

Supramolecular Chemistry

Second Edition

Jonathan W. Steed

Department of Chemistry, Durham University, UK

Jerry L. Atwood

Department of Chemistry, University of Missouri, Columbia, USA

 **WILEY**

A John Wiley and Sons, Ltd, Publication

Contents

About the Authors	xxi
Preface to the First Edition	xxiii
Preface to the Second Edition	xxv
Acknowledgements	xxvii
1 Concepts	1
1.1 Definition and Development of Supramolecular Chemistry	2
1.1.1 What is Supramolecular Chemistry?	2
1.1.2 Host–Guest Chemistry	3
1.1.3 Development	4
1.2 Classification of Supramolecular Host–Guest Compounds	6
1.3 Receptors, Coordination and the Lock and Key Analogy	6
1.4 Binding Constants	9
1.4.1 Definition and Use	9
1.4.2 Measurement of Binding Constants	11
1.5 Cooperativity and the Chelate Effect	17
1.6 Preorganisation and Complementarity	22
1.7 Thermodynamic and Kinetic Selectivity, and Discrimination	26
1.8 Nature of Supramolecular Interactions	27
1.8.1 Ion–ion Interactions	27
1.8.2 Ion–Dipole Interactions	27
1.8.3 Dipole–Dipole Interactions	28
1.8.4 Hydrogen Bonding	28
1.8.5 Cation– π Interactions	32
1.8.6 Anion– π Interactions	33
1.8.7 π – π Interactions	33
1.8.8 Van der Waals Forces and Crystal Close Packing	35
1.8.9 Closed Shell Interactions	36
1.9 Solvation and Hydrophobic Effects	38
1.9.1 Hydrophobic Effects	38
1.9.2 Solvation	39
1.10 Supramolecular Concepts and Design	41
1.10.1 Host Design	41
1.10.2 Informed and Emergent Complex Matter	42
1.10.3 Nanochemistry	44

Summary	45
Study Problems	45
Suggested Further Reading	46
References	47
2 The Supramolecular Chemistry of Life	49
2.1 Biological Inspiration for Supramolecular Chemistry	50
2.2 Alkali Metal Cations in Biochemistry	50
2.2.1 Membrane Potentials	50
2.2.2 Membrane Transport	53
2.2.3 Rhodopsin: A Supramolecular Photonic Device	60
2.3 Porphyrins and Tetrapyrrole Macrocycles	61
2.4 Supramolecular Features of Plant Photosynthesis	63
2.4.1 The Role of Magnesium Tetrapyrrole Complexes	63
2.4.2 Manganese-Catalysed Oxidation of Water to Oxygen	68
2.5 Uptake and Transport of Oxygen by Haemoglobin	70
2.6 Enzymes and Coenzymes	74
2.6.1 Characteristics of Enzymes	74
2.6.2 Mechanism of Enzymatic Catalysis	77
2.6.3 Coenzymes	79
2.6.4 The Example of Coenzyme B ₁₂	80
2.7 Neurotransmitters and Hormones	83
2.8 Semiochemistry in the Natural World	85
2.9 DNA	86
2.9.1 DNA Structure and Function	86
2.9.2 Site-Directed Mutagenesis	91
2.9.3 The Polymerase Chain Reaction	92
2.9.4 Binding to DNA	93
2.9.5 DNA Polymerase: A Processive Molecular Machine	97
2.10 Biochemical Self-Assembly	99
Summary	102
Study Problems	102
References	103
3 Cation-Binding Hosts	105
3.1 Introduction to Coordination Chemistry	106
3.1.1 Supramolecular Cation Coordination Chemistry	106
3.1.2 Useful Concepts in Coordination Chemistry	106
3.1.3 EDTA – a Classical Supramolecular Host	112

