114
rat tumor example, 103
schizophrenia example, 523, 526
Slovenia survey, 463
curse of dimensionality, 495
CV, coefficient of variation, 6
data augmentation, 293
data collection, 197-236
censored and truncated data, 224228
experiments, 214-220
formal models, 199-202
ignorability, 202-205
observational studies, 220-224
randomization, 218-220
sample surveys, 205-214
data reduction, 85
de Finetti's theorem, 105, 134
debugging, 270-271
comparing inferences from several models, 482
EM algorithm, 321
in Stan and R, 605-606
decision analysis, 12, 26, 99, 237-258
and Bayesian inference, 237-239
medical screening example, 245-246
personal and institutional perspectives, 256
radon example, 246-256
survey incentives example, 239-244
utility, 238, 245, 248, 256
decision trees, 238, 245, 252
delta method, 99
density regression, 568-571
dependent Dirichlet process (DDP), 562564, 572
derivatives, computation of, 313
design of surveys, experiments, and observational studies, 197-236
designs that 'cheat', 219
deviance, 192
deviance information criterion (DIC), 172173, 177, 192
discussion, 182
educational testing example, 179
differences between data and population, 207, 221, 223, 237, 422
differential equation model in toxicology, 477-485
dilution assay, example of a nonlinear model, 471-476, 485
dimensionality, curse of, 495
Dirichlet distribution, 69, 578, 583
Dirichlet process, 545-574
Dirichlet process mixtures, 549-557
discrepancy measure, 145
discrete data
adapting continuous models, 458
latent-data formulation, 408
logistic regression, 406
multinomial models, 423-428
Poisson regression, 406
probit regression, 406
discrete probability updating, 9,245
dispersion parameter for generalized linear models, 405
distinct parameters and ignorability, 202
distribution, 575-584
Bernoulli, 584
beta, $30,34,60,578,582$
beta-binomial, 60, 578, 584
binomial, 578, 583
Cauchy, 98
$\chi^{2}, 576,581$
Dirichlet, 69, 578, 583
double exponential, 368, 493, 576
exponential, 576, 581
gamma, 45, 576, 581
Gaussian, see normal distribution
inverse- $\chi^{2}, 576,581$
inverse-gamma, 43, 576, 581
inverse-Wishart, 72, 576, 582
Laplace, 368, 493, 576
LKJ correlation, 576, 582
log-logistic, 578
logistic, 578
lognormal, 576, 580
long-tailed, 435
multinomial, 578, 584
multivariate normal, $79,576,580$
marginals and conditionals, 580
multivariate $t, 319,578$
negative binomial, 44, 132, 578, 584
normal, 575, 576
normal-inverse- $\chi^{2}, 67,82$
Pareto, 493
Poisson, 578, 583
scaled inverse- $\chi^{2}, 43,65,576,581$
$t, 66,578,582$
uniform, 575, 576
Weibull, 576, 581
Wishart, 576, 582
divorce rates, 105, 135
dog metabolism example, 380
dose-response relation, 74
double exponential distribution, 368, 493, 576
$\mathrm{E}_{\text {old }}, 320$
ECM and ECME algorithms, 323, 348
educational testing experiments, see SAT coaching experiments
effective number of parameters, 169-182
educational testing example, 179
effective number of simulation draws, 286288
efficiency, 91
eight schools, see SAT coaching experiments
elections
forecasting presidential elections, 165166, 171-172, 383-388
incumbency in U.S. Congress, 358364
polling in Slovenia, 463-466
polling in U.S., 422-423, 456-462
probability of a tie, 27
EM algorithm, 320-325
AECM algorithm, 324
as special case of variational inference, 337
debugging, 321
ECM and ECME algorithms, 323, 348
for missing-data models, 452
parameter expansion, 325,348
SEM and SECM algorithms, 324325
empirical Bayes, why we prefer to avoid the term, 104
environmental health
allergen measurements, 472
perchloroethylene, 477
radon, 246
EP, see expectation propagation
estimands, 4, 24, 267
exchangeable models, 5, 26, 104-108, 230
and explanatory variables, 5
and ignorability, 230
no conflict with robustness, 436
objections to, 107, 126
universal applicability of, 107
