

- 1 Introduction to Olfaction: Perception, Anatomy, Physiology, and Molecular Biology p. 1
- 1.1 Introduction to Olfaction p. 1
- 1.2 Odor Classification Schemes Based on Adjective Descriptors p. 4
- 1.3 Odor Classification Based on Chemical Properties p. 7
- 1.3.1 History of Structure-activity Studies of Olfaction p. 8
- 1.3.2 Odor Structures Associated with Specific Odor Classes Based on Qualitative Descriptors p. 8
- 1.3.3 Relationship of Physicochemical Parameters to Classifications of Odor Based on Similarity Measures p. 11
- 1.3.4 Molecular Parameters and Odor Thresholds p. 16
- 1.3.5 Conclusions Regarding Physicochemical Parameters and Odor Quality p. 16
- 1.4 Physiology and Anatomy of Olfaction p. 17
- 1.4.1 Basic Anatomy p. 17
- 1.4.2 Transduction and Adaptation of Olfactory Signals p. 20
- 1.5 Molecular Biology Of Olfaction p. 21
- 1.6 Taste p. 23
- 1.6.1 Taste Classification Schemes Based on Sensory Properties p. 23
- 1.6.2 Physiology and Anatomy of Taste p. 23
- 1.6.3 Transduction of Taste Signals p. 25
- 1.6.4 Molecular Biology of Taste p. 25
- 1.7 Final Comment p. 26
- 2 Chemical Sensing in Humans and Machines p. 33
- 2.1 Human Chemosensory Perception of Airborne Chemicals p. 33
- 2.2 Nasal Chemosensory Detection p. 34
- 2.2.1 Thresholds for Odor and Nasal Pungency p. 35
- 2.2.2 Stimulus-Response (Psychometric) Functions for Odor and Nasal Pungency p. 37
- 2.3 Olfactory and Nasal Chemesthetic Detection of Mixtures of Chemicals p. 38
- 2.4 Physicochemical Determinants of Odor and Nasal Pungency p. 39
- 2.4.1 The Linear Solvation Model p. 39
- 2.4.2 Application of the Solvation Equation to Odor and Nasal Pungency Thresholds p. 40
- 2.5 Human Chemical Sensing: Olfactometry p. 42
- 2.5.1 Static Olfactometry p. 42
- 2.5.2 Dynamic Olfactometry p. 44
- 2.5.3 Environmental Chambers p. 45
- 2.6 Instruments for Chemical Sensing: Gas Chromatography-Olfactometry p. 47
- 2.6.1 Charm Analysis p. 48
- 2.6.2 Aroma Extract Dilution Analysis (AEDA) p. 49
- 2.6.3 Osme Method p. 50
- 3 Odor Handling and Delivery Systems p. 55
- 3.1 Introduction p. 55
- 3.2 Physics of Evaporation p. 56
- 3.3 Sample Flow System p. 57
- 3.3.1 Headspace Sampling p. 57
- 3.3.2 Diffusion Method p. 60

- 3.3.3 Permeation Method p. 61
- 3.3.4 Bubbler p. 61
- 3.3.5 Method using a Sampling Bag p. 62
- 3.4 Static System p. 64
- 3.5 Preconcentrator p. 65
- 3.5.2 Sensitivity Enhancement p. 65
- 3.5.2 Removal of Humidity p. 66
- 3.5.3 Selectivity Enhancement by Varying Temperature p. 66
- 3.6 Measurement of Sensor Directly Exposed to Ambient Vapor p. 70
- 3.6.1 Analysis of Transient Sensor Response using an Optical Tracer p. 70
- 3.6.2 Homogenous Sensor Array for Visualizing Gas/Odor Flow p. 72
- 3.6.3 Response of Sensor Mounted on an Odor-Source Localization System p. 74
- 3.7 Summary p. 74
- 4 Introduction to Chemosensors p. 79
- 4.1 Introduction p. 79
- 4.2 Survey and Classification of Chemosensors p. 79