3.2	The Crown Ethers	114
3.2.1	Discovery and Scope	114
3.2.2	Synthesis	116
3.3	The Lariat Ethers and Podands	118
3.3.1	Podands	118
3.3.2	Lariat Ethers	120
3.3.3	Bibracchial Lariat Ethers	121
3.4	The Cryptands	122
3.5	The Spherands	125
3.6	Nomenclature of Cation-Binding Macrocycles	127
3.7	Selectivity of Cation Complexation	129
3.7.1	General Considerations	129
3.7.2	Conformational Characteristics of Crown Ethers	130
3.7.3	Donor Group Orientation and Chelate Ring Size Effects	132
3.7.4	Cation Binding by Crown Ethers	135
3.7.5	Cation Binding by Lariat Ethers	140
3.7.6	Cation Binding by Cryptands	142
3.7.7	Preorganisation: Thermodynamic Effects	144
3.7.8	Preorganisation: Kinetic and Dynamic Effects	147
3.8	Solution Behaviour	149
3.8.1	Solubility Properties	149
3.8.2	Solution Applications	149
3.9	Synthesis: The Template Effect and High Dilution	153
3.9.1	The Template Effect	153
3.9.2	High-Dilution Synthesis	157
3.10	Soft Ligands for Soft Metal Ions	160
3.10.1	Nitrogen and Sulfur Analogues of Crown Ethers	160
3.10.2	Nitrogen and Sulfur Analogues of Cryptands	163
3.10.3	Azamacrocycles: Basicity Effects and the Example of Cyclam	164
3.10.4	Phosphorus-Containing Macrocycles	167
3.10.5	Mixed Cryptates	168
3.10.6	Schiff Bases	170
3.10.7	Phthalocyanines	172
3.10.8	Torands	173
3.11	Proton Binding: The Simplest Cation	173
3.11.1	Oxonium Ion Binding by Macrocycles in the Solid State	174
3.11.2	Solution Chemistry of Proton Complexes	177
3.12	Complexation of Organic Cations	180
3.12.1	Binding of Ammonium Cations by Corands	181
3.12.2	Binding of Ammonium Cations by Three-Dimensional Hosts	183
3.12.3	Ditopic Receptors	184
3.12.4	Chiral Recognition	185
3.12.5	Amphiphilic Receptors	193
3.12.6	Case Study: Herbicide Receptors	194

3.13	Alkalides and Electrdes	195
3.14	The Calixarenes	197
3.14.1	Cation Complexation by Calixarenes	198
3.14.2	Phase Transport Equilibria	204
3.14.3	Cation Complexation by Hybrid Calixarenes	206
3.15	Carbon Donor and π-acid Ligands	208
3.15.1	Mixed C-Heteroatom Hosts	209
3.15.2	Hydrocarbon Hosts	211
3.16	The Siderophores	213
3.16.1	Naturally Occurring Siderophores	213
3.16.2	Synthetic Siderophores	215
	Summary	217
	Study Problems	217
	Thought Experiment	218
	References	219
4	Anion Binding	223
4.1	Introduction	224
4.1.1	Scope	224
4.1.2	Challenges in Anion Receptor Chemistry	225
4.2	Biological Anion Receptors	227
4.2.1	Anion Binding Proteins	228
4.2.2	Arginine as an Anion Binding Site	229
4.2.3	Main Chain Anion Binding Sites in Proteins: Nests	230
4.2.4	Pyrrole-Based Biomolecules	231
4.3	Concepts in Anion Host Design	232
4.3.1	Preorganisation	232
4.3.2	Entropic Considerations	233
4.3.3	Considerations Particular to Anions	234
4.4	From Cation Hosts to Anion Hosts – a Simple Change in pH	236
4.4.1	Tetrahedral Receptors	236
4.4.2	Shape Selectivity	238
4.4.3	Ammonium-Based Podands	239
4.4.4	Two-Dimensional Hosts	240
4.4.5	Cyclophane Hosts	246
4.5	Guanidinium-Based Receptors	248
4.6	Neutral Receptors	251
4.6.1	Zwitterions	253
4.6.2	Amide-Based Receptors	253
4.6.3	Urea and Thiourea Derivatives	255
4.6.4	Pyrrole Derivatives	257
4.6.5	Peptide-Based Receptors	258

