
Contents

List of Figures.....	xxi
List of Tables	xxv
List of Materials on Accompanying Disk.....	xxvii
Series Preface—International Forensic Science Series	xxxi
Foreword	xxxiii
Acknowledgments	xxxvii
Authors	xxxix
Prologue	xli

Section I An Introduction to Forensic Metrology for Lawyers, Judges, and Forensic Scientists

Chapter 1 Science, Metrology, and the Law	3
1.1 Science!	3
1.1.1 Science and the Law	3
1.1.2 A Foundation for Science in the Courtroom	4
1.2 What is Science?	5
1.2.1 Knowledge of the Physical Universe	5
1.2.1.1 Descriptive versus Explanatory	5
1.2.1.2 Example: Quantum Considerations	6
1.2.1.3 Knowledge as Description and Model	6
1.2.1.4 Example: The Ptolemaic Model of the Universe	7
1.2.2 Empiricism	8
1.2.2.1 Information versus Fact	9
1.2.2.2 Example: Blood Alcohol Measurements..	9
1.2.2.3 Incomplete Information	9
1.2.3 Recap	10
1.2.4 Hallmarks of Science	10
1.2.4.1 Falsifiability and Testability	10
1.2.4.2 Puzzle Solving	11
1.2.4.3 Example: Puzzle Solving in Forensic Toxicology.....	11
1.2.4.4 Predicting Novel Phenomena.....	12
1.2.4.5 Example: Prediction of a New Planet ..	12
1.2.4.6 The Scientific Method	13
1.2.4.7 Defining Terms, Concepts, and Phenomena	14
1.2.4.8 Example: What Is an Analogue?	15

1.2.5	Specific Principles of Reasoning: The Inferential Process	15
1.2.5.1	Rules of Inference.....	16
1.2.5.2	Example: Chemistry and Rules of Inference	17
1.2.5.3	Hierarchy of Inferential Rules	17
1.2.5.4	Creation and Destruction of Inferential Rules	18
1.2.6	Epistemological Robustness of Scientific Conclusions.....	18
1.2.6.1	Example: Error Analysis and the Discovery of Planetary Laws	19
1.2.7	A Working Definition of Science	20
1.3	Forensic Science and the Law	22
1.3.1	Science in the Courtroom	22
1.3.2	Forensic Science as Science	23
1.4	Metrology: The Science of Measurement	24
1.4.1	Measurement	24
1.4.2	Components of Measurement	25
1.4.2.1	The Quantity Intended to Be Measured ..	25
1.4.2.2	An Exercise in Comparison	25
1.4.2.3	Universally Accepted Scales	26
1.4.2.4	How to Measure	26
1.4.2.5	Performing the Measurement	27
1.4.2.6	Conclusions Supported	27
1.4.2.7	Information and Inference	28
1.4.3	Metrology.....	28
1.4.3.1	Who Is a “Metrologist”?	29
1.4.3.2	Forensic Metrology	29
1.5	Why Forensic Metrology for Judges, Lawyers, and Scientists?	30
	Endnotes	30
Chapter 2	Introduction to Measurement: The Measurand	33
2.1	What is Measurement?	33
2.1.1	Definition	33
2.1.1.1	Comparison as Experiment	33
2.1.1.2	Quantity	33
2.1.1.3	Quantity Value	34
2.1.1.4	Measurement Unit	34
2.1.1.5	Quantitative Information.....	34
2.1.1.6	Measurement Summary.....	35
2.2	The Measurand	35
2.2.1	Specification of the Measurand.....	35
2.2.1.1	Example: Ambiguity in Specification....	36
2.2.2	The Well-Defined Measurand	36

