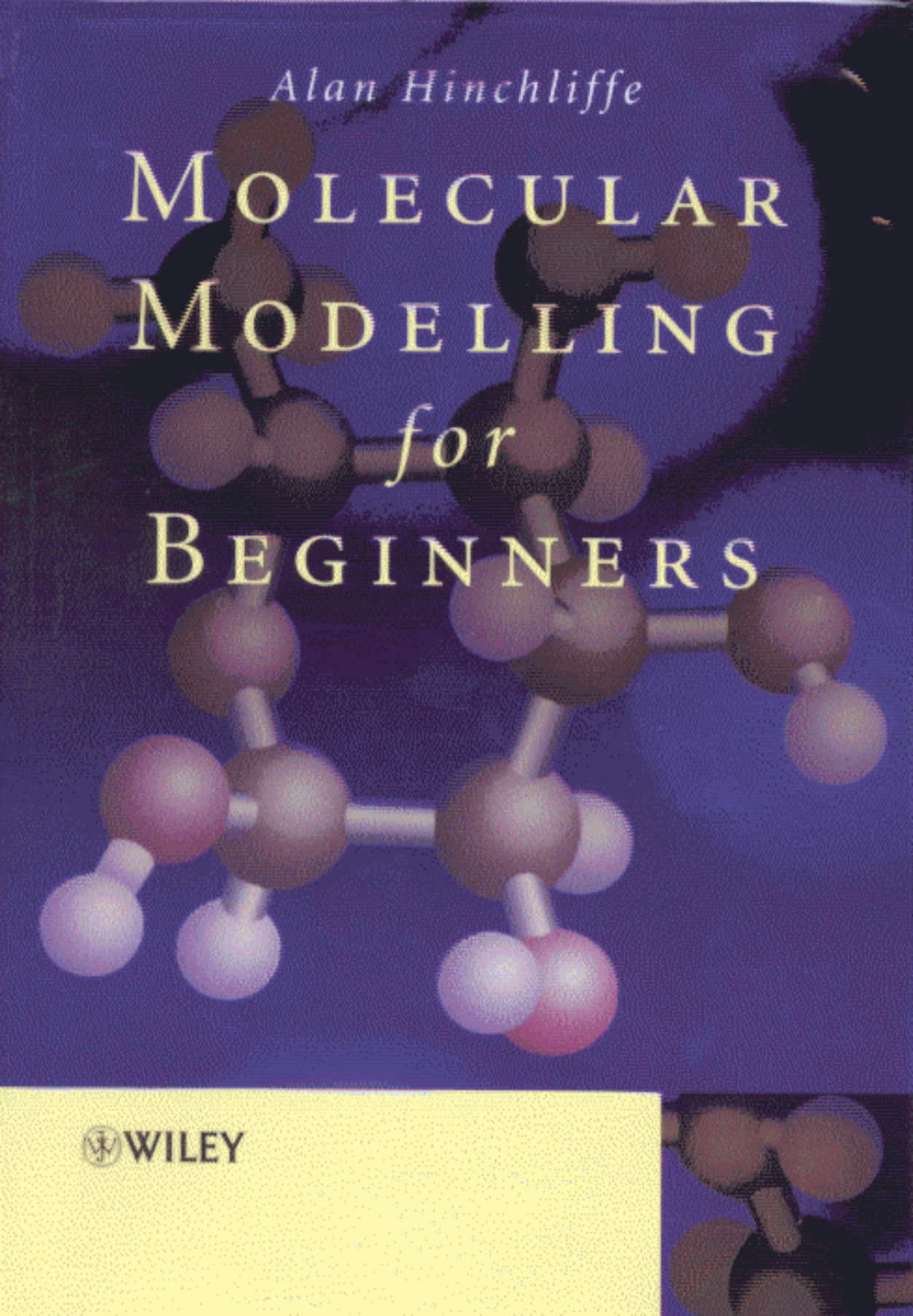




Alan Hinchliffe

MOLECULAR
MODELLING
for
BEGINNERS

 WILEY

Contents

Preface	xiii
List of Symbols	xvii
1 Introduction	1
1.1 Chemical Drawing	1
1.2 Three-Dimensional Effects	2
1.3 Optical Activity	3
1.4 Computer Packages	4
1.5 Modelling	4
1.6 Molecular Structure Databases	6
1.7 File Formats	7
1.8 Three-Dimensional Displays	8
1.9 Proteins	10
2 Electric Charges and Their Properties	13
2.1 Point Charges	13
2.2 Coulomb's Law	15
2.3 Pairwise Additivity	16
2.4 The Electric Field	17
2.5 Work	18
2.6 Charge Distributions	20
2.7 The Mutual Potential Energy U	21
2.8 Relationship Between Force and Mutual Potential Energy	22
2.9 Electric Multipoles	23
2.9.1 Continuous charge distributions	26
2.9.2 The electric second moment	26
2.9.3 Higher electric moments	29
2.10 The Electrostatic Potential	29
2.11 Polarization and Polarizability	30
2.12 Dipole Polarizability	31
2.12.1 Properties of polarizabilities	33
2.13 Many-Body Forces	33
3 The Forces Between Molecules	35
3.1 The Pair Potential	35
3.2 The Multipole Expansion	37
3.3 The Charge-Dipole Interaction	37
3.4 The Dipole-Dipole Interaction	39

3.5	Taking Account of the Temperature	41
3.6	The Induction Energy	41
3.7	Dispersion Energy	43
3.8	Repulsive Contributions	44
3.9	Combination Rules	46
3.10	Comparison with Experiment	46
3.10.1	Gas imperfections	47
3.10.2	Molecular beams	47
3.11	Improved Pair Potentials	47
3.12	Site-Site Potentials	48
4	Balls on Springs	51
4.1	Vibrational Motion	52
4.2	The Force Law	55
4.3	A Simple Diatomic	56
4.4	Three Problems	57
4.5	The Morse Potential	60
4.6	More Advanced Potentials	61
5	Molecular Mechanics	63
5.1	More About Balls on Springs	63
5.2	Larger Systems of Balls on Springs	65
5.3	Force Fields	67
5.4	Molecular Mechanics	67
5.4.1	Bond-stretching	68
5.4.2	Bond-bending	69
5.4.3	Dihedral motions	69
5.4.4	Out-of-plane angle potential (inversion)	70
5.4.5	Non-bonded interactions	71
5.4.6	Coulomb interactions	72
5.5	Modelling the Solvent	72
5.6	Time-and-Money-Saving Tricks	72