4.7	Inert Metal-Containing Receptors	259
4.7.1	General Considerations	259
4.7.2	Organometallic Receptors	261
4.7.3	Hydride Sponge and Other Lewis Acid Chelates	268
4.7.4	Anticrowns	271
4.8	Common Core Scaffolds	276
4.8.1	The Trialkylbenzene Motif	277
4.8.2	Cholapods	278
	Summary	281
	Study Problems	281
	Thought Experiments	282
	References	282
5	Ion Pair Receptors	285
5.1	Simultaneous Anion and Cation Binding	286
5.1.1	Concepts	286
5.1.2	Contact Ion Pairs	287
5.1.3	Cascade Complexes	289
5.1.4	Remote Anion and Cation Binding Sites	291
5.1.5	Symport and Metals Extraction	295
5.1.6	Dual-Host Salt Extraction	298
5.2	Labile Complexes as Anion Hosts	299
5.3	Receptors for Zwitterions	303
	Summary	304
	Study Problems	304
	References	305
6	Molecular Guests in Solution	307
6.1	Molecular Hosts and Molecular Guests	308
6.1.1	Introduction	308
6.1.2	Some General Considerations	308
6.2	Intrinsic Curvature: Guest Binding by Cavitands	310
6.2.1	Building Blocks	310
6.2.2	Calixarenes and Resorcarenes	311
6.2.3	Dynamics of Guest Exchange in Cavities	320
6.2.4	Glycoluril-Based Hosts	323
6.2.5	Kohnkene	326
6.3	Cyclodextrins	327
6.3.1	Introduction and Properties	327
6.3.2	Preparation	331
6.3.3	Inclusion Chemistry	331
6.3.4	Industrial Applications	335

6.4	Molecular Clefts and Tweezers	336
6.5	Cyclophane Hosts	340
6.5.1	General Aspects	340
6.5.2	Cyclophane Nomenclature	341
6.5.3	Cyclophane Synthesis	342
6.5.4	Molecular 'Iron Maidens'	345
6.5.5	From Tweezers to Cyclophanes	346
6.5.6	The Diphenylmethane Moiety	347
6.5.7	Guest Inclusion by Hydrogen Bonding	353
6.5.8	Charge-Transfer Cyclophanes	357
6.6	Constructing a Solution Host from Clathrate-Forming Building Blocks: The Cryptophanes	358
6.6.1	Construction of Containers from a Curved Molecular Building Block	358
6.6.2	Complexation of Halocarbons	361
6.6.3	Competition with Solvent	363
6.6.4	Complexes with Alkyl Ammonium Ions and Metals	364
6.6.5	Methane and Xenon Complexation	365
6.6.6	An 'Imploding' Cryptophane	366
6.6.7	Hemicryptophanes	367
6.7	Covalent Cavities: Carcerands and Hemicarcerands	370
6.7.1	Definitions and Synthesis	370
6.7.2	Template Effects in Carcerand Synthesis	373
6.7.3	Complexation and Constrictive Binding	373
6.7.4	Carcerism	375
6.7.5	Inclusion Reactions	376
6.7.6	Giant Covalent Cavities	379
	Summary	381
	Study Problems	381
	Thought Experiment	382
	References	382
7	Solid-State Inclusion Compounds	385
7.1	Solid-State Host-Guest Compounds	386
7.2	Clathrate Hydrates	387
7.2.1	Formation	387
7.2.2	Structures and Properties	388
7.2.3	Problems and Applications	391
7.3	Urea and Thiourea Clathrates	393
7.3.1	Structure	393
7.3.2	Guest Order and Disorder	394
7.3.3	Applications of Urea Inclusion Compounds	398

7.4	Other Channel Clathrates	399
7.4.1	Trimesic Acid	399
7.4.2	Helical Tubulands and Other Di-ols	401
7.4.3	Perhydrotriphenylene: Polarity Formation	403
7.5	Hydroquinone, Phenol, Dianin's Compound and the Hexahost Strategy	406
7.6	Tri-<i>o</i>-thymotide	410
7.6.1	Inclusion Chemistry	410
7.6.2	Synthesis and Derivatives	412
7.6.3	Applications	413
7.7	Cyclotrimeratrylene	414
7.7.1	Properties	414
7.7.2	Synthesis	414
7.7.3	Inclusion Chemistry	416
7.7.4	Network Structures	418
7.8	Inclusion Compounds of the Calixarenes	419
7.8.1	Organic-Soluble Calixarenes	419
7.8.2	Fullerene Complexation	423
7.8.3	Water-Soluble Calixarenes	426
7.9	Solid-Gas and Solid-Liquid Reactions in Molecular Crystals	429
7.9.1	The Importance of Gas Sorption	429
7.9.2	Gas Sorption by Calixarenes	431
7.9.3	Gas Sorption by Channel Hosts	434
7.9.4	Gas Sorption by Coordination Complex Hosts	435
	Summary	437
	Study Problems	438
	References	438
8	Crystal Engineering	441
8.1	Concepts	442
8.1.1	Introduction	442
8.1.2	Tectons and Synthons	443
8.1.3	The Special Role of Hydrogen Bonding	447
8.1.4	Hydrogen Bond Acidity and Basicity	452
8.2	Crystal Nucleation and Growth	453
8.2.1	Theory of Crystal Nucleation and Growth	453
8.2.2	NMR Spectroscopy as a Tool to Probe Nucleation	455
8.2.3	Crystal Growth at Air-Liquid Interfaces	456
8.2.4	Chirality Induction: The Adam Effect	458
8.2.5	Dyeing Crystal Interfaces	462
8.2.6	Hourglass Inclusions	464
8.2.7	Epitaxy: Engineering Crystals	467
8.2.8	Crystals as Genes?	469
8.2.9	Mechanochemistry and Topochemistry	470