2.2.2.1	Example: Weighing Drugs.....	37
2.3	Intended to be Measured versus Subject to Measurement.....	38
2.3.1	The “Measurand Problem”	38
2.3.2	Direct and Indirect Measurements	39
2.3.3	Measurement Model	40
2.3.4	Measurement Function.....	40
2.3.5	Example: Measurement Function in Blood Alcohol Testing	41
2.4	Case Study: The Measurand in Forensic Breath Alcohol Testing	41
2.4.1	Blood Alcohol Concentration	42
2.4.2	Breath Tests to Measure BAC	42
2.4.3	Failure of a Model.....	43
2.4.4	Refining the Model.....	44
2.4.4.1	Breath Alcohol as Measurement Indication	44
2.4.4.2	A “New” Measurement Function	44
2.4.5	Breath Alcohol as Measurand	45
2.4.5.1	What Is Breath?	45
2.4.5.2	What Is Breath Alcohol Concentration? .	46
2.4.6	Simplifying the Model: End-Expiratory Breath	47
2.4.7	End-Expiratory Breath: An Underdefined Measurand	47
2.4.7.1	A Set of Quantities Satisfying the Defined Measurand	47
2.4.7.2	Multivalued.....	48
2.4.7.3	How Badly Underdefined?	49
2.4.7.4	Constitutional Infirmitiess?	51
2.4.8	The Measurand Problem in Breath Alcohol Testing	51
2.4.8.1	Three Types of Breath Test Jurisdictions	52
2.4.8.2	Summary of the Measurand Problem ..	54
2.4.9	Most Rational Measurand for a Breath Test: BAC?	54
	Endnotes	55
Chapter 3	Weights and Measures.....	57
3.1	Weights and Measures Generally	57
3.1.1	Ambiguity in Measurement.....	57
3.1.2	Overcoming Ambiguity	58
3.1.3	Recognized Importance	59
3.1.4	The International System of Weights and Measures.....	59
3.2	International System of Quantities (ISQ)	60

3.2.1	Derived Quantities and Quantity Relationships.....	61
3.2.2	Quantity Dimensions.....	62
3.2.3	Quantities of the Same Kind.....	63
3.3	The International System of Units	63
3.3.1	Measurement Units	63
3.3.2	Quantity Value Is Dependent Upon Units	63
3.3.3	The International System of Units.....	64
3.3.4	Acceptable Non-SI Units	66
3.3.5	Large and Small Values Expressed in Units	67
3.3.6	Units of Measure in Forensic Practice	68
3.3.6.1	Nonuniform Conventions	69
3.3.6.2	Origin of $\frac{\text{g}}{\text{210 L}}$ Unit Convention in Forensic Breath Alcohol Testing	70
3.3.7	Definitions and History of SI Units	71
3.3.7.1	The Meter: Base Unit of Length	72
3.3.7.2	The Kilogram: Base Unit of Mass	73
3.3.7.3	The Second: Base Unit of Time	73
3.3.7.4	The Ampere: Base Unit of Electric Current.....	74
3.3.7.5	The Kelvin: Base Unit of Thermodynamic Temperature	75
3.3.7.6	The Mole: Base Unit of the Amount of Substance	76
3.3.7.7	The Candela: Base Unit of Luminous Intensity	78
3.3.8	Ensuring That Reported Units Correspond to Their Definition	79
3.4	Metrological Traceability	80
3.4.1	Property of a Measurement Result	80
3.4.2	Related to a Reference	80
3.4.3	Unbroken Chain of Comparisons.....	81
3.4.4	Uncertainty	82
3.4.5	Documentation	82
3.4.6	A Fundamental Element of Good Measurement Results	82
3.4.7	The Role of National Metrological Authorities	83
3.4.8	Traceability in Forensics.....	83
3.5	The National Institute of Standards and Technology	85
3.5.1	State Weights and Measures	86
3.5.2	Case Note: A Question of Supremacy in Forensic Science?	87
	Endnotes	87
Chapter 4	Validation and Good Measurement Practices.....	91
4.1	Finding an Appropriate Method	91

