

# Contents

<b>Preface</b>	<b>xv</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Experiments All Around Us	2
1.2 Objectives for Experimental Designs	3
1.3 Planned Experimentation versus Use of Observational Data	5
1.4 Basic Design Concepts	6
1.4.1 Randomization	6
1.4.2 Replication versus Repeated Measurements	7
1.4.3 Example	8
1.4.4 Size of an Effect That Can be Detected	11
1.5 Terminology	12
1.6 Steps for the Design of Experiments	13
1.6.1 Recognition and Statement of the Problem	14
1.6.2 Selection of Factors and Levels	14
1.6.2.1 Choice of Factors	14
1.6.2.2 Choice of Levels	15
1.7 Processes Should Ideally be in a State of Statistical Control	18
1.8 Types of Experimental Designs	20
1.9 Analysis of Means	20
1.10 Missing Data	22
1.11 Experimental Designs and Six Sigma	22
1.12 Quasi-Experimental Design	23
1.13 Summary	23
References	23
Exercises	26

<b>2</b>	<b>Completely Randomized Design</b>	<b>31</b>
2.1	Completely Randomized Design	31
2.1.1	Model	32
2.1.2	Example: One Factor, Two Levels	33
2.1.2.1	Assumptions	33
2.1.3	Examples: One Factor, More Than Two Levels	35
2.1.3.1	Multiple Comparisons	36
2.1.3.2	Unbalanced and Missing Data	39
2.1.3.3	Computations	40
2.1.4	Example Showing the Effect of Unequal Variances	41
2.2	Analysis of Means	42
2.2.1	ANOM for a Completely Randomized Design	43
2.2.1.1	Example	44
2.2.2	ANOM with Unequal Variances	45
2.2.2.1	Applications	47
2.2.3	Nonparametric ANOM	47
2.2.4	ANOM for Attributes Data	47
2.3	Software for Experimental Design	48
2.4	Missing Values	48
2.5	Summary	48
	Appendix	49
	References	49
	Exercises	51
<b>3</b>	<b>Designs that Incorporate Extraneous (Blocking) Factors</b>	<b>56</b>
3.1	Randomized Block Design	56
3.1.1	Assumption	57
3.1.2	Blocking an Out-of-Control Process	60
3.1.3	Efficiency of a Randomized Block Design	61
3.1.4	Example	61
3.1.4.1	Critique	63
3.1.5	ANOM	64
3.2	Incomplete Block Designs	65
3.2.1	Balanced Incomplete Block Designs	65
3.2.1.1	Analysis	66
3.2.1.2	Recovery of Interblock Information	68
3.2.1.3	ANOM	68
3.2.2	Partially Balanced Incomplete Block Designs	69
3.2.2.1	Lattice Design	70
3.2.3	Nonparametric Analysis for Incomplete Block Designs	70
3.2.4	Other Incomplete Block Designs	70
3.3	Latin Square Design	71
3.3.1	Assumptions	72
3.3.2	Model	74

CONTENTS	vii
3.3.3 Example	74
3.3.4 Efficiency of a Latin Square Design	77
3.3.5 Using Multiple Latin Squares	77
3.3.6 ANOM	79
3.4 Graeco–Latin Square Design	80
3.4.1 Model	80
3.4.2 Degrees of Freedom Limitations on the Design Construction	81
3.4.3 Sets of Graeco–Latin Square Designs	82
3.4.4 Application	82
3.4.5 ANOM	83
3.5 Youden Squares	84
3.5.1 Model	85
3.5.2 Lists of Youden Designs	86
3.5.3 Using Replicated Youden Designs	86
3.5.4 Analysis	86
3.6 Missing Values	86
3.7 Software	89
3.8 Summary	90
References	91
Exercises	93
<b>4 Full Factorial Designs with Two Levels</b>	<b>101</b>
4.1 The Nature of Factorial Designs	101
4.2 The Deleterious Effects of Interactions	106
4.2.1 Conditional Effects	107
4.2.1.1 Sample Sizes for Conditional Effects Estimation	113
4.2.2 Can We “Transform Away” Interactions?	114
4.3 Effect Estimates	114
4.4 Why Not One-Factor-at-a-Time Designs?	115
4.5 ANOVA Table for Unreplicated Two-Factor Design?	116
4.6 The $2^3$ Design	119
4.7 Built-in Replication	122
4.8 Multiple Readings versus Replicates	123
4.9 Reality versus Textbook Examples	124
4.9.1 Factorial Design but not “Factorial Model”	124
4.10 Bad Data in Factorial Designs	127
4.10.1 ANOM Display	134
4.11 Normal Probability Plot Methods	136
4.12 Missing Data in Factorial Designs	138
4.12.1 Resulting from Bad Data	139
4.12.2 Proposed Solutions	140
4.13 Inaccurate Levels in Factorial Designs	140
4.14 Checking for Statistical Control	141
4.15 Blocking $2^k$ Designs	142