expectation propagation, 338-343
cavity distribution, 339
extensions, 343
logistic regression example, 340-343
moment matching, 339
picture of, 342
tilted distribution, 339
experiments, 214-220
completely randomized, 214-216
definition, 214
distinguished from observational studies, 220
Latin square, 216
randomization, 218-220
randomized block, 216
sequential, 217, 235
explanatory variables, see regression models
exponential distribution, 576, 581
exponential families, 36,338
exponential model, 46, 61
external validation, 142, 167
record linkage example, 17
toxicology example, 484
factorial analysis, internet example, 397398
Federalist papers, 447
finite-population inference, 200-203, 205209, 212, 214-216, 232
in Anova, 396-397
Fisher information, 88
fixed effects, 383
and finite-population models in Anova, 397
football point spreads, 13-16, 26, 27
forecasting presidential elections, 142, 383388
hierarchical model, 386
problems with ordinary linear regression, 385
frequency evaluations, 91-92, 98
frequentist perspective, 91
functional data analysis, 512-513
gamma distribution, 45, 576, 581
Gaussian distribution, see normal distribution
Gaussian processes, 501-517
birthdays example, 505-510
golf putting, 517
latent, 510-512
logistic, 513-515
gay marriage data, 499
generalized linear models, 405-434
computation, 409-412
hierarchical, 409
hierarchical logistic regression, 422423
hierarchical Poisson regression, 420422
overdispersion, 407, 431, 433
prior distribution, 409
simple logistic regression example, 74-78
genetics, 8,183
simple example of Bayesian inference, 8-9, 27
geometric mean (GM), 6
geometric standard deviation (GSD), 6
Gibbs sampler, 276-278, 280-281, 291
all-at-once for hierarchical regression, 393
assessing convergence, 281-286
blockwise for hierarchical regression, 392
efficiency, 293-295
examples, 289, 440, 465, 528
hierarchical linear models, 288-290, 392-394, 396
parameter expansion for hierarchical regression, 393, 396
picture of, 277
programming in R, 596-606
special case of Metropolis-Hastings algorithm, 281
girl births, proportion of, 37-39
global mode, why it is not special, 311
GM (geometric mean), 6
golf putting
Gaussian process, 517
nonlinear model for, 486, 499
goodness-of-fit testing, see model checking
graphical models, 133
graphics
examples of use in model checking, 143, 144, 154-158
jittering, 14, 15, 27
posterior predictive checks, 153-159
grid approximation, 76-77, 263

GSD (geometric standard deviation), 6

Hamiltonian (hybrid) Monte Carlo, 300307, 601-605
hierarchical model example, 305-307, 601-605
leapfrog algorithm, 301
mass matrix, 301
momentum distribution, 301
no U-turn sampler, 304
programming in R, 601-605
tuning, 303
heteroscedasticity in linear regression, 369376
parametric model for, 372
hierarchical Dirichlet process (HDP), 564566
hierarchical linear regression, 381-404
computation, 392-394, 396
interpretation as a single linear regression, 389
hierarchical logistic regression, 422-423
hierarchical models, 5, 101-137, 381-404
analysis of variance (Anova), 395
binomial, 109-113, 136
bivariate normal, 209-210
business school grades, 391-392
cluster sampling, 210-212
computation, 108-113
forecasting elections, 383-388
logistic regression, 422-423
many batches of random effects election forecasting example, 386
polling example, 422-423
meta-analysis, 124-128, 423-425
multivariate, 390-392, 423-425, 456462
no unique way to set up, 389
normal, 113-128, 288-290, 326-330
NYPD stops, 420-422
pharmacokinetics example, 480-481
Poisson, 137, 420-422
pre-election polling, 209-210
prediction, 108, 118
prior distribution, see hyperprior distribution
radon, 246-256
rat tumor example, 109-113
SAT coaching, 119-124
schizophrenia example, 524-533
stratified sampling, 209-210
survey incentives, 239-244
hierarchical Poisson regression, 420-422