- 4.3 Chemoresistors p. 81
- 4.3.1 MOS p. 81
- 4.3.2 Organic CPs p. 84
- 4.4 Chemocapacitors (CAP) p. 87
- 4.5 Potentiometric Odor Sensors p. 88
- 4.5.1 Mosfet p. 88
- 4.6 Gravimetric Odor Sensors p. 89
- 4.6.1 QCM p. 90
- 4.6.2 SAW p. 92
- 4.7 Optical Odor Sensors p. 93
- 4.7.1 SPR p. 93
- 4.7.2 Fluorescent Odor Sensors p. 94
- 4.7.3 Other Optical Approaches p. 95
- 4.8 Thermal (Calorimetric) Sensors p. 96
- 4.9 Amperometric Sensors p. 96
- 4.10 Summary of Chemical Sensors p. 98
- 5 Signal Conditioning and Preprocessing p. 105
- 5.1 Introduction p. 105
- 5.2 Interface Circuits p. 106
- 5.2.1 Chemoresistors p. 106
- 5.2.2 Acoustic Wave Sensors p. 110
- 5.2.3 Field-Effect Gas Sensors p. 112
- 5.2.4 Temperature Control p. 113
- 5.3 Signal Conditioning p. 114
- 5.3.1 Operational Amplifiers p. 114
- 5.3.2 Buffering p. 116
- 5.3.3 Amplification p. 116
- 5.3.4 Filtering p. 116
- 5.3.5 Compensation p. 118
- 5.4 Signal Preprocessing p. 120

- 5.4.1 Baseline Manipulation p. 120
- 5.4.2 Compression p. 122
- 5.4.3 Normalization p. 123
- 5.5 Noise in Sensors and Circuits p. 125
- 5.6 Outlook p. 128
- 5.6.1 Temperature Modulation p. 128
- 5.7 Conclusions p. 129
- 5.8 Acknowledgements p. 130
- 6 Pattern Analysis for Electronic Noses p. 133
- 6.1 Introduction p. 134
- 6.1.1 Nature of Sensor Array Data p. 135
- 6.1.2 Classification of Analysis Techniques p. 136
- 6.1.3 Overview p. 137
- 6.2 Statistical Pattern Analysis Techniques p. 138
- 6.2.1 Linear Calibration Methods p. 139
- 6.2.2 Linear Discriminant Analysis (LDA) p. 140
- 6.2.3 Principal Components Analysis (PCA) p. 141
- 6.2.4 Cluster Analysis (CA) p. 143
- 6.3 'Intelligent' Pattern Analysis Techniques p. 145
- 6.3.1 Multilayer Feedforward Networks p. 146
- 6.3.2 Competitive and Feature Mapping Networks p. 150
- 6.3.3 'Fuzzy' Based Pattern Analysis p. 152
- 6.3.4 Neuro-Fuzzy Systems (NFS) p. 154
- 6.4 Outlook and Conclusions p. 155
- 6.4.1 Criteria for Comparison p. 155
- 6.4.2 Intelligent Sensor Systems p. 157
- 6.4.3 Conclusions p. 158
- 7 Commercial Electronic Nose Instruments p. 161
- 7.1 Introduction p. 161
- 7.1.1 Geographical Expansion p. 162
- 7.1.2 Scientific and Technological Broadening p. 162
- 7.1.3 Conceptual Expansion p. 163
- 7.2 Commercial Availability p. 164
- 7.2.1 Global Market Players p. 164
- 7.2.2 Handheld Devices p. 170
- 7.2.3 Enthusiastic Sensor Developers p. 171
- 7.2.4 Non-Electronic Noses p. 173
- 7.2.5 Specific Driven Applications p. 175
- 7.3 Some Market Considerations p. 176
- 8 Optical Electronic Noses p. 181
- 8.1 Introduction p. 181
- 8.1.1 Optical Sensors p. 181
- 8.1.2 Advantages and Disadvantages of Optical Transduction p. 182
- 8.2 Optical Vapor Sensing p. 183
- 8.2.1 Waveguides p. 183
- 8.2.2 Luminescent Methods p. 183

- 8.2.3 Colorimetric Methods p. 185
- 8.2.4 Surface Plasmon Resonance (SPR) p. 187
- 8.2.5 Interference and Reflection-Based Methods p. 189