5.6.1	United atoms	72
5.6.2	Cut-offs	73
5.7	Modern Force Fields	73
5.7.1	Variations on a theme	74
5.8	Some Commercial Force Fields	75
5.8.1	DREIDING	75
5.8.2	MM1	75
5.8.3	MM2 (improved hydrocarbon force field)	76
5.8.4	AMBER	77
5.8.5	OPLS (Optimized Potentials for Liquid Simulations)	78
5.8.6	R. A. Johnson	78
6	The Molecular Potential Energy Surface	79
6.1	Multiple Minima	79
6.2	Saddle Points	80
6.3	Characterization	82
6.4	Finding Minima	82
6.5	Multivariate Grid Search	83
6.5.1	Univariate search	84

6.6	Derivative Methods	84
6.7	First-Order Methods	85
6.7.1	Steepest descent	85
6.7.2	Conjugate gradients	86
6.8	Second-Order Methods	87
6.8.1	Newton–Raphson	87
6.8.2	Block diagonal Newton–Raphson	90
6.8.3	Quasi-Newton–Raphson	90
6.8.4	The Fletcher–Powell algorithm [17]	91
6.9	Choice of Method	91
6.10	The Z Matrix	92
6.11	Tricks of the Trade	94
6.11.1	Linear structures	94
6.11.2	Cyclic structures	95
6.12	The End of the Z Matrix	97
6.13	Redundant Internal Coordinates	99
7	A Molecular Mechanics Calculation	101
7.1	Geometry Optimization	101
7.2	Conformation Searches	102
7.3	QSARs	104
7.3.1	Atomic partial charges	105
7.3.2	Polarizabilities	107
7.3.3	Molecular volume and surface area	109
7.3.4	$\log(P)$	110
8	Quick Guide to Statistical Thermodynamics	113
8.1	The Ensemble	114
8.2	The Internal Energy U_{th}	116
8.3	The Helmholtz Energy A	117
8.4	The Entropy S	117
8.5	Equation of State and Pressure	117
8.6	Phase Space	118
8.7	The Configurational Integral	119
8.8	The Virial of Clausius	121
9	Molecular Dynamics	123
9.1	The Radial Distribution Function	124
9.2	Pair Correlation Functions	127
9.3	Molecular Dynamics Methodology	128
9.3.1	The hard sphere potential	128
9.3.2	The finite square well	128
9.3.3	Lennard-Jonesium	130
9.4	The Periodic Box	131
9.5	Algorithms for Time Dependence	133
9.5.1	The leapfrog algorithm	134
9.5.2	The Verlet algorithm	134
9.6	Molten Salts	135
9.7	Liquid Water	136
9.7.1	Other water potentials	139
9.8	Different Types of Molecular Dynamics	139
9.9	Uses in Conformational Studies	140