8.3	Understanding Crystal Structures	476
8.3.1	Graph Set Analysis	476
8.3.2	Etter's Rules	478
8.3.3	Crystal Deconstruction	481
8.3.4	Crystal Engineering Design Strategies	482
8.4	The Cambridge Structural Database	484
8.5	Polymorphism	487
8.5.1	The Importance of Polymorphism	487
8.5.2	Types of Polymorphism	489
8.5.3	Controlling Polymorphism	492
8.6	Co-crystals	493
8.6.1	Scope and Nomenclature	493
8.6.2	Designer Co-crystals	494
8.6.3	Hydrates	497
8.7	$Z' > 1$	498
8.8	Crystal Structure Prediction	500
8.8.1	Soft vs. Hard Predictions	500
8.8.2	Crystal Structure Calculation	501
8.8.3	The CCDC Blind Tests	504
8.9	Hydrogen Bond Synthons – Common and Exotic	505
8.9.1	Hydrogen Bonded Rings	505
8.9.2	Hydrogen Bonds to Halogens	510
8.9.3	Hydrogen Bonds to Cyanometallates	511
8.9.4	Hydrogen Bonds to Carbon Monoxide Ligands	512
8.9.5	Hydrogen Bonds to Metals and Metal Hydrides	514
8.9.6	CH Donor Hydrogen Bonds	517
8.10	Aromatic Rings	519
8.10.1	Edge-to-Face and Face-to-Face Interactions	519
8.10.2	Aryl Embraces	522
8.10.3	Metal- π Interactions	523
8.11	Halogen Bonding and Other Interactions	524
8.12	Crystal Engineering of Diamondoid Arrays	526
	Summary	530
	Study Problems	531
	Thought Experiment	532
	References	532
9	Network Solids	537
9.1	What Are Network Solids?	538
9.1.1	Concepts and Classification	538
9.1.2	Network Topology	539
9.1.3	Porosity	542

9.2	Zeolites	543
9.2.1	Composition and Structure	543
9.2.2	Synthesis	547
9.2.3	MFI Zeolites in the Petroleum Industry	548
9.3	Layered Solids and Intercalates	550
9.3.1	General Characteristics	550
9.3.2	Graphite Intercalates	553
9.3.3	Controlling the Layers: Guanidinium Sulfonates	554
9.4	In the Beginning: Hoffman Inclusion Compounds and Werner Clathrates	556
9.5	Coordination Polymers	561
9.5.1	Coordination Polymers, MOFs and Other Terminology	561
9.5.2	0D Coordination Clusters	562
9.5.3	1D, 2D and 3D Structures	564
9.5.4	Magnetism	568
9.5.5	Negative Thermal Expansion	570
9.5.6	Interpenetrated Structures	571
9.5.7	Porous and Cavity-Containing Structures	575
9.5.8	Metal-Organic Frameworks	578
9.5.9	Catalysis by MOFs	583
9.5.10	Hydrogen Storage by MOFs	583
	Summary	586
	Study Problem	587
	References	587
10	Self-Assembly	591
10.1	Introduction	592
10.1.1	Scope and Goals	592
10.1.2	Concepts and Classification	594
10.2	Proteins and Foldamers: Single Molecule Self-Assembly	598
10.2.1	Protein Self-Assembly	598
10.2.2	Foldamers	599
10.3	Biochemical Self-Assembly	600
10.3.1	Strict Self-Assembly: The Tobacco Mosaic Virus and DNA	600
10.3.2	Self-Assembly with Covalent Modification	602
10.4	Self-Assembly in Synthetic Systems: Kinetic and Thermodynamic Considerations	604
10.4.1	Template Effects in Synthesis	604
10.4.2	A Thermodynamic Model: Self-Assembly of Zinc Porphyrin Complexes	606
10.4.3	Cooperativity and the Extended Site Binding Model	610
10.4.4	Double Mutant Cycles – Quantifying Weak Interactions	615
10.4.5	Probability of Self-Assembly	616