- 8.2.6 Scanning Light-Pulse Technique p. 191
- 8.3 The Tufts Artificial Nose p. 191
- 8.4 Conclusion p. 198
- 9 Hand-held and Palm-Top Chemical Microsensor Systems for Gas Analysis p. 201
- 9.1 Introduction p. 201
- 9.2 Conventional Hand-held Systems p. 203
- 9.2.1 Hardware Setup p. 203
- 9.2.2 Fundamentals of the Sensing Process p. 205
- 9.2.3 Commercially Available Instruments Based on Conventional Technology p. 206
- 9.3 Silicon-Based Microsensors p. 211
- 9.3.1 Micromachining Techniques p. 212
- 9.3.2 Microstructured Chemocapacitors p. 213
- 9.3.3 Micromachined Resonating Cantilevers p. 216
- 9.3.4 Micromachined Calorimetric Sensors p. 219
- 9.3.5 Single-Chip Multisensor System p. 221
- 9.3.6 Operation Modes for CMOS Microsystems p. 223
- 9.4 Summary and Outlook p. 226
- 10 Integrated Electronic Noses and Microsystems for Chemical Analysis p. 231
- 10.1 Introduction p. 231
- 10.2 Microcomponents for Fluid Handling p. 233
- 10.2.1 Microchannels and Mixing Chambers p. 233
- 10.2.2 Microvalves p. 238
- 10.2.3 Micropumps p. 241
- 10.3 Integrated E-Nose Systems p. 245
- 10.3.1 Monotype Sensor Arrays p. 245
- 10.3.2 Multi-type Sensor Arrays p. 250
- 10.4 Microsystems for Chemical Analysis p. 251
- 10.4.1 Gas Chromatographs p. 251
- 10.4.2 Mass Spectrometers p. 255
- 10.4.3 Optical Spectrometers p. 258
- 10.5 Future Outlook p. 260
- 11 Electronic Tongues and Combinations of Artificial Senses p. 267
- 11.1 Introduction p. 267
- 11.2 Electronic Tongues p. 269
- 11.2.1 Measurement Principles p. 269
- 11.2.2 Potentiometric Devices p. 270
- 11.2.3 Voltammetric Devices p. 275
- 11.2.3 Piezoelectric Devices p. 283
- 11.3 The Combination or Fusion of Artificial Senses p. 284
- 11.3.1 The Combination of an Electronic Nose and an Electronic Tongue p. 285
- 11.3.2 The Artificial Mouth and Sensor Head p. 286
- 11.4 Conclusions p. 287
- 12 Dynamic Pattern Recognition Methods and System Identification p. 293

- 12.1 Introduction p. 293
- 12.2 Dynamic Models and System Identification p. 294
 - 12.2.1 Linear Models p. 295
 - 12.2.2 Multi-exponential Models p. 297
 - 12.2.3 Non-linear Models p. 300
- 12.3 Identifying a Model p. 304
 - 12.3.1 Non-Parametric Approach p. 304
 - 12.3.2 Parametric Approach p. 308
- 12.4 Dynamic Models and Intelligent Sensor Systems p. 309
 - 12.4.1 Dynamic Pattern Recognition for Selectivity Enhancement p. 311
 - 12.4.2 Calibration Time Reduction p. 314
 - 12.4.3 Building of Response Models p. 315
 - 12.4.4 Drift Counteraction p. 317
- 12.5 Outlook p. 319
- 13 Drift Compensation, Standards, and Calibration Methods p. 325
 - 13.1 Physical Reasons for Drift and Sensor Poisoning p. 325
 - 13.2 Examples of Sensor Drift p. 329
 - 13.3 Comparison of Drift and Noise p. 331
 - 13.4 Model Building Strategies p. 332
 - 13.5 Calibration Transfer p. 332
 - 13.6 Drift Compensation p. 333
 - 13.6.1 Reference Gas Methods p. 335
 - 13.6.2 Modeling of Sensor Behavior p. 339