4.16	The Role of Expected Mean Squares in Experimental Design	144
4.17	Hypothesis Tests with Only Random Factors in $2^k$ Designs? Avoid Them!	146
4.18	Hierarchical versus Nonhierarchical Models	147
4.19	Hard-to-Change Factors	148
4.19.1	Software for Designs with Hard-to-Change Factors	150
4.20	Factors Not Reset	150
4.21	Detecting Dispersion Effects	150
4.22	Software	151
4.23	Summary	151
	Appendix A Derivation of Conditional Main Effects	152
	Appendix B Relationship Between Effect Estimates and Regression Coefficients:	153
	Appendix C Precision of the Effect Estimates	153
	Appendix D Expected Mean Squares for the Replicated $2^2$ Design	153
	Appendix E Expected Mean Squares, in General	155
	References	157
	Exercises	162
<b>5</b>	<b>Fractional Factorial Designs with Two Levels</b>	<b>169</b>
5.1	$2^{k-1}$ Designs	170
5.1.1	Which Fraction?	176
5.1.2	Effect Estimates and Regression Coefficients	177
5.1.3	Alias Structure	177
5.1.4	What if I Had Used the Other Fraction?	179
5.2	$2^{k-2}$ Designs	181
5.2.1	Basic Concepts	185
5.3	Designs with $k - p = 16$	187
5.3.1	Normal Probability Plot Methods when $k - p = 16$	187
5.3.2	Other Graphical Methods	188
5.4	Utility of Small Fractional Factorials vis-à-vis Normal Probability Plots	188
5.5	Design Efficiency	190
5.6	Retrieving a Lost Defining Relation	190
5.7	Minimum Aberration Designs and Minimum Confounded Effects Designs	192
5.8	Blocking Factorial Designs	194
5.8.1	Blocking Fractional Factorial Designs	195
5.8.1.1	Blocks of Size 2	200
5.9	Foldover Designs	201
5.9.1	Semifolding	203
5.9.1.1	Conditional Effects	208
5.9.1.2	Semifolding a $2^{k-1}$ Design	210

CONTENTS	<b>ix</b>
5.9.1.3 General Strategy?	215
5.9.1.4 Semifolding with Software	215
5.10 John's 3/4 Designs	216
5.11 Projective Properties of $2^{k-p}$ Designs	219
5.12 Small Fractions and Irregular Designs	220
5.13 An Example of Sequential Experimentation	222
5.13.1 Critique of Example	224
5.14 Inadvertent Nonorthogonality—Case Study	225
5.15 Fractional Factorial Designs for Natural Subsets of Factors	226
5.16 Relationship Between Fractional Factorials and Latin Squares	228
5.17 Alternatives to Fractional Factorials	229
5.17.1 Designs Attributed to Genichi Taguchi	229
5.18 Missing and Bad Data	230
5.19 Plackett–Burman Designs	230
5.20 Software	230
5.21 Summary	233
References	234
Exercises	238
<b>6 Designs With More Than Two Levels</b>	<b>248</b>
6.1 $3^k$ Designs	248
6.1.1 Decomposing the $A*B$ Interaction	251
6.1.2 Inference with Unreplicated $3^k$ Designs	252
6.2 Conditional Effects	255
6.3 $3^{k-p}$ Designs	257
6.3.1 Understanding $3^{k-p}$ Designs	259
6.3.2 Constructing $3^{k-p}$ Designs	260
6.3.3 Alias Structure	262
6.3.4 Constructing a $3^{3-1}$ Design	262
6.3.5 Need for Mixed Number of Levels	263
6.3.6 Replication of $3^{k-p}$ Designs?	264
6.4 Mixed Factorials	264
6.4.1 Constructing Mixed Factorials	265
6.4.2 Additional Examples	266
6.5 Mixed Fractional Factorials	274
6.6 Orthogonal Arrays with Mixed Levels	275
6.7 Minimum Aberration Designs and Minimum Confounded Effects Designs	277
6.8 Four or More Levels	278
6.9 Software	280
6.10 Catalog of Designs	284
6.11 Summary	284
References	284
Exercises	286