10 Monte Carlo	143
10.1 Introduction	143
10.2 MC Simulation of Rigid Molecules	148
10.3 Flexible Molecules	150
11 Introduction to Quantum Modelling	151
11.1 The Schrödinger Equation	151
11.2 The Time-Independent Schrödinger Equation	153
11.3 Particles in Potential Wells	154
11.3.1 The one-dimensional infinite well	154
11.4 The Correspondence Principle	157
11.5 The Two-Dimensional Infinite Well	158
11.6 The Three-Dimensional Infinite Well	160
11.7 Two Non-Interacting Particles	161
11.8 The Finite Well	163
11.9 Unbound States	164
11.10 Free Particles	165
11.11 Vibrational Motion	166
12 Quantum Gases	171
12.1 Sharing Out the Energy	172
12.2 Rayleigh Counting	174
12.3 The Maxwell Boltzmann Distribution of Atomic Kinetic Energies	176
12.4 Black Body Radiation	177
12.5 Modelling Metals	180
12.5.1 The Drude model	180
12.5.2 The Pauli treatment	183
12.6 The Boltzmann Probability	184
12.7 Indistinguishability	188
12.8 Spin	192
12.9 Fermions and Bosons	194
12.10 The Pauli Exclusion Principle	194
12.11 Boltzmann's Counting Rule	195
13 One-Electron Atoms	197
13.1 Atomic Spectra	197
13.1.1 Bohr's theory	198
13.2 The Correspondence Principle	200
13.3 The Infinite Nucleus Approximation	200
13.4 Hartree's Atomic Units	201
13.5 Schrödinger Treatment of the H Atom	202
13.6 The Radial Solutions	204
13.7 The Atomic Orbitals	206
13.7.1 $l = 0$ (s orbitals)	207
13.7.2 The p orbitals	210
13.7.3 The d orbitals	211
13.8 The Stern-Gerlach Experiment	212
13.9 Electron Spin	215
13.10 Total Angular Momentum	216
13.11 Dirac Theory of the Electron	217
13.12 Measurement in the Quantum World	219

14 The Orbital Model	221
14.1 One- and Two-Electron Operators	221
14.2 The Many-Body Problem	222
14.3 The Orbital Model	223
14.4 Perturbation Theory	225
14.5 The Variation Method	227
14.6 The Linear Variation Method	230
14.7 Slater Determinants	233
14.8 The Slater–Condon–Shortley Rules	235
14.9 The Hartree Model	236
14.10 The Hartree–Fock Model	238
14.11 Atomic Shielding Constants	239
14.11.1 Zener's wavefunctions	240
14.11.2 Slater's rules	241
14.12 Koopmans' Theorem	242
15 Simple Molecules	245
15.1 The Hydrogen Molecule Ion H_2^+	246
15.2 The LCAO Model	248
15.3 Elliptic Orbitals	251
15.4 The Heitler–London Treatment of Dihydrogen	252
15.5 The Dihydrogen MO Treatment	254
15.6 The James and Coolidge Treatment	256
15.7 Population Analysis	256
15.7.1 Extension to many-electron systems	258
16 The HF–LCAO Model	261
16.1 Roothaan's Landmark Paper	262
16.2 The $\hat{J}$ and $\hat{K}$ Operators	264
16.3 The HF–LCAO Equations	264
16.3.1 The HF–LCAO equations	267
16.4 The Electronic Energy	268
16.5 Koopmans' Theorem	269
16.6 Open Shell Systems	269
16.7 The Unrestricted Hartree–Fock Model	271
16.7.1 Three technical points	273
16.8 Basis Sets	273
16.8.1 Clementi and Raimondi	274
16.8.2 Extension to second-row atoms	275
16.8.3 Polarization functions	276
16.9 Gaussian Orbitals	276
16.9.1 STO/ n G	280
16.9.2 STO/4–31G	282
16.9.3 Gaussian polarization and diffuse functions	283
16.9.4 Extended basis sets	283
17 HF–LCAO Examples	287
17.1 Output	289
17.2 Visualization	293
17.3 Properties	294
17.3.1 The electrostatic potential	295