 - 13.6.3 Pattern-Oriented Techniques for Classification p. 340
 - 13.6.4 Drift-Free Parameters p. 343
 - 13.6.5 Self-Adapting Models p. 343
 - 13.7 Conclusions p. 344
- 14 Chemical Sensor Array Optimization: Geometric and Information Theoretic Approaches p. 347
 - 14.1 The Need for Array Performance Definition and Optimization p. 347
 - 14.2 Historical Perspective p. 349
 - 14.3 Geometric Interpretation p. 351
 - 14.3.1 Linear Transformations p. 352
 - 14.4 Noise Considerations p. 355
 - 14.4.1 Number of Discriminable Features p. 355
 - 14.4.2 Measurement Accuracy p. 357
 - 14.4.3 2-Sensor 2-Odor Example p. 360
 - 14.5 Non-linear Transformations p. 363
 - 14.6 Array Performance as a Statistical Estimation Problem p. 366
 - 14.7 Fisher Information Matrix and the Best Unbiased Estimator p. 367
 - 14.8 FIM Calculations for Chemosensors p. 369
 - 14.8.1 2-Sensor 2-Odor Example p. 370
 - 14.9 Performance Optimization p. 370
 - 14.9.1 Optimization Example p. 371
 - 14.10 Conclusions p. 373
 - 14.A Overdetermined Case p. 375

- 14.B General Case with Gaussian Input Statistics p. 375
- 14.C Equivalence Between the Geometric Approach and the Fisher Information Maximization p. 375
- 15 Correlating Electronic Nose and Sensory Panel Data p. 377
- 15.2 Sensory Panel Methods p. 378
- 15.2.1 Odor Perception p. 378
- 15.2.2 Measurement of Detectability p. 379
- 15.2.3 Transforming the Measurement of the Subject to the Subject's Measurement of an Odor p. 379
- 15.2.4 Assessor Selection p. 380
- 15.2.5 Types of Dynamic Dilution Olfactometry p. 380
- 15.2.6 Assessment of Odor Intensity p. 384
- 15.2.7 Assessment of Odor Quality p. 386
- 15.2.8 Judgment of Hedonic Tone p. 387
- 15.3 Applications of Electronic Noses for Correlating Sensory Data p. 387
- 15.4 Algorithms for Correlating Sensor Array Data with Sensory Panels p. 388
- 15.4.1 Multidimensional Scaling p. 389
- 15.4.2 Regression Methods p. 390
- 15.4.3 Principal Components Regression p. 391
- 15.4.4 Partial Least Squares Regression p. 391
- 15.4.5 Neural Networks p. 392
- 15.4.6 Fuzzy-Based Data Analysis p. 392
- 15.5 Correlations of Electronic Nose Data with Sensory Panel Data p. 393
- 15.5.1 Data from Mouldy Grain p. 394
- 15.6 Conclusions p. 396
- 16 Machine Olfaction for Mobile Robots p. 399
- 16.1 Introduction p. 399
- 16.2 Olfactory-Guided Behavior of Animals p. 400
- 16.2.1 Basic Behaviors Found in Small Organisms p. 400
- 16.2.2 Plume Tracking p. 400
- 16.2.3 Trail Following by Ant p. 402
- 16.3 Sensors and Signal Processing in Mobile Robots p. 403
- 16.3.1 Chemical Sensors p. 403
- 16.3.2 Robot Platforms p. 404
- 16.4 Trail Following Robots p. 404
- 16.4.1 Odor Trails to Guide Robots p. 404
- 16.4.2 Robot Implementations p. 406
- 16.4.3 Engineering Technologies for Trail-Following Robots p. 406
- 16.5 Plume Tracking Robots p. 407
- 16.5.1 Chemotactic Robots p. 408
- 16.5.2 Olfactory Triggered Anemotaxis p. 410