<b>7</b>	<b>Nested Designs</b>	<b>291</b>
7.1	Various Examples	294
7.2	Software Shortcomings	295
7.2.1	A Workaround	295
7.3	Staggered Nested Designs	298
7.4	Nested and Staggered Nested Designs with Factorial Structure	300
7.5	Estimating Variance Components	300
7.6	ANOM for Nested Designs?	302
7.7	Summary	302
	References	302
	Exercises	304
<b>8</b>	<b>Robust Designs</b>	<b>311</b>
8.1	“Taguchi Designs?”	312
8.2	Identification of Dispersion Effects	314
8.3	Designs with Noise Factors	316
8.4	Product Array, Combined Array, or Compound Array?	318
8.5	Software	320
8.6	Further Reading	322
8.7	Summary	322
	References	323
	Exercises	326
<b>9</b>	<b>Split-Unit, Split-Lot, and Related Designs</b>	<b>330</b>
9.1	Split-Unit Design	331
9.1.1	Split-Plot Mirror Image Pairs Designs	336
9.1.2	Split-Unit Designs in Industry	336
9.1.3	Split-Unit Designs with Fractional Factorials	340
9.1.4	Blocking Split-Plot Designs	342
9.1.5	Split-Unit Plackett-Burman Designs	343
9.1.6	Examples of Split-Plot Designs for Hard-to-Change Factors	343
9.1.7	Split-Split-Plot Designs	345
9.2	Split-Lot Design	345
9.2.1	Strip-Plot Design	346
9.2.1.1	Applications of Strip-Block (Strip-Plot) Designs	347
9.3	Commonalities and Differences Between these Designs	349
9.4	Software	350
9.5	Summary	351
	References	351
	Exercises	354

CONTENTS	<b>xi</b>
<b>10 Response Surface Designs</b>	<b>360</b>
10.1 Response Surface Experimentation: One Design or More Than One?	362
10.2 Which Designs?	364
10.3 Classical Response Surface Designs versus Alternatives	364
10.3.1 Effect Estimates?	369
10.4 Method of Steepest Ascent (Descent)	370
10.5 Central Composite Designs	373
10.5.1 CCD Variations	377
10.5.2 Small Composite Designs	377
10.5.2.1 Draper–Lin Designs	378
10.5.3 Additional Applications	383
10.6 Properties of Space-Filling Designs	384
10.7 Applications of Uniform Designs	386
10.8 Box–Behnken Designs	386
10.8.1 Application	388
10.9 Conditional Effects?	389
10.10 Other Response Surface Designs	390
10.10.1 Hybrid Designs	390
10.10.2 Uniform Shell Designs	393
10.10.3 Koshal Designs	393
10.10.4 Hoke Designs	394
10.11 Blocking Response Surface Designs	394
10.11.1 Blocking Central Composite Designs	394
10.11.2 Blocking Box–Behnken Designs	396
10.11.3 Blocking Other Response Surface Designs	396
10.12 Comparison of Designs	397
10.13 Analyzing the Fitted Surface	398
10.13.1 Characterization of Stationary Points	401
10.13.2 Confidence Regions on Stationary Points	402
10.13.3 Ridge Analysis	403
10.13.3.1 Ridge Analysis with Noise Factors	404
10.13.4 Optimum Conditions and Regions of Operability	404
10.14 Response Surface Designs for Computer Simulations	404
10.15 ANOM with Response Surface Designs?	405
10.16 Further Reading	405
10.17 The Present and Future Direction of Response Surface Designs	406
10.18 Software	406
10.19 Catalogs of Designs	408
10.20 Summary	408
References	409
Exercises	414