4.1.1	Method Validation	91
4.1.2	Characteristics Subject to Validation.....	93
4.1.3	Method Verification.....	94
4.1.4	Example: Consequences of Failing to Validate/Verify a Method.....	94
4.1.5	Fitness for Purpose	96
4.2	Good Measurement Practices	97
4.2.1	Performing a Measurement	97
4.2.2	Standard Operating Procedures.....	97
4.2.2.1	Example: SOPs in Forensic Toxicology.....	98
4.2.3	Calibration	99
4.2.3.1	Common Calibration Technique	99
4.2.3.2	Calibration, Bias, and the Best Estimate of a Measurand's Value.....	100
4.2.3.3	Calibration and Bias in Forensic Measurements	101
4.2.3.4	Example: Calibration Requirements in the Courtroom	103
4.2.3.5	Required for Valid Measurement.....	106
4.2.3.6	Range of Calibration	106
4.2.3.7	Example: Range of Calibration in Breath Alcohol Measurements	107
4.2.3.8	Example: Measurements by Law Enforcement Officers in the Field	107
4.3	Consensus Standards	109
4.3.1	ISO 17025: The Gold Standard.....	111
4.3.2	Metrological Terminology: The VIM and the TAM.....	111
4.3.3	Consensus Standards for Chemical Measurements	112
4.3.4	Consensus Standards in Forensic Practice	112
4.3.5	Example: Consensus Standards in the Courtroom ..	113
4.4	Accreditation	115
4.4.1	Accrediting the Accreditors: ILAC.....	116
4.4.2	NIST's Role in Accreditation.....	116
4.4.2.1	Case Note: Accreditation as a Party Admission	117
4.4.3	Accreditation in Forensic Science.....	117
	Endnotes	118

Chapter 5	Result Interpretation-I: Metrological Prerequisites to Knowledge.....	123
5.1	Result Interpretation.....	123
5.2	Metrological Prerequisites to Knowledge	123
5.2.1	Specification of the Measurand	124

5.2.2	The International System of Weights and Measures	124
5.2.3	Method Validation	125
5.2.4	Good Measurement Practices.....	125
5.3	Circumscribing and Ranking Available Inferences	125
5.4	Limitations of Knowledge	126
5.5	Accounting for Limitations	126
	Endnotes	127
Chapter 6	Result Interpretation-II: Measurement Error	129
6.1	Result Interpretation.....	129
6.2	Illusions of Certainty	129
6.3	Accuracy and Reliability	130
6.3.1	Relative and Qualitative.....	130
6.3.2	Example: Misleading in the Courtroom.....	131
6.3.3	Usefulness	132
6.4	Measurement Error	132
6.4.1	Error Analysis	133
6.4.2	Systematic Error and Bias	133
6.4.3	Random Error and Standard Deviation.....	135
6.4.3.1	Example: Random Error in Forensic Measurements	136
6.4.4	Mean Measured Values	138
6.4.4.1	Types of Means	139
6.4.4.2	Standard Deviation of the Mean	141
6.4.4.3	Outliers	141
6.4.4.4	Example: Forensics and Problems with Outliers	142
6.4.5	Error Analysis and Estimates of a Quantity's Value	144
6.4.6	The Confidence Interval	145
6.4.6.1	What Does the Confidence Interval Tell Us?.....	146
6.4.7	Total Error and Evaluating Estimates	147
6.4.7.1	Frequentist Statistical Theory	148
6.4.7.2	Systematic and Random Errors in Frequentist Statistics	148
6.4.7.3	The Best Error Analysis Can Offer	149
6.4.8	Beyond the Constraints of Measurement Error	149
	Endnotes	150
Chapter 7	Result Interpretation-III: Measurement Uncertainty	151
7.1	Result Interpretation.....	151
7.2	Response to Limitations of Measurement Error Approach	151
7.2.1	Replacing Error	152