- 16.5.3 Multiphase Search Algorithm p. 411
- 16.6 Other Technologies in Developing Plume Tracking Systems p. 413
- 16.6.1 Olfactory Video Camera p. 413
- 16.6.2 Odor Compass p. 414
- 16.7 Concluding Remarks p. 416

- 17 Environmental Monitoring p. 419
- 17.1 Introduction p. 419
- 17.1.1 Water p. 419
- 17.1.2 Land p. 421
- 17.1.3 Air p. 421
- 17.2 Special Considerations for Environmental Monitoring p. 425
- 17.2.1 Sample Handling Problems p. 425
- 17.2.2 Signal Processing Challenges p. 426
- 17.3 Case Study 1: Livestock Odor Classification p. 426
- 17.3.1 Background p. 426
- 17.3.2 Description of the problem p. 427
- 17.3.3 Methods p. 427
- 17.3.4 Signal Processing Algorithms p. 428
- 17.3.5 Results p. 429
- 17.3.6 Discussion p. 429
- 17.4 Case Study 2: Swine Odor Detection Thresholds p. 430
- 17.4.1 Description of the Problem p. 430
- 17.4.2 Methods p. 431
- 17.4.3 Results p. 431
- 17.4.4 Discussion p. 431
- 17.5 Case Study 3: Biofilter Evaluation p. 432
- 17.5.1 Description of the Problem p. 432
- 17.5.2 Methods p. 432
- 17.5.3 Results p. 434
- 17.5.4 Discussion p. 436
- 17.6 Case Study 4: Mold Detection p. 437
- 17.6.1 Background p. 437
- 17.6.2 Description of the Problem p. 437
- 17.6.3 The NC State E-Nose p. 437
- 17.6.4 Methods p. 440
- 17.6.5 Results p. 440
- 17.6.6 Discussion p. 441
- 17.7 Future Directions p. 441
- 18 Medical Diagnostics and Health Monitoring p. 445
- 18.1 Introduction p. 445
- 18.2 Special Considerations in Medical/Healthcare Applications p. 449
- 18.3 Monitoring Metabolic Defects in Humans Using a Conducting Polymer Sensor Array to Measure Odor p. 450
- 18.3.1 Background p. 450
- 18.3.2 Methodology p. 451
- 18.3.3 Results p. 452
- 18.4 The Use of an Electronic Nose for the Detection of Bacterial Vaginosis p. 454
- 18.4.1 Background p. 454
- 18.4.2 Methodology p. 456
- 18.4.3 Results p. 456
- 18.4.4 Discussion p. 457

- 18.4.5 Conclusion p. 458
- 18.5 Conclusion p. 458
- 19 Recognition of Natural Products p. 461
- 19.1 Introduction p. 461
- 19.2 Recent Literature Review p. 462
- 19.3 Sampling Techniques p. 462
- 19.3.1 Sample Containment p. 462
- 19.3.2 Sample Treatments p. 468
- 19.3.3 Instrument and Sample Conditioning p. 469
- 19.3.4 Sample Storage p. 470
- 19.3.5 Seasonal Variations p. 471
- 19.3.6 Inherent Variability of Natural Products p. 471
- 19.4 Case Study: The Rapid Detection of Natural Products as a Means of Identifying Plant Species p. 471
- 19.4.1 Wood Chip Sorting p. 472
- 19.4.2 Experimental Procedure p. 472
- 19.4.3 SPME-GC Analysis of the Sapwood of the Conifers Used in Pulp and Paper Industries p. 473
- 19.4.4 Conclusion: Wood Chip Sorting p. 475
- 19.5 Case Study: Differentiation of Essential Oil-Bearing Plants p. 475
- 19.5.1 Golden Rod Essential Oils p. 475
- 19.5.2 Essential Oils of Tansy p. 477
- 19.5.3 Conclusion: Essential Oils p. 478
- 19.6 Conclusion and Future Outlook p. 478