hierarchical regression, 381-404
prediction, 387
highest posterior density interval, 33

HMC, see Hamiltonian Monte Carlo
horseshoe prior distribution for regression coefficients, 378
hybrid Monte Carlo, see Hamiltonian Monte Carlo
hyperparameter, 35, 101, 105
hyperprior distribution, 107-108
informative, 480-481
noninformative, 108, 110, 111, 115, $117,135,424,526$
hypothesis testing, 145, 150
identifiability, 365
ignorability, 202-205, 230, 450
and exchangeability, 230
incumbency example, 359
strong, 203
ignorable and known designs, 203
ignorable and known designs given covariates, 203
ignorable and unknown designs, 204
iid (independent and identically distributed), 5
ill-posed systems
differential equation model in toxicology, 477-485
mixture of exponentials, 486
importance ratio, 264
importance resampling (sampling- importance resampling, SIR), 266, 271, 273, 319
examples, 441, 442
why you should sample without replacement, 266
importance sampling, 265, 271
bridge sampling, 347,348
for marginal posterior densities, 440
path sampling, 347-348
unreliability of, 265
improper posterior distribution, see posterior distribution
improper prior distribution, see prior distribution
imputation, see multiple imputation
inclusion indicator, 200, 449
incumbency advantage, 358-364
two variance parameters, 374
indicator variables, 366
for mixture models, 519
inference
discrete examples, 8-11
one of the three steps of Bayesian data analysis, 3
inference, finite-population and superpopulation, 201-202, 212, 214
completely randomized experiments, 215-216, 232
in Anova, 396-397
pre-election polling, 208-209
simple random sampling, 205-206
information criteria, 169-182
information matrix, 84,88
informative prior distribution
alternative to selecting regression variables, 367-369
spell checking example, 10
toxicology example, 480
institutional decision analysis, 256
instrumental variables, 224
integrated nested Laplace approximation (INLA), 343
intention-to-treat effect, 224
interactions
in basis-function models, 497
in Gaussian processes, 504, 511
in loglinear models, 429
in regression models, 242, 367
internet connect times, 397-398
intraclass correlation, 382
inverse probability, 56
inverse- $\chi^{2}$ distribution, 576, 581
inverse-gamma distribution, 43, 576, 581
inverse-Wishart distribution, 72, 576, 582
iterative proportional fitting (IPF), 430431
iterative simulation, see Markov chain Monte Carlo, 293-310
iterative weighted least squares (EM for robust regression), 444
jackknife, 96
Jacobian, 22
Jeffreys' rule for noninformative prior distributions, 52-53, 57, 59
jittering, 14, 15, 27
joint posterior distribution, 63
Kullback-Leibler divergence, 88, 331-336, 585-587
connection to deviance, 192
label switching in mixture models, 533
Laplace distribution, 368, 493, 576
Laplace's method for numerical integration, 318, 348
large-sample inference, 83-92
lasso (regularized regression), 368-369, 379
latent continuous models for discrete data, 408
latent-variable regression, 515
Latin square experiment, 216-217
LD50, 77-78
leapfrog algorithm for Hamiltonian Monte Carlo, 301
leave-one-out cross-validation, 175-177 discussion, 182
educational testing example, 179
life expectancy, quality-adjusted, 245
likelihood, 7-10
complete-data, 200
observed-data, 201
likelihood principle, 8,26
misplaced appeal to, 198
linear regression, 353-380, see also regression models
$t$ errors, 444-445
analysis of residuals, 361
classical, 354
conjugate prior distribution, 376378
as augmented data, 377
correlated errors, 369-376
errors in $x$ and $y, 379,380$
heteroscedasticity, 369-376
parametric model for, 372
hierarchical, 381-404
interpretation as a single linear regression, 389
incumbency example, 358-364
known covariance matrix, 370
model checking, 361
posterior simulation, 356
prediction, 357, 364