7.2.2	The GUM	152
7.2.3	Bayesian Probability	153
7.3	Measurement Uncertainty: Ideas and Concepts	153
7.3.1	The Lingering Effects of Error	154
7.3.1.1	Systematic and Random Effects.....	154
7.3.1.2	Best Estimate of a Measurand's Value ..	155
7.3.2	Measurement as Packet of Values	156
7.3.3	Belief	157
7.3.4	Measurement as Probability Distribution	157
7.3.4.1	Example: State of Knowledge as a Probability Distribution	157
7.3.5	Mapping Measurement to "Reality"	160
7.3.6	Reasonably Attributable Values	160
7.3.7	Expanded Uncertainty and Coverage Intervals ..	162
7.3.8	Reporting Results	164
7.3.9	Measure of the Epistemological Robustness of Conclusions.....	164
7.4	Case Notes: Measurement Uncertainty in the Courtroom	165
7.4.1	Legal Background	165
7.4.2	The National Academy of Sciences	168
7.4.3	Example: The Importance of Uncertainty in the Courtroom	169
7.4.4	Recognizing the Necessity of Uncertainty in Achieving Justice.....	171
7.4.5	Rejecting Science	173
7.4.6	Example: The Fatal Flaw—Identical Results ... Different Meanings.....	174
7.4.7	Overcoming Bad Law	176
7.5	Overview of Mechanics Provided by the GUM	177
7.5.1	Two Types of Uncertainty: Type A and Type B....	177
7.5.1.1	Equivalency of Uncertainties	178
7.5.1.2	Objective versus Subjective	178
7.5.2	Standard Uncertainty	179
7.5.2.1	Example: Type B Determination of Standard Uncertainty	179
7.5.3	Step 1: Identifying Systematic Effects and Their Associated Uncertainty	180
7.5.3.1	Example: Type A Analysis	180
7.5.3.2	Example: Type B Analysis	182
7.5.4	Step 2: Identifying Sources and Magnitudes of Uncertainty	184
7.5.4.1	No Accounting for Poor Performance ..	185
7.5.5	Step 3: Quantifying Uncertainties	186
7.5.5.1	Example: Type A Evaluation	186
7.5.5.2	Example: Type B Evaluation	186

7.5.6	Step 4: Documenting Sources and Magnitudes	187
7.5.7	Step 5: Combined Uncertainty	187
7.5.7.1	Overcoming the Limitations of the Error Approach.....	188
7.5.7.2	Relating Uncertainties	188
7.5.7.3	Uncertainties Directly Affecting Result	188
7.5.7.4	Addition through Modeling: The Law of Propagation of Uncertainty	189
7.5.7.5	Applications of Propagation of Uncertainty	190
7.5.7.6	Example: Applications of Propagation of Uncertainty in Forensic Science.....	191
7.5.8	Expanded Uncertainty and Coverage Intervals	192
7.5.9	Reporting Results	195
7.5.9.1	Reporting Forensic Results	195
7.5.10	Tricks of the Trade: Reverse Engineering Probabilities	196
7.6	The Top-Down Approach	197
7.7	Propagation of Distributions Method.....	198
7.8	Choices, Choices	199
7.8.1	Uncertain Choices and the Law	199
7.9	Case Study: Definitional Uncertainty in Breath Alcohol Testing	200
7.9.1	Definitional Uncertainty	200
7.9.2	Determining Definitional Uncertainty	201
7.9.3	Combining Definitional Uncertainty	202
7.9.4	Expanded Uncertainty	203
7.10	Result Interpretation in the Uncertainty Paradigm.....	203
	Endnotes	204
Chapter 8	Epistemological Structure of Metrology.....	207
8.1	The Acquisition of Knowledge through Measurement	207
8.2	A Brief Outline of the Epistemological Structure of Metrology	207
8.2.1	Specification of the Measurand.....	208
8.2.2	The International System of Weights and Measures	208
8.2.3	Method Validation	209
8.2.4	Good Measurement Practices.....	209
8.2.5	Measurement Uncertainty	209
	Endnote	210

