

# Subject Index

- Analysis of Means (ANOM), 20–22, 42–47,  
64, 68–69, 121, 135, 152, 405
  - assumptions, 555
  - for attributes data, 47
  - nonparametric, 47
  - with unequal variances, 45
- Analysis of Variance (ANOVA), 20–22, 35,  
58, 62–64, 75, 81, 83, 116, 117, 123,  
134, 152
  - identity, 40
  - Kruskal–Wallis, 46
- Basic concepts
  - blocking, 13
  - choice of factor levels, 14, 15, 17
  - experimental design objectives, 3
  - experimental units, 12
  - experimentation, 13, 162
    - by students, 162
    - steps, 13
  - hypothesis testing, 9
  - power, 38
  - randomization, 6, 7, 13, 223
    - complete, 31
    - restricted, 148
  - replication, 8, 123, 551
    - built in, 122
  - sample size determination, 9–11
  - selecting factors, 14
  - sequential experimentation, 3, 4
    - example of, 222–225
  - training for designing experiments,  
544–545
    - use of catapult, 545
  - treatments, 12
  - unbalanced data, 40
- Bayes plot, 138
- Box–Cox transformation, 232
- Classification and regression trees (CART),  
107
- Consolidated Standards of Reporting Trials  
(CONSORT), 430
- Designs
  - Addelman, 86
  - analytic studies, 500
  - assessing the capability of a system,  
528
  - calibration, 525–526
    - constrained least squares, 525
    - method of Lagrangian multipliers, 525
  - catalog of, 284
  - categorical response variables, 524
  - completely randomized design
    - assumptions, 32–33
    - checking, 34
    - degrees of freedom, 41

Designs (*cont.*)

- efficiency relative to RCB design, 61
- unequal variances, 41–42
- computer experiments, 523
  - space-filling designs, 523–524
- cost-minimizing, 522
- Cotter, 487–488
  - factor correlations, 488
- cross-classified (factorial), 292
- crossover (changeover), 429
  - advantages, 430
  - applications, 429–430
  - computer analysis, 437
  - designs for carryover effects, 432–435
    - Williams squares, 433–434
      - example, 435–436
  - disadvantages, 430, 431
  - examples, 431
  - optimal, 431, 432
- efficiency, 190
  - df-efficiency, 222
  - D-efficiency, 320, 330, 486, 487, 506–507
  - G-efficiency, 283, 330
- equileverage, 501–503
- factorial, 101
  - $2^2$ , 101–102
    - example, 103–106
  - $2^3$ , 119–120
    - examples, 120–122
  - $2^5$ , 136
  - $2^k$ , 142
    - blocking, 141
    - example, 142–144
  - $3^2$ , 248
    - decomposing the A\*B interaction, 251
      - example, 252
  - $3^k$ , 248–257
    - inference, 252
    - interaction components, 250, 277, 288
    - linear effect, 253
    - quadratic effect, 253
- bad data, 127–130
  - example, 131–134
- blocking, 194
- missing data, 138–140
- mixed factorials, 263–266
  - constructing, 265
  - examples, 264, 266–273
  - need for, 263–264
- Graeco-Latin square, 74, 80–84, 91
  - application, 82
  - degrees of freedom limitations, 81–82
  - hyper, 90–91
  - model, 80
  - power, 82
  - sets of, 82, 84
  - use of ANOM, 83
- incomplete block designs, 65–71, 90
  - $\alpha$ -designs, 70–71, 90
  - balanced (BIB), 65–69, 84, 85, 526
    - analysis, 66–68
    - recovery of interblock information, 68
    - use of ANOM, 68–69
  - lattice, 70, 79
  - nonparametric analysis, 70
  - partially balanced, 69–70
- John's 3/4 designs, 216–219
- Latin square, 70–79, 84–85, 228, 562
  - assumptions, 72–74
  - efficiency, 77
  - example, 74–76
  - missing values, 86
    - example, 88
  - model, 74
  - standard form, 71, 72
  - use of ANOM, 76, 79
  - using multiple Latin squares, 77–79
- microarray experiments, 529–530
- mixture, 522–523
  - ANOM, 523
  - optimal, 523
- model-robust, 528–529
- multiple responses, 452–453
- nested (hierarchical), 291
  - ANOM, 302
  - applications, 292–293
  - estimating variance components, 300–301
  - examples, 294–298
  - factor, 292
    - model, 292
  - factorial, 291
  - software shortcomings, 295–296
    - a workaround, 295–296