10.5	Self-Assembling Coordination Compounds	620
10.5.1	Design and Notation	620
10.5.2	A Supramolecular Cube	621
10.5.3	Molecular Squares and Boxes	624
10.5.4	Self-Assembly of Metal Arrays	637
10.6	Self-Assembly of Closed Complexes by Hydrogen Bonding	641
10.6.1	Tennis Balls and Softballs: Self-Complementary Assemblies	641
10.6.2	Heterodimeric Capsules	646
10.6.3	Giant Self-Assembling Capsules	646
10.6.4	Rosettes	651
10.7	Catenanes and Rotaxanes	653
10.7.1	Overview	653
10.7.2	Statistical Approaches to Catenanes and Rotaxanes	655
10.7.3	Rotaxanes and Catenanes Involving π - π Stacking Interactions	656
10.7.4	Hydrogen Bonded Rotaxanes and Catenanes	666
10.7.5	Metal and Auxiliary Linkage Approaches to Catenanes and Rotaxanes	669
10.7.6	Molecular Necklaces	677
10.8	Helicates and Helical Assemblies	678
10.8.1	Introduction	678
10.8.2	Synthetic Considerations	681
10.8.3	[4 + 4] Helicates	682
10.8.4	[6 + 6] Helicates	683
10.8.5	Self-Recognition and Positive Cooperativity	684
10.8.6	Cyclic Helicates	686
10.8.7	Anion-Based Helices	687
10.8.8	Hydrogen-Bonded Helices	687
10.9	Molecular Knots	691
10.9.1	The Topology of Knots	691
10.9.2	Trefoil Knots	693
10.9.3	Other Knots	696
10.9.4	Borromean Rings	697
	Summary	700
	Study Problems	701
	Thought Experiment	702
	References	702
11	Molecular Devices	707
11.1	Introduction	708
11.1.1	Philosophy of Molecular Devices	708
11.1.2	When Is a Device Supramolecular?	708

11.2	Supramolecular Photochemistry	710
11.2.1	Photophysical Fundamentals	710
11.2.2	Mechanisms of Energy and Electron Transfer	713
11.2.3	Bimetallic Systems and Mixed Valence	715
11.2.4	Bipyridine and Friends as Device Components	716
11.2.5	Bipyridyl-Type Light Harvesting Devices	718
11.2.6	Light-Conversion Devices	725
11.2.7	Non-Covalently Bonded Systems	726
11.3	Information and Signals: Semiochemistry and Sensing	730
11.3.1	Supramolecular Semiochemistry	730
11.3.2	Photophysical Sensing and Imaging	731
11.3.3	Colorimetric Sensors and the Indicator Displacement Assay	738
11.3.4	Electrochemical Sensors	742
11.4	Molecule-Based Electronics	746
11.4.1	Molecular Electronic Devices	746
11.4.2	Molecular Wires	746
11.4.3	Molecular Rectifiers	750
11.4.4	Molecular Switches	752
11.4.5	Molecular Logic	756
11.4.6	Towards Addressable Molecular Devices	760
11.5	Molecular Analogues of Mechanical Machines	762
11.6	Nonlinear Optical Materials	765
11.6.1	Origins of Nonlinear Optical Effects	765
11.6.2	Second-Order Nonlinear Optical Materials	768
11.6.3	Third Harmonic Generation Nonlinear Optical Materials	771
	Summary	771
	Study Problems	771
	References	772
12	Biological Mimics and Supramolecular Catalysis	777
12.1	Introduction	778
12.1.1	Understanding and Learning from Biochemistry	778
12.1.2	Characteristics of Biological Models	779
12.2	Cyclodextrins as Enzyme Mimics	780
12.2.1	Enzyme Modelling Using an Artificial Host Framework	780
12.2.2	Cyclodextrins as Esterase Mimics	782
12.2.3	Functionalised Cyclodextrins	783
12.3	Corands as ATPase Mimics	785