with correlations, 371
residuals, 358, 362
robust, 444-445
several variance parameters, 369376
weighted, 372
link function, 405, 407
LKJ correlation distribution, 576, 582
location and scale parameters, 54
log densities, 261
log-logistic distribution, 578
logistic distribution, 578
logistic regression, 74-78, 406
for multinomial data, 423
hierarchical, 422-423
latent-data interpretation, 408
logit (logistic, log-odds) transformation, 22, 125
loglinear models, 428-431
prior distributions, 429
lognormal distribution, 576, 580
longitudinal data
survey of adolescent smoking, 211212
maps
artifacts in, 47-51, 57
cancer rates, 47-51
for model checking, 143
MAR (missing at random), 202, 450
a more reasonable assumption than MCAR, 450
marginal and conditional means and variances, 21
marginal posterior distribution, 63, 110, 111, 122, 261
approximation, 325-326
computation for the educational testing example, 594-595
computation using importance sampling, 440
EM algorithm, 320-325
Markov chain, 275
Markov chain Monte Carlo (MCMC), 275310
adaptive algorithms, 297
assessing convergence, 281-286
between/within variances, 283
simple example, 285
auxiliary variables, 297-299, 309
burn-in, why we prefer the term warmup, 282
data augmentation, 293
effective number of simulation draws, 286-288
efficiency, 280, 293-296
Gibbs sampler, 276-278, 280-281, 291
assessing convergence, 281-286
efficiency, 293-295
examples, 277, 289, 392, 440, 465, 528
picture of, 277
programming in R, 596-606
Hamiltonian (hybrid) Monte Carlo, 300-307, 309
hierarchical model example, 305307
leapfrog algorithm, 301
mass matrix, 301
momentum distribution, 301
no U-turn sampler, 304
tuning, 303
inference, 281-286
Metropolis algorithm, 278-280, 291
efficient jumping rules, 295-297
examples, 278, 290
generalizations, 293-300
picture of, 276
programming in R, 598-599
relation to optimization, 279

Metropolis-Hastings algorithm, 279, 291
generalizations, 293-300
multiple sequences, 282
output analysis, 281-288
overdispersed starting points, 283
parallel tempering, 299-300
perfect simulation, 309
regeneration, 309
reversible jump sampling, 297-299, 309
simulated tempering, 309
slice sampling, 297, 309
thinning, 282
trans-dimensional, 297-299, 309
warm-up, 282
matrix and vector notation, 4
maximum entropy, 57
maximum likelihood, 93
MCAR (missing completely at random), 450
measurement error models
hierarchical, 133
linear regression with errors in $x$ and y, 380
nonlinear, 471-476
medical screening, example of decision analysis, 245-246
meta-analysis, 133,137
beta-blockers study, 124-128, 423425
bivariate model, 423-425
goals of, 125
survey incentives study, 239-242
Metropolis algorithm, 278-280, 291
efficient jumping rules, 295-297
examples, 278, 290
generalizations, 293-300
picture of, 276
programming in R, 598-599
relation to optimization, 279
Metropolis-Hastings algorithm, 279, 291
generalizations, 293-300
minimal analysis, 217
missing at random (MAR), 202, 450
a more reasonable assumption than MCAR, 450
a slightly misleading phrase, 202
missing completely at random (MCAR), 450
missing data, 449-467
and EM algorithm, 452, 454
intentional, 198
monotone pattern, 453, 455, 459462
multinomial model, 462
multivariate normal model, 454-456
multivariate $t$ model, 456
notation, 199, 449-452
paradigm for data collection, 199
Slovenia survey, 463-466
unintentional, 198, 204, 449
mixed-effects model, 382
mixture models, 17, 20, 105, 135, 519543
computation, 523-524
continuous, 520
de Finetti's theorem and, 105
Dirichlet process, 549-557
discrete, 519
exponential distributions, 486
hierarchical, 525
label switching, 533
model checking, 531, 532
prediction, 530
schizophrenia example, 524-533
mixture of exponentials, as example of an ill-posed system, 478, 486
model, see also hierarchical models, re-
gression models, etc.