- staggered, 298–300
  - with factorial structure, 300
- nonlinear models, 528
- non-normal responses, 529
- nonorthogonal, 212
  - inadvertent, 225
- nonregular, 170
  - defined, 170
- one-factor-at-a-time (OFAT) designs, 3, 115–116, 483–487
  - advantages, 486, 487
  - nonorthogonality, 486, 487
  - OFAT designs versus OFAT experimentation, 484
  - statistical process control checks, 487
  - strict, 485, 486
- optimal, 69, 503–507
  - applications, 507
  - criticisms, 504, 505
  - D-optimal, 279, 281, 282, 330, 364, 504, 507, 508, 512, 513, 532
    - Bayesian, 504–505
    - CONVERT algorithm, 505
  - E-optimal, 505
  - G-optimal, 505
  - GH-optimal, 511
  - incorporating costs, 522
  - I-optimal, 364
  - L-optimal, 505
  - model-robust, 504
  - Q-optimal, 511
- orthogonal arrays, 102, 138, 170, 229, 282, 321, 499
  - combined, 314, 316, 318
  - compound, 318, 319
  - inner, 314, 318, 321, 326
  - mixed levels, 275–277, 321
  - outer, 314, 318, 321, 326
  - product, 314–316, 318
- orthogonal main effect plans, 278, 489
- Plackett–Burman, 212, 215, 230, 231, 336, 378–379, 381, 383, 405, 489, 532
  - applications, 494–498, 542
  - foldover, 494
  - projective properties, 493, 494
- projective properties, 170
- randomized complete block (RCB)
  - design, 56–64, 77, 195, 344
  - assumption, 57–58
  - efficiency, 61
  - missing values, 86–87
  - number of blocks to use, 59
  - use of ANOM, 64
- repeated measures, 425
  - advantages, 425
  - carryover effects, 427
  - crossover designs, 429
  - example, 428
  - how many?, 437
  - missing data and imputation, 438
- response surface, 360
  - applications of, 361
  - blocking, 394–397
  - Box–Behnken, 386–389, 477, 478, 502
    - blocking, 396
    - rotatability, 387
  - central composite (CCD), 361, 363, 365, 368, 369, 373–377, 385, 389, 395, 397, 405, 495, 502
    - blocking, 394–395
    - centerpoints, 373–376
    - example, 383–384
    - face centered cube, 377, 404
    - inscribed (CCI), 377, 388
    - uniform precision design, 375
  - comparison, 397
  - desirable properties, 360–361
    - orthogonality, 375
    - rotatability, 375–377
  - Doehlert (uniform shell) designs, 393
    - applications, 393
  - Draper–Lin (small composite) designs, 377–383
    - blocking, 396, 397
  - eligible projected, 363
  - for computer simulations, 404
  - Hoke, 394, 397
  - hybrid, 390
    - 311A, 391
  - Koshal, 393
  - noncentral composite, 405
  - number of designs to use, 362–364
  - optimal, 405
  - row-column, 406
  - small factor changes, 364
  - split factorial, 405
- restricted regions of operability, 508–514
  - examples, 508–514

Designs (*cont.*)

- robust, 311
- rotation, 488
- saturated, 105, 138, 489
- screening, 15, 360, 489–500
  - p*-efficient, 500
- space-filling, 369, 385, 386, 514–521
  - Latin hypercube, 369, 519–521
    - example, 520–521
  - properties, 384–386
  - sphere-packing, 369, 385, 518–519
  - uniform, 364, 366, 368, 369, 389, 507, 514–518
    - applications, 386
    - definition, 515
- split-plot, 345–346, 349
  - use of fractional factorials, 345–346
- split-plot, 330–331, 349, 351, 560
  - blocking, 342–343
  - example, 333
    - analysis, 333–335
      - versus incorrect complete randomization analysis, 335
  - in industry, 336
    - example, 336–338, 355
  - mirror image pairs design, 336
  - Plackett–Burman designs, 343
  - subplot, 332, 349
    - error, 333
      - independent of whole plot error, 339
  - whole plot, 331–332, 338, 349
    - error, 332
  - with fractional factorials, 340–342
    - example, 341
  - with hard-to-change factors, 343
    - examples, 343–345
- split-split-plot, 345
- split-unit, 330–331
- strip-plot (strip-block), 346–349
  - applications, 347–349
  - example, 346–347
    - use of fractional factorials, 346–348
- supersaturated, 489, 498–500, 513, 563
  - nonorthogonality, 499
- Taguchi, 312–315, 320–322, 544
  - equivalent to suboptimal fractional factorials, 313
- trend-free, 521–522

- unreplicated, 114, 116
- weighing, 524–528
- with noise factors, 316–318
- Youden design, 84–86
  - lists of, 86
  - model, 85
  - replicated, 86