12.4	Cation-Binding Hosts as Transacylase Mimics	788
12.4.1	Chiral Corands	788
12.4.2	A Structure and Function Mimic	790
12.5	Metallobiosites	792
12.5.1	Haemocyanin Models	793
12.5.2	Zinc-Containing Enzymes	795
12.6	Haem Analogues	798
12.6.1	Models of Oxygen Uptake and Transport	798
12.6.2	Cytochrome P-450 Models	803
12.6.3	Cytochrome c Oxidase Models	807
12.7	Vitamin B₁₂ Models	808
12.8	Ion Channel Mimics	809
12.9	Supramolecular Catalysis	813
12.9.1	Abiotic Supramolecular Catalysis	813
12.9.2	Dynamic Combinatorial Libraries	817
12.9.3	Self-Replicating Systems	819
12.9.4	Emergence of Life	823
	Summary	825
	Study Problems	825
	Thought Experiment	826
	References	826
13	Interfaces and Liquid Assemblies	829
13.1	Order in Liquids	830
13.2	Surfactants and Interfacial Ordering	831
13.2.1	Surfactants, Micelles and Vesicles	831
13.2.2	Surface Self-Assembled Monolayers	837
13.3	Liquid Crystals	839
13.3.1	Nature and Structure	839
13.3.2	Design of Liquid Crystalline Materials	846
13.3.3	Supramolecular Liquid Crystals	848
13.3.4	Liquid Crystal Displays	851
13.4	Ionic Liquids	852
13.5	Liquid Clathrates	854
	Summary	858
	Study Problems	858
	References	859

14	Supramolecular Polymers, Gels and Fibres	861
14.1	Introduction	862
14.2	Dendrimers	862
14.2.1	Structure and Nomenclature	862
14.2.2	Preparation and Properties of Molecular Dendrimers	866
14.2.3	Dendrimer Host–Guest Chemistry	869
14.2.4	Supramolecular Dendrimer Assemblies	872
14.2.5	Dendritic Nanodevices	874
14.3	Covalent Polymers with Supramolecular Properties	876
14.3.1	Amphiphilic Block Copolymers	876
14.3.2	Molecular Imprinted Polymers	879
14.4	Self-Assembled Supramolecular Polymers	880
14.5	Polycatenanes and Polyrotaxanes	883
14.6	Biological Self-Assembled Fibres and Layers	885
14.6.1	Amyloids, Actins and Fibrin	885
14.6.2	Bacterial S-Layers	887
14.7	Supramolecular Gels	888
14.8	Polymeric Liquid Crystals	893
	Summary	894
	Study Problems	895
	References	895
15	Nanochemistry	899
15.1	When Is Nano Really Nano?	900
15.2	Nanotechnology: The ‘Top Down’ and ‘Bottom Up’ Approaches	900
15.3	Templated and Biomimetic Morphosynthesis	902
15.4	Nanoscale Photonics	905
15.5	Microfabrication, Nanofabrication and Soft Lithography	907
15.6	Assembly and Manipulation on the Nanoscale	912
15.6.1	Chemistry with a Microscope Tip	912
15.6.2	Self-Assembly on Surfaces	914
15.6.3	Addressing Single Molecules	918
15.6.4	Atomic-Level Assembly of Materials	920
15.7	Nanoparticles	921
15.7.1	Nanoparticles and Colloids: Definition and Description	921
15.7.2	Gold Nanoparticles	922
15.7.3	Quantum Dots	925
15.7.4	Non-Spherical Nanoparticles	927

15.8 Endohedral Fullerenes, Nanotubes and Graphene	927
15.8.1 Fullerenes as Hosts	928
15.8.2 Carbon Nanotubes	931
15.8.3 Graphene	935
15.8.4 Afterword – Damascus Steel	935
Summary	936
Thought Experiment	937
References	937
Index	941