- 20 Process Monitoring p. 481
- 20.1 Introduction p. 481
- 20.1.1 On-line Bioprocess Monitoring p. 482
- 20.1.2 At-line Food Process Monitoring p. 483
- 20.2 Previous Work p. 483
- 20.2.1 Quantitative Bioprocess Monitoring p. 483
- 20.2.2 Qualitative Bioprocess Monitoring p. 485
- 20.2.3 At-line Food Process Monitoring p. 486
- 20.3 Special Considerations p. 487
- 20.4 Selected Process Monitoring Examples p. 487
- 20.4.1 On-line Monitoring of Bioprocesses p. 487
- 20.4.2 At-line Monitoring of a Feed Raw Material Production Process p. 488
- 20.4.3 Monitoring Setup p. 489
- 20.4.4 Signal Processing p. 489
- 20.4.5 Chemometrics p. 491
- 20.5 Future Prospects p. 501
- 21 Food and Beverage Quality Assurance p. 505
- 21.1 Introduction p. 505
- 21.2 Literature Survey p. 507
- 21.3 Methodological Issues in Food Measurement with Electronic Nose p. 510
- 21.4 Selected Case p. 511
- 21.4.1 LibraNose p. 511

- 21.4.2 Case Study: Fish Quality p. 515
- 21.5 Conclusions p. 520
- 21.6 Future Outlook p. 521
- 22 Automotive and Aerospace Applications p. 525
- 22.1 Introduction p. 525
- 22.2 Automotive Applications p. 525
- 22.3 Aerospace Applications p. 526
- 22.4 Polymer Composite Films p. 529
- 22.5 Electronic Nose Operation in Spacecraft p. 530
- 22.5.1 The JPL Enose Flight Experiment p. 532
- 22.5.2 Data Analysis p. 533
- 22.5.3 Pattern Recognition Method p. 536
- 22.6 Method Development p. 536
- 22.6.1 Levenberg-Marquart Nonlinear Least Squares Method p. 537
- 22.6.2 Single gases p. 539
- 22.6.3 Mixed Gases p. 541
- 22.6.4 STS-95 Flight Data Analysis Results p. 541
- 22.7 Future Directions p. 543
- 22.7.1 Sensors p. 543
- 22.7.2 Data Acquisition p. 543
- 22.7.3 Data Analysis p. 544
- 22.8 Conclusion p. 545
- 23 Detection of Explosives p. 547
- 23.1 Introduction p. 547
- 23.2 Previous Work p. 548
- 23.3 State-of-the-art of Various Explosive Vapor Sensors p. 549
- 23.4 Case Study p. 557
- 23.5 Conclusions p. 559
- 23.6 Future Directions p. 559
- 24 Cosmetics and Fragrances p. 561
- 24.1 Introduction p. 561
- 24.2 The Case for an Electronic Nose in Perfumery p. 562
- 24.3 Current Challenges and Limitations of Electronic Noses p. 563
- 24.4 Literature Review of Electronic Noses in Perfumery and Cosmetics p. 564
- 24.5 Special Considerations for using Electronic Noses to Classify and Judge Quality of Perfumes, PRMs, and Products p. 566
- 24.6 Case Study 1: Use in Classification of PRMs with Different Odor Character but of Similar Composition p. 567
- 24.6.1 The Problem p. 567
- 24.6.2 Methods p. 568
- 24.6.3 Results p. 568
- 24.6.4 Conclusions for Case Study 1 p. 570
- 24.7 Case Study 2: Use in Judging the Odor Quality of a Sunscreen Product p. 570
- 24.7.1 Background p. 570
- 24.7.2 The Problem p. 572
- 24.7.3 Equipment and Methods p. 573

- 24.7.4 Results p. 574
- 24.7.5 Conclusions for Case Study 2 p. 575
- 24.8 Conclusions p. 575
- 24.9 Future Directions p. 576
- Index p. 579