beta-binomial, 438
binomial, 29, 37, 80, 147
Cauchy, 59, 437
Dirichlet process, 545
exponential, 46, 61
lognormal, 188
multinomial, 69, 79, 423-428
multivariate normal, 70
negative binomial, 437, 446
nonlinear, 471-486
normal, 39, 41, 42, 60, 64-69
overdispersed, 437-439
Poisson, 43, 45, 59, 61
Polya urn, 549
robit, 438
robust or nonrobust, 438-439
$t, 293,437,441-445$
underidentified, 89
model averaging, 193, 297
model building, one of the three steps of Bayesian data analysis, 3
model checking, 141-164, 187-195
adolescent smoking example, 148150
election forecasting example, 142, 386
incumbency example, 361
one of the three steps of Bayesian data analysis, 3
power transformation example, 189
pre-election polling, 210
psychology examples, 154-157
residual plots, 158, 476, 484
SAT coaching, 159-161
schizophrenia example, 531, 532
speed of light example, 143, 146
spelling correction example, 11
toxicology example, 483
model comparison, 178-184
model complexity, see effective number of parameters
model expansion, 184-192
continuous, 184, 372, 439
schizophrenia example, 531-532
model selection
bias induced by, 181
why we reluctantly do it, $178,183-$ 184, 367
moment matching in expectation propagation, 339
momentum distribution for Hamiltonian Monte Carlo, 301
monitoring convergence of iterative simulation, 281-286
monotone missing data pattern, 453, 455, 459-462
Monte Carlo error, 267, 268, 272
Monte Carlo simulation, 267-310
multilevel models, see hierarchical models
multimodal posterior distribution, 299, 319
multinomial distribution, 578, 584
multinomial logistic regression, 426
multinomial model, 69, 79
for missing data, 462
multinomial probit model, 432
multinomial regression, 408, 423-428
parameterization as a Poisson regression, 427
multiparameter models, 63-82
multiple comparisons, 96, 134, 150, 186
multiple imputation, 201, 451-454
combining inferences, 453
pre-election polling, 456-462
Slovenia survey, 463-466
multiple modes, 311, 321
multivariate models
for nonnormal data, 423-425
hierarchical, 390-392
prior distributions noninformative, 458
multivariate normal distribution, 576, 580
multivariate $t$ distribution, 319, 578
natural parameter for an exponential family, 36
negative binomial distribution, 44, 132, 578, 584
as overdispersed alternative to Poisson, 437, 446
nested Dirichlet process (NDP), 566-568
neural networks, 485
New York population, 188-191
Newcomb's speed of light experiment, 66, 79
Newton's method for optimization, 312
no interference between units, 200
no U-turn sampler for Hamiltonian Monte Carlo, 304
non-Bayesian methods, 92-97, 100
difficulties for SAT coaching experiments, 119
nonconjugate prior distributions, see prior distribution
nonidentified parameters, 89
nonignorable and known designs, 204
nonignorable and unknown designs, 204
noninformative prior distribution, 51-57
binomial model, 37, 53
difficulties, 54
for hyperparameters, $108,110,111$, $115,117,526$
in Stan, 594
Jeffreys' rule, 52-53, 57, 59
multivariate normal model, 73
normal model, 64
pivotal quantities, 54, 57
nonlinear models, 471-486
Gaussian processes, 501-517
golf putting, 486, 499
mixture of exponentials, 486
serial dilution assay, 471-476
splines, 487-499
toxicology, 477-485
nonparametric methods, 96
nonparametric models, 501-517, 545-574
nonparametric regression, 487-499
nonrandomized studies, 220
normal approximation, 83-87, 318-319
bioassay experiment, 86
for generalized linear models, 409
lower-dimensional, 85
meta-analysis example, 125
multimodal, 319
normal distribution, 575, 576
normal model, $39,41,60,64-69$, see also linear regression and hierarchical models
multivariate, 70, 454-462
power-transformed, 188-191, 194195
normalizing factors, 7, 345-349
notation for data collection, 199
notation for observed and missing data, 199, 449, 452
nuisance parameters, 63
numerical integration, 271, 318-319, 345348
Laplace's method, 318, 348
numerical posterior predictive checks, 143152
NYPD stops example, 420-422
objective assignment of probability distributions
football example, 13-16
record linkage example, 16-19