## Dual response problem, 406

## Effects

- conditional main, 107, 109, 114, 115, 121, 133, 134, 147, 179, 208, 209, 255–257, 317, 318, 372, 380, 381, 388, 389–390, 407, 467, 485, 492
  - derivation of, 152
  - example, 108, 113
  - necessary sample sizes for, 113
  - two-split, 181
- confounded, 5, 12
- dispersion, 150, 312
  - detecting, 150, 314
- estimates, 114
  - precision of, 153
  - relationship with regression coefficients, 153, 177
- interaction, 102, 106, 134
  - control  $\times$  noise, 315, 319
  - generalized, 318
  - noise  $\times$  noise, 316
  - transformations, 114
  - Tukey test for, 117–118
- location, 312
- main, 102
- partial confounding, 5
- simple, 107
- Evolutionary Operation (EVOP), 363–364, 531
  - Box–EVOP, 531
  - dealing with interactions, 531
  - simplex, 364
- Expected mean squares, 144–146, 273
  - for replicated  $2^2$  design, 153–155
  - in general, 155–157
  - simple method of determining, 146
- Factors
  - control, 311, 316, 318, 321
  - fixed, 32, 101, 146

- hard to change, 148–150, 212, 267, 332, 335, 344, 484, 487, 507, 522
  - software, 150
- noise, 311, 312, 316, 318, 321
- not reset, 150
- qualitative, 6, 101
- quantitative, 6, 101
- random, 32, 146
  - hypothesis tests, 146–147
- False discovery rate (FDR), 137
- Fractional factorials, 169
  - $3/4$  fractions, 216–219
  - $2^{k-p}$ , 176, 186
    - projective properties, 219–220
  - $2^{k-1}$ , 170–181
  - $2^{k-2}$ , 181–187
    - example, 182–184
  - $2^{3-1}$ , 171, 176, 178
  - $2^{4-1}$ , 175, 180
  - $2^{5-2}$ , 191
  - $2^{6-2}$ , 202
  - $3^{k-p}$ , 257–262, 362
    - constructing, 260–262
    - linear and quadratic effects, 259
    - minimum aberration, 277
    - minimum confounded effects, 277
    - projective properties, 259
  - $3^{k-1}$ , 262–263
    - alias structure, 262
  - $3^{3-1}$ , 262–263
  - 4 or more levels
    - method of replacement, 278
  - $4^{3-1}$ , 279
  - 16–point designs, 187
  - aliases and alias structure, 174, 177–179, 283
    - partial aliasing/partial confounding, 174
  - alternatives to, 229
  - bad data, 230
  - blocking, 195
    - examples, 196, 199
    - size two blocks, 200–201
  - confounded effects, 174
  - defining relation, 171
    - retrieving lost relation, 190–192
  - df-efficiency, 222
  - foldover, 178, 200–203
    - of a  $2^{k-1}$  design, 201
    - mirror image, 200, 201
    - semi-foldover, 203–216, 233
      - of a  $2^{k-2}$  design, 204
      - with software, 215
    - shortcomings, 203
    - for natural subsets of factors, 226–228
    - irregular fraction, 216, 220, 221
    - minimum aberration, 192–194
    - missing data, 230
    - mixed level, 274–275
      - linear effects, 276
      - quadratic effects, 276
    - number of clear effects criterion, 192–194
    - one fraction better than another?, 179–181
    - post-fractionation, 226, 227, 348–349
    - pre-fractionation, 226
    - projective properties, 170
    - relationship with Latin squares, 228–229
    - replicated, 223
    - resolution, 169, 187, 212, 233
      - defined, 170
    - small fractions, 220
- Gage R&R (reproducibility and repeatability) study, 295
- Gantt charts, 13
- Generalized  $F$ -test, 42, 46
- Hadamard matrix, 488
- Journal of Statistics Education*, 544
- Lenth's sample size determination applet, 11, 39, 59, 77
- Lenth's PSE method, 124, 126–129, 131, 136–139, 173, 188, 233, 252, 319, 338, 470, 485, 489, 496, 560
- Leverage values, 385, 501
  - saturated design, 501
- Lurking variable, 6
- Measurement capability studies, 523
- Missing data, 22, 39–40, 48, 230
- Modeling variability, 316
- Models
  - generalized linear, 529
  - hierarchical, 147, 390
  - mixed, 58
  - nonhierarchical, 147, 378, 390, 407
  - unrestricted, 156