Section II Mathematical Background

Chapter 9	Models and Uncertainty	217
9.1	Where Do the Uncertainties Come From?	217
9.2	Uncertainty: A Random Quantity	217
9.3	Definition of a Mathematical Model	218
9.4	Deterministic and Stochastic Behavior	219
9.5	Equivalence of Models	220
9.6	Distinction between Conditional Information \mathcal{I} and Environmental Information \mathcal{E}	221
9.7	Uncertainty, Decisions, Risk	221
Chapter 10	Logic, Plausibility, and Probability	225
10.1	Logical Arguments and Reasoning	225
10.2	Inductive Reasoning: Plausibility and Probability	225
10.3	Logical Reasoning	225
10.3.1	Deductive Reasoning	226
10.3.1.1	Deductive Logic: Validity and Soundness	226
10.3.2	Inductive Reasoning	226
10.3.2.1	Statistical Syllogism	227
10.3.2.2	Simple Induction	227
10.3.2.3	Inductive Logic	227
10.3.3	Abductive Reasoning	227
10.4	Truth, Plausibility, Credibility, Probability	228
10.4.1	Numerical Values	230
10.5	Plausibility and Probability	230
10.5.1	Shorthand Notation	231
10.5.2	Venn Diagram	231
10.6	Examples of Plausibility	232
10.6.1	Deductive Reasoning: A Special Subset of Plausibility	232
10.6.2	Kleptoparasitism	233
Chapter 11	Bayes' Relation	235
11.1	Notation Used for Bayesian Inference	236
11.2	Examples of the Use of Bayes' Relation	236
11.2.1	Medical Tests Using Frequencies	237
11.2.2	Relative Likelihood: Effect of Data	239
11.2.3	The Monte Hall Problem: A Study in Conditional Probabilities	239
11.2.4	Actors	241
11.2.5	Anticipated Measurement Results	242
11.3	Inference and Domination of the Measurements	243

Chapter 12	Statistics and the Characterizing of Uncertainties	245
12.1	Why Statistics	245
12.2	Data and Populations	245
12.3	Relative Frequency	248
12.3.1	Central Tendencies: Expected Values and Averages	248
12.3.2	Dispersion (Deviation) of Samples	248
12.3.3	Equivalent Values for the Population	249
12.3.4	Sample versus Global Frequencies	249
12.3.5	Deviations from Expected Values	250
12.4	Statistical Distributions	250
12.4.1	The Bernoulli (Binomial) Distribution: The Urn Problem	251
12.4.1.1	Expected Value and Standard Deviation of W	252
12.4.1.2	Plot of Monte Carlo Simulation	252
12.4.1.3	Inverse Probability of the Bernoulli Distribution	252
12.4.2	The Normal Distribution: The Bell Curve	254
12.4.2.1	Central Limit Theorem	255
12.4.2.2	Range of Variable for a Normal Distribution	256
12.4.3	Student's t -Distribution	257
12.5	How Many Samples Are Needed: The Law of Large Numbers	258
12.6	Frequency versus Probability	260
12.7	Conclusions	262
Chapter 13	Hypothesis Testing, Evidence, Likelihood, Data	263
13.1	Scientific Method	263
13.2	Hypothesis Testing	263
13.3	Types of Hypothesis Problems	264
13.3.1	Single Hypothesis	264
13.3.2	Binary Hypotheses	265
13.3.3	Urn Problem Treated as an Hypothesis	266
13.3.4	The Best Hypothesis: Repetitive Experiments	268
13.4	Considering All Other Hypotheses Related to the Evidence	270
13.4.1	Jurisprudence	272
13.5	Causal versus Logical Independence	272
13.5.1	Confirmation	273
Chapter 14	Confidence and Credible Intervals, Statistical Inference	275
14.1	The Confidence Interval	275
14.2	CI and Coverage Rates	276
14.2.1	Binomial Distribution	277