objectivity of Bayesian inference, 13, 24
observational studies, 220-224
difficulties with, 222
distinguished from experiments, 220
incumbency example, 358-364
observed at random, 450
observed data, see missing data
observed information, 84
odds ratio, 8, 80, 125
offsets for generalized linear models, 407
chess example, 428
police example, 420
optimization and the Metropolis algorithm, 279
ordered logit and probit models, 408, 426
outcome variable, 353
outliers, models for, 435
output analysis for iterative simulation, 281-288
overdispersed models, 407, 431, 433, 437439
overfitting, 101, 367, 409
$p$-values, 98, 145, see also model checking
Bayesian (posterior predictive), 146
classical, 145
interpretation of, 150
packages, see software
paired comparisons with ties, 432
multinomial model for, 427
parallel tempering for MCMC, 299-300
parameter expansion
election forecasting example, 393
for Anova computation, 396
for EM algorithm, 325, 348
for hierarchical regression, 393, 396
programming in R, 600-601
parameters, 4
frequentist distinction between parameters and predictions, 94, 401
Pareto distribution, 493
partial pooling, see shrinkage
path sampling, 347-348
perchloroethylene, 477
perfect simulation for MCMC, 309
permutation tests, 96
personal (subjective) probability, 13, 256
pharmacokinetics, 480-481
philosophy, references to discussions of, 26
pivotal quantities, 54, 57, 66
pivotal quantity, 151
point estimation, 85, 91, 99
Poisson distribution, 578, 583
Poisson model, 43, 59, 61
parameterized in terms of rate and exposure, 45
Poisson regression, 82, 406, 433
for multinomial data, 426
hierarchical, 420-422
police stops, example of hierarchical Poisson regression, 420-422
Polya urn model, 549
pooling, partial, 25, 115
population distribution, 101
posterior distribution, 3, 7, 10
as compromise, $32,40,58$
improper, 54, 90, 135
joint, 63
marginal, 63
normal approximation, see normal approximation
predictive, 7
summaries of, 32
use as prior distribution when new data arrive, 9, 251
posterior intervals, 3, 33, 267
posterior modes, 311-330
approximate conditional posterior density using marginal modes, 325
conditional maximization (stepwise ascent), 312
EM algorithm for marginal posterior modes, 320-325, 348
ECM and ECME algorithms, 323, 456, 526
examples, $322,329,444,465,526$
generalized EM algorithm, 321
marginal posterior density increases at each step, 329
missing data, 452, 454
SEM algorithm, 465
SEM and SECM algorithms, 324325
joint mode, problems with, 350
Newton's method, 312
posterior predictive checks, 143-161, see also model checking
graphical, 153-159
numerical, 143-152
posterior predictive distribution, 7
hierarchical models, 108, 118
linear regression, 357
missing data, 202
mixture model, 530
multivariate normal model, 72
normal model, 66
speed of light example, 144
posterior simulation, 22-24, 267-310, see also Markov chain Monte Carlo (MCMC)
computation in R and Stan, 589606
direct, 263-264
grid approximation, 76-77, 263
hierarchical models, 112
how many draws are needed, 267, 268, 272
rejection sampling, 264
simple problems, 78
two-dimensional, 76, 82
using inverse cdf, 23
poststratification, 222, 422-423, 460
potential scale reduction factor, 285
power transformations, 188-191, 194-195
pre-election polling, 69, 79, 233-234, 422423
in Slovenia, 463-466
missing data, 456-466
state-level opinions from national polls, 422-423
stratified sampling, 207-210
precision (inverse of variance), 40
prediction, see posterior predictive distribution
predictive simulation, 28
predictor variables, see regression models, explanatory variables
predictors
including even if not 'statistically significant', 241-244
selecting, 186
principal stratification, 223-224
prior distribution, 6, 10
boundary-avoiding, 313-318
conjugate, 35-37, 56
binomial model, 34-35, 38
exponential model, 46
generalized linear models, 409
linear regression, 376-378
multinomial model, 69, 429, 462
multivariate normal model, 71, 72
normal model, 40, 43, 67
Poisson model, 44
estimation from past data, 102
for covariance matrices