17.4	Geometry Optimization	297
17.4.1	The Hellmann–Feynman Theorem	297
17.4.2	Energy minimization	298
17.5	Vibrational Analysis	300
17.6	Thermodynamic Properties	303
17.6.1	The ideal monatomic gas	304
17.6.2	The ideal diatomic gas	306
17.6.3	q_{rot}	306
17.6.4	q_{vib}	307
17.7	Back to L-phenylalanine	308
17.8	Excited States	309
17.9	Consequences of the Brillouin Theorem	313
17.10	Electric Field Gradients	315
18	Semi-empirical Models	319
18.1	Hückel π -Electron Theory	319
18.2	Extended Hückel Theory	322
18.2.1	Roald Hoffman	323
18.3	Pariser, Parr and Pople	324
18.4	Zero Differential Overlap	325
18.5	Which Basis Functions Are They?	327
18.6	All Valence Electron ZDO Models	328
18.7	Complete Neglect of Differential Overlap	328
18.8	CNDO/2	329
18.9	CNDO/S	330
18.10	Intermediate Neglect of Differential Overlap	330
18.11	Neglect of Diatomic Differential Overlap	331
18.12	The Modified INDO Family	331
18.12.1	MINDO/3	332
18.13	Modified Neglect of Overlap	333
18.14	Austin Model 1	333
18.15	PM3	333
18.16	SAM1	334
18.17	ZINDO/1 and ZINDO/S	334
18.18	Effective Core Potentials	334
19	Electron Correlation	337
19.1	Electron Density Functions	337
19.1.1	Fermi correlation	339
19.2	Configuration Interaction	339
19.3	The Coupled Cluster Method	340
19.4	Møller–Plesset Perturbation Theory	341
19.5	Multiconfiguration SCF	346
20	Density Functional Theory and the Kohn–Sham LCAO Equations	347
20.1	The Thomas–Fermi and $X\alpha$ Models	348
20.2	The Hohenberg–Kohn Theorems	350
20.3	The Kohn–Sham (KS–LCAO) Equations	352
20.4	Numerical Integration (Quadrature)	353
20.5	Practical Details	354

20.6	Custom and Hybrid Functionals	355
20.7	An Example	356
20.8	Applications	358



Miscellany 361

21.1	Modelling Polymers	361
21.2	The End-to-End Distance	363
21.3	Early Models of Polymer Structure	364
21.3.1	The freely jointed chain	366
21.3.2	The freely rotating chain	366
21.4	Accurate Thermodynamic Properties; The G1, G2 and G3 Models	367
21.4.1	G1 theory	367
21.4.2	G2 theory	369
21.4.3	G3 theory	369
21.5	Transition States	370
21.6	Dealing with the Solvent	372
21.7	Langevin Dynamics	373
21.8	The Solvent Box	375
21.9	ONIOM or Hybrid Models	376

Appendix: A Mathematical Aide-Mémoire 379

A.1	Scalars and Vectors	379
A.2	Vector Algebra	380
A.2.1	Vector addition and scalar multiplication	380
A.2.2	Cartesian coordinates	381
A.2.3	Cartesian components of a vector	381
A.2.4	Vector products	382
A.3	Scalar and Vector Fields	384
A.4	Vector Calculus	384
A.4.1	Differentiation of fields	385
A.4.2	The gradient	386
A.4.3	Volume integrals of scalar fields	387
A.4.4	Line integrals	388
A.5	Determinants	389
A.5.1	Properties of determinants	390
A.6	Matrices	391
A.6.1	The transpose of a matrix	391
A.6.2	The trace of a square matrix	392
A.6.3	Algebra of matrices	392
A.6.4	The inverse matrix	393
A.6.5	Matrix eigenvalues and eigenvectors	393
A.7	Angular Momentum	394
A.8	Linear Operators	396
A.9	Angular Momentum Operators	399

References 403

Index 407