- Modular arithmetic, 251, 279
- Multiple comparisons, 36, 37
  - Bonferroni intervals, 37, 38
  - Scheffé's procedure, 38, 59, 60
- Multiple readings, 8, 117, 123
- Multiple response optimization, 447
  - desirability function, 449
    - composite desirability, 450, 457
    - example, 450
    - exponential, 464
    - importance constant, 451, 460, 461, 468
    - maximization, 450, 457
    - minimization, 450
    - target value, 451
    - weight constant, 451, 460, 461
  - desirability graph, 456
  - dual response optimization, 452
  - examples, 453–463
  - frequent assumptions, 447
  - global optimum, 448
  - Hooke–Jeeves method, 450, 463, 464
  - local optima, 448, 450
  - overlaid contour plots, 447–449
  - pitfalls, 447, 455
  - variations, 463–464
    - genetic algorithm approach, 464
    - generalized reduced gradient algorithm, 463–464
    - mean squared error method, 464
    - piecewise desirability function, 463
- Multi-vari plot, 530–531
- NIST/SEMATECH e-Handbook of Statistical Methods*, 18, 86, 111, 188, 347, 360, 525, 545
- Normal probability plot methods, 136, 187, 188, 194, 560
- Optimum operating conditions, 225, 360, 404
  - methods for determining, 360
- Organizations cited
  - American Society for Quality (ASQ), 1
  - Booth Dispensers, Ltd., 499
  - Morton Powder Coatings, 343
  - National Institute of Standards and Technology (NIST), 111, 135, 225, 524, 525
  - Procter and Gamble, 320
  - Rayovac, 347–348
  - Rothamsted Experimental Station, 179, 182
- Pareto effects chart/analysis, 126, 180, 213, 214, 255, 498
- Processes in/out of statistical control, 18, 19, 189, 255, 267
  - blocking out-of-control process, 60–61
  - checking for, 141, 266, 487
  - check runs, 19
- Quasi-experimental design, 23
- $R^2$ , 208, 255, 266, 271, 273, 373, 497
- Region of operability, 364
  - irregular design space, 386
  - restricted, 387, 404, 508–514
    - debarred observations, 387, 508, 509, 514
- Response surface methodology (RSM), 360
  - analyzing fitted surface, 398–404
    - contours of constant response, 398
    - ridge analysis, 403–404
      - method of Lagrangian multipliers, 403
      - with noise variables, 404
    - rising ridge, 398
    - stationary points, 400–403
      - confidence regions on, 402–403
  - in a three-stage operation, 418
  - in the food industry, 417
  - method of steepest ascent/descent, 370–373, 561
    - example, 371–372
    - modified method, 405
    - scale-independent methods, 373
- Satterthwaite's procedure, 271, 272
- Shainin's variables search approach, 500
- Six Sigma, 22
- Sliding reference distribution, 36
- Software for experimental design, 48, 89–90, 151, 333, 350, 531–532
  - Cornerstone, 471
  - Dataplot, 135
  - Design-Expert, 1, 11, 48, 89, 90, 151, 154, 157, 175, 176, 177, 192, 201, 215,

- 216, 217, 230–232, 246, 250, 252,  
279–281, 282, 291, 295, 313, 321,  
326, 328, 350, 369, 371, 379, 380,  
391–393, 396, 397, 407, 438, 452,  
457–462, 467–471, 480, 490, 492,  
498, 504, 505, 518, 532
- D.o.E. Fusion Pro, 48, 151, 230, 232, 283,  
295, 321, 350, 356, 392, 407
- Echip, 471
- Gendex DOE toolkit, 90, 408, 511, 522
- GOSSET, 1, 505
- JMP, 1, 48, 89, 90, 157, 176, 187, 192,  
201, 230–233, 265, 278–279, 281,  
282, 289, 295, 297, 321, 366, 370,  
375, 392, 407, 408, 427, 438,  
455–458, 460, 461, 464, 468–471,  
480, 488, 505, 511, 512, 516–519,  
532
- MathWorks, 520
- MAPLE, 403
- MINITAB, 1, 48, 64, 67, 87, 89, 90, 109,  
124, 127, 131, 135, 143, 146, 149,  
150, 154, 157, 176, 180, 186, 192,  
201, 230–233, 243, 244, 248–250,  
252, 255, 256, 269, 271–273, 275,  
280, 287, 295, 300, 301, 321, 350,  
365, 366, 374, 386, 392, 395, 396,  
398, 401, 407, 408, 427, 438, 445,  
452, 470, 471, 475, 490, 491, 493,  
495, 501, 532
- MIXSOFT, 523
- R (CROSSDES), 434, 438
- RS/1, 508
- RS/Discover, 295, 350, 532
- SAS Software, 64, 89–90, 157, 230, 271,  
295, 297, 347, 350, 370, 404, 425,  
434, 437
- SPSS, 438
- Stat-ease, Inc., 130, 208, 221, 343
- Statgraphics, 90, 233, 408
- Statistica, 233
- Statistical process control methods, 19
- Stepwise regression, 122, 207, 208, 277,  
497, 499
- Strong heredity assumption, 109
- Weak heredity assumption, 109
- Yates' algorithm, 172, 174
- Yates order, 102–103, 127, 130, 134, 354