noninformative, 458
hierarchical, see hierarchical models and hyperprior distribution
improper, 52, 82
and Bayes factors, 194
informative, 34-46, 480-481
nonconjugate, $36,38,75$
noninformative, 51-57, 93
$t$ model, 443
binomial model, 37, 53
difficulties, 54
for hyperparameters, 108, 110, 111, 115, 117, 526
generalized linear models, 409
in Stan, 590, 594
Jeffreys' rule, 52-53, 57, 59
linear regression, 355
multinomial model, 464
multivariate normal model, 73
normal model, 64
pivotal quantities, 54, 57
warnings, see posterior distribution, improper
predictive, 7
proper, 52
weakly informative, 55-57, 128-132, 313-318
in Stan, 594
prior predictive checks, 162,164
prior predictive distribution, 7
normal model, 41
probability, 19-22, 26
assignment, 13-19, 26, 27
foundations, 11-13, 25
notation, 6
probability model, 3
probit regression, 406
for multinomial data, 426, 432
Gibbs sampler, 408
latent-data interpretation, 408
probit transformation, 22
programming tips, 270-271, 605-606
propensity scores, 204, 221, 222, 230
proper prior distribution, see prior distribution
proportion of female births, 29, 37-39
psychological data, 154-157, 524-533
PX-EM algorithm, 325, 348, see also parameter expansion

QR decomposition, 356, 378
quality-adjusted life expectancy, 245
quasi-Newton optimization, 313
R , see software
$\widehat{R}$ for monitoring convergence of iterative simulation, 285
radial basis functions, 487
radon decision problem, 194, 246-256, 378
random probability measure (RPM), 545574
random-effects model, 382-388
analysis of variance (Anova), 395
and superpopulation model in Anova, 397
election forecasting example, 386
non-nested example, 422-423
several batches, 383
randomization, 218-220
and ignorability, 220, 230
complete, 218
given covariates, 219
randomized blocks, 231
rank test, 97
rat tumors, 102-103, 109-113, 133
ratio estimation, 93, 98
record linkage, 16-19
record-breaking data, 230
reference prior distributions, see noninformative prior distribution
regeneration for MCMC, 309
regression models, 353-380, see also linear regression
Bayesian justification, 354
explanatory variables, 5, 200, 353, 365-367
exchangeability, 5
exclude when irrelevant, 367
ignorable models, 203
goals of, 364-365
hierarchical, 381-404
variable selection, 367
why we prefer to use informative prior distributions, 367-369
regression to the mean, 95
regression trees, 485
regularization, 52, 113-124, 368-369, 493
rejection sampling, 264, 273
picture of, 264
replications, 145
residual plots, 162, 358
binned, 157-158
dilution example, 476
incumbency example, 362
nonlinear models, 476, 484
pain relief example, 158
toxicology example, 484

## SUBJECT INDEX

residuals, 157
response surface, 126
response variable, 353
reversible jump sampling for MCMC, 297299, 309
ridge regression, 401
robit regression (robust alternative to logit and probit), 438
robust inference, 162, 185, 192, 435-447
for regression, 444-445
SAT coaching, 441-444
various estimands, 191
rounded data, 80, 234
sampling, 205-214, see also surveys
capture-recapture, 233
cluster, 210-212, 232
poststratification, 222, 422-423
ratio estimation, 93,98
stratified, 206-210
unequal selection probabilities, 212214, 233-234
SAT coaching experiments, 119-124
difficulties with natural non-Bayesian methods, 119
information criteria and effective number of parameters, 179
model checking for, 159-161
robust inference for, 441-444
scale parameter, 43
scaled inverse- $\chi^{2}$ distribution, 43, 576, 581
scaled inverse-Wishart model, 74, 390
schizophrenia reaction times, example of mixture modeling, 524-533
selection of predictors, 186
SEM and SECM algorithms, 324-325, 348
sensitivity analysis, 160-161, 184-185, 435447
and data collection, 191
and realistic models, 191
balanced and unbalanced data, 221
cannot be avoided by setting up a super-model, 141
estimating a population total, 188191
incumbency example, 363
SAT coaching, 441-444
using $t$ models, 443-444
various estimands, 191
sequential designs, 217, 235
serial dilution assay, example of a nonlinear model, 471-476, 485
sex ratio, 29, 37-39