<b>11 Repeated Measures Designs</b>	<b>425</b>
11.1 One Factor	426
11.1.1 The Example in Section 2.1.2	428
11.2 More Than One Factor	428
11.3 Crossover Designs	429
11.4 Designs for Carryover Effects	432
11.5 How Many Repeated Measures?	437
11.6 Further Reading	438
11.7 Software	438
11.8 Summary	439
References	439
Exercises	444
<b>12 Multiple Responses</b>	<b>447</b>
12.1 Overlaying Contour Plots	448
12.2 Seeking Multiple Response Optimization with Desirability Functions	449
12.2.1 Weight and Importance	451
12.3 Dual Response Optimization	452
12.4 Designs Used with Multiple Responses	452
12.5 Applications	453
12.6 Multiple Response Optimization Variations	463
12.7 The Importance of Analysis	469
12.8 Software	469
12.9 Summary	471
References	472
Exercises	474
<b>13 Miscellaneous Design Topics</b>	<b>483</b>
13.1 One-Factor-at-a-Time Designs	483
13.2 Cotter Designs	487
13.3 Rotation Designs	488
13.4 Screening Designs	489
13.4.1 Plackett–Burman Designs	489
13.4.1.1 Projection Properties of Plackett–Burman Designs	493
13.4.1.2 Applications	494
13.4.2 Supersaturated Designs	498
13.4.2.1 Applications	499
13.4.3 Lesser-Known Screening Designs	500
13.5 Design of Experiments for Analytic Studies	500
13.6 Equileverage Designs	501
13.6.1 One Factor, Two Levels	502
13.6.2 Are Commonly Used Designs Equileverage?	502

CONTENTS	<b>xiii</b>
13.7 Optimal Designs	503
13.7.1 Alphabetic Optimality	504
13.7.2 Applications of Optimal Designs	507
13.8 Designs for Restricted Regions of Operability	508
13.9 Space-Filling Designs	514
13.9.1 Uniform Designs	515
13.9.1.1 From Raw Form to Coded Form	518
13.9.2 Sphere-Packing Designs	518
13.9.3 Latin Hypercube Design	519
13.10 Trend-Free Designs	521
13.11 Cost-Minimizing Designs	522
13.12 Mixture Designs	522
13.12.1 Optimal Mixture Designs or Not?	523
13.12.2 ANOM	523
13.13 Design of Measurement Capability Studies	523
13.14 Design of Computer Experiments	523
13.15 Design of Experiments for Categorical Response Variables	524
13.16 Weighing Designs and Calibration Designs	524
13.16.1 Calibration Designs	525
13.16.2 Weighing Designs	526
13.17 Designs for Assessing the Capability of a System	528
13.18 Designs for Nonlinear Models	528
13.19 Model-Robust Designs	528
13.20 Designs and Analyses for Non-normal Responses	529
13.21 Design of Microarray Experiments	529
13.22 Multi-Vari Plot	530
13.23 Evolutionary Operation	531
13.24 Software	531
13.25 Summary	532
References	533
Exercises	542
<b>14 Tying It All Together</b>	<b>544</b>
14.1 Training for Experimental Design Use	544
References	545
Exercises	546
<b>Answers to Selected Exercises</b>	<b>551</b>
<b>Appendix: Statistical Tables</b>	<b>565</b>
<b>Author Index</b>	<b>575</b>
<b>Subject Index</b>	<b>587</b>