14.2.2	Normal Distribution	278
14.3	Bayesian Credible Intervals C_I	279
14.3.1	Are Confidence and Credible Intervals Always Different	280
14.3.1.1	Frequentist-Confidence Interval	280
14.3.1.2	Bayesian-Credible Interval	281
14.3.1.3	Robot and Plausibility	281
14.3.2	Second Example.....	281
14.3.2.1	Comparison.....	283
Chapter 15	Least Squares, Parameter Estimation, and Correlation	285
15.1	The Car Problem: A Toy Problem	285
15.2	Interval Estimation	286
15.2.1	Interval Estimation of V_0 and d for the Car Problem	287
15.2.2	Interval Method of Parameter Estimation versus Least Squares	287
15.3	Least Squares (LS)	289
15.4	Hierarchical Bayesian and Likelihood	290
15.4.1	Maximum Likelihood versus Bayesian Inference ..291	
15.4.1.1	Noninformative Prior, Maximum Likelihood	292
15.4.2	Marginalization.....	293
15.4.2.1	Estimation of the Standard Deviation of Measured Data	295
15.4.3	Priors.....	296
15.4.3.1	Influence of the Prior	298
15.4.4	Improper Priors: Marginalization Paradox	298
15.4.4.1	Marginalization Paradoxes	299
15.4.4.2	Objective Bayesian Inference	301
15.4.5	Solving Equation 15.10	302
15.4.5.1	Numerical Integration	302
15.4.5.2	Monte Carlo Integration	303
15.4.5.3	Fundamentals of Monte Carlo Integration	303
15.4.5.4	Errors in x and MCMC	305
15.4.5.5	MCMC–Metropolis–Hastings	307
15.4.6	Gibbs Sampling	310
15.4.7	\mathcal{M} versus Likelihood Model	311
15.5	MCMC versus Gaussian Quadrature	312
15.6	Correlations	312
15.6.1	Sensitivity and Information	315
15.6.1.1	Fisher’s Information and Matrix	315
15.6.2	Spurious Correlations and Conditional Correlations	316
15.6.3	Simpson’s Paradox and Confounding Variables....	318

15.6.4	Use of Residuals for Estimating Properties of ϵ	318
15.6.4.1	Non-Time Series	321
15.6.4.2	Treatment of Correlations in the GUM	321
15.7	Conclusions about Statistical Analysis	321
Chapter 16	Measurements: Errors versus Uncertainty	323
16.1	The Model and Uncertainty	323
16.2	Measurements	323
16.3	Representing the Measurement	325
16.3.1	Estimators	325
16.3.2	Representing the Base Value, $A = \hat{y}$	325
16.3.2.1	Maximum <i>A Posterior</i> Probability	326
16.3.2.2	Maximum Likelihood	326
16.3.2.3	Loss Functions and Risk, Bayes' Estimators	326
16.3.3	Arithmetic and Weighted Means, LS, and Maximum Likelihood	327
16.3.3.1	Gaussian Distribution of Errors	328
16.3.4	Representing the Uncertainty, $\pm U$	328
16.3.4.1	Where Do Errors and Uncertainty Come From?	328
16.4	Traditional Error Analysis: Propagation of Errors	328
16.4.1	Shortcomings of Error Propagation	330
16.4.2	Theory of Uncertainty	331
16.5	Drawbacks of Theory of Uncertainty	333
16.6	Examples of Uncertainty: $z = f(x, y)$	333
16.6.1	Example 1: Effects of Nonindependent Model Variables	333
16.6.2	Example 2: $z = x/y$	335
16.6.3	Marginalization by Transformed Variables: $z = x/y$	336
16.6.4	Sensor Calibration, $z = x/c$	337
16.6.5	Combined Uncertainty	340
16.6.6	Systematic versus Random Errors	341
Chapter 17	Plausibility and the Law	343
17.1	Arguments for Bayesian Inference	344
17.2	Arguments against Bayesian Inference	345
17.3	Arguments Both for and against Bayesian Inference	346
17.4	Additional References about the Law	346
Chapter 18	Reading List	349
18.1	Basic Reading	349

Section III For the Mathematically Adventurous

Chapter 19 Example: Effect of a Calibration Constant	353
19.1 Common Value of the Calibration Constant	353
19.1.1 Exact Solution for $p(z)$	353
19.1.2 Treatment by Theory of Propagation of Errors	354
19.1.3 $z = xc$	355
19.2 Example 2: Independent Values of c , Method 2A	357
19.2.1 Method 2B	358
19.2.2 Method 3	358
19.2.3 Method 4	360
19.2.4 Method 5	361
19.2.5 Correction of Method 1	361
19.3 Effect of Correlation of c	361
19.4 Summary	361
19.4.1 Effect of the Number of Measurements and $\sigma(c)$	362
19.5 Confidence in $\sigma(x)$ and $\sigma(c)$	362
References.....	365
Appendix A: Statistical Equations	373
Appendix B: Symbols	381
Appendix C: Glossary	385
Appendix D: Metrology Organizations and Standards	393
Appendix E: Legal Authorities	399
Index.....	405