shrinkage, $32,40,45,113-124,132,368-$ 369, 490, 493
graphs of, 113, 122
simple random sampling, 205-206
difficulties of estimating a population total, 188
simulated tempering for MCMC, 309
simulation, see posterior simulation
single-parameter models, 29-62
SIR, see importance resampling
slice sampling for MCMC, 297, 309
Slovenia survey, 463-466
small-area estimation, 133
software, 589-606
Bugs, 27, 133, 269, 272
debugging, 270-271, 605-606
extended example using Stan and R, 589-605
programming tips, 270-271, 605-606
R, 22, 27, 589-606
R programming, 594-606
running Stan from R, 589
setting up, 589
Stan, 22, 269, 307-308, 589-594
speed of light example, 66, 143
posterior predictive checks, 146
spelling correction, simple example of Bayesian inference, 9-11
splines, 487-499
gay marriage, 499
golf putting, 499
multivariate, 495-498
sports
football, 13-16, 26
golf, 486, 499, 517
stability, 200
stable estimation, 91
stable unit treatment value assumption, 200, 231
Stan, 307-308, 589-594
standard errors, 85
state-level opinions from national polls, 422-423
statistical packages, see software
statistically significant but not practically significant, 151
regression example, 363
stepwise ascent, 312
stepwise regression, Bayesian interpretation of, 367
stratified sampling, 206-210
hierarchical model, 209-210, 292
pre-election polling, 207-210
strong ignorability, 203
Student- $t$ model, see $t$ model
subjectivity, $12,13,26,28,100,248,256$
sufficient statistics, $36,93,338$
summary statistics, 85
superpopulation inference, 200-203, 205206, 208, 209, 212, 214-216, 232
in Anova, 396-397
supplemented EM (SEM) algorithm, 324325
survey incentives, example of meta-analysis and decision analysis, 239-244
surveys, 205-214, 454-466, see also sampling
adolescent smoking, 148-150
Alcoholics Anonymous, 213-214
incentives to increase response rates, 239-244
pre-election polling, 207-210, 422423, 456-466
telephone, unequal sampling probabilities, 233-234
$t$ approximation, 319
$t$ distribution, 66, 578, 582
$t$ model, 437, 441-445
computation using data augmentation, 293-294
computation using parameter expansion, 295
interpretation as mixture, 437
tail-area probabilities, see $p$-values
target distribution (for iterative simulation), 261
test statistics and test quantities, 145
choosing, 147
examples, see model checking
graphical, 153-159
numerical, 143-152
thinning of MCMC sequences, 282
three steps of Bayesian data analysis, 3
tilted distribution in expectation propagation, 339
toxicology model, as example of an illposed system, 477-485
trans-dimensional MCMC, 297-299, 309
transformations, 21, 99
logarithmic, 380
logistic (logit, log-odds), 22, 125
not needed for incentives example, 241
not needed for incumbency example, 360
power, 188-191, 194-195
probit, 22
rat tumor example, 110
to improve MCMC efficiency, 293295
to reduce correlations in hierarchical models, 480
useful in setting up a multivariate model, 424
treatment variable, 353
truncated data, 224-228
$2 \times 2$ tables, $80,125,423-425$
type I errors, why we do not care about, 150
U.S. House of Representatives, 358
unbiasedness, see bias
unbounded likelihoods, 90
underidentified models, 89
uniform distribution, 575, 576
units, 353
unnormalized densities, 7,261
unseen species, estimating the number of, 349
utility in decision analysis, 238, 245, 248, 256
variable selection, why we prefer to use informative prior distributions, 367
variance matrix, see covariance matrix
variational inference, 331-338
EM as special case, 337
hierarchical model example, 332-335
model checking for, 336
picture of, 334, 335, 342
variational lower bound, 336
varying intercepts and slopes, 390-392
vector and matrix notation, 4
warm-up for MCMC sequences, 282
Watanabe-Akaike or widely available information criterion (WAIC), 173174, 177
discussion, 182
educational testing example, 179
weakly informative prior distribution, 5557, 128-132, 313-318
in Stan, 594
Weibull distribution, 576, 581
Wilcoxon rank test, 97
Wishart distribution, 576, 582
$y^{\text {rep }}, 145$
$\tilde{y}, 4,7,145$

