NWChem User Documentation

Release 5.1

Molecular Sciences Software Group
W.R. Wiley Environmental Molecular Sciences Laboratory
Pacific Northwest National Laboratory
P.O. Box 999, Richland, WA 99352

December 2007

DISCLAIMER

This material was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the United States Department of Energy, nor Battelle, nor any of their employees, MAKES ANY WARRANTY, EXPRESS OR IMPLIED, OR ASSUMES ANY LEGAL LIABILITY OR RESPONSIBILITY FOR THE ACCURACY, COMPLETENESS, OR USEFULNESS OF ANY INFORMATION, APPARATUS, PRODUCT, SOFTWARE, OR PROCESS DISCLOSED, OR REPRESENTS THAT ITS USE WOULD NOT INFRINGE PRIVATELY OWNED RIGHTS.

LIMITED USE

This software (including any documentation) is being made available to you for your internal use only, solely for use in performance of work directly for the U.S. Federal Government or work under contracts with the U.S. Department of Energy or other U.S. Federal Government agencies. This software is a version which has not yet been evaluated and cleared for commercialization. Adherence to this notice may be necessary for the author, Battelle Memorial Institute, to successfully assert copyright in and commercialize this software. This software is not intended for duplication or distribution to third parties without the permission of the Manager of Software Products at Pacific Northwest National Laboratory, Richland, Washington, 99352.

ACKNOWLEDGMENT

This software and its documentation were produced with Government support under Contract Number DE-AC05-76RL01830 awarded by the United States Department of Energy. The Government retains a paid-up non-exclusive, irrevocable worldwide license to reproduce, prepare derivative works, perform publicly and display publicly by or for the Government, including the right to distribute to other Government contractors.

AUTHOR DISCLAIMER

This software contains proprietary information of the authors, Pacific Northwest National Laboratory (PNNL), and the US Department of Energy (USDOE). The information herein shall not be disclosed to others, and shall not be reproduced whole or in part, without written permission from PNNL or USDOE. The information contained in this document is provided "AS IS" without guarantee of accuracy. Use of this software is prohibited without **written** permission from PNNL or USDOE. The authors, PNNL, and USDOE make no representations or warranties whatsoever with respect to this software, including the implied warranty of merchant-ability or fitness for a particular purpose. The user assumes all risks, including consequential loss or damage, in respect to the use of the software. In addition, PNNL and the authors shall not be obligated to correct or maintain the program, or notify the user community of modifications or updates that will be made over the course of time.

Contents

1 Introduction **21**

1.1 Citation 21

1.2 User Feedback 22

2 Getting Started **25**

2.1 Input File Structure 25

2.2 Simple Input File — SCF geometry optimization 26

2.3 Water Molecule Sample Input File 27

2.4 Input Format and Syntax for Directives 29

2.4.1 Input Format 29

2.4.2 Format and syntax of directives 30

3 NWChem Architecture **33**

3.1 Database Structure 33

3.2 Persistence of data and restart 35

4 Functionality **37**

4.1 Molecular electronic structure 37

4.2 Relativistic effects 39

4.3 Pseudopotential plane-wave electronic structure 39

4.4 Molecular dynamics 40

4.5 Python 40

4.6 Parallel tools and libraries (ParSoft) 41

5 Top-level directives **43**

5.1 `START` and `RESTART` — Start-up mode 43

5.2 `SCRATCH_DIR` and `PERMANENT_DIR` — File directories 45

5.3 MEMORY — Control of memory limits . . . 46
5.4 ECHO — Print input file . . . 48
5.5 TITLE — Specify job title . . . 48
5.6 PRINT and NOPRINT — Print control . . . 48
5.7 SET — Enter data in the RTDB . . . 50
5.8 UNSET — Delete data in the RTDB . . . 51
5.9 STOP — Terminate processing . . . 51
5.10 TASK — Perform a task . . . 52
5.10.1 TASK Directive for Electronic Structure Calculations . . . 52
5.10.2 TASK Directive for Special Operations . . . 54
5.10.3 TASK Directive for the Bourne Shell . . . 54
5.10.4 TASK Directive for QM/MM simulations . . . 55
5.10.5 TASK Directive for BSSE calculations . . . 56
5.11 CHARGE — Total system charge . . . 58
5.12 ECCE_PRINT — Print information for Ecce . . . 59

6 Geometries **61**
6.1 Keywords on the GEOMETRY directive . . . 62
6.2 SYMMETRY — Symmetry Group Input . . . 64
6.3 Cartesian coordinate input . . . 65
6.4 ZMATRIX — Z-matrix input . . . 66
6.5 ZCOORD — Forcing internal coordinates . . . 71
6.6 Applying constraints in geometry optimizations . . . 72
6.7 SYSTEM — Lattice parameters for periodic systems . . . 73

7 Basis sets **75**
7.1 Basis set library . . . 77
7.2 Explicit basis set definition . . . 78
7.3 Combinations of library and explicit basis set input . . . 79

8 Effective Core Potentials **81**
8.1 Scalar ECPs . . . 82
8.2 Spin-orbit ECPs . . . 84

9 Relativistic All-electron Approximations **87**
9.1 Douglas-Kroll approximation . . . 88

9.2 Zeroth Order regular approximation (ZORA) . . . 89
9.3 Dyall's Modified Dirac Hamitonian approximation . . . 89

10 Hartree-Fock or Self-consistent Field 93

10.1 Wavefunction type . . . 93
10.2 SYM — use of symmetry . . . 94
10.3 ADAPT – symmetry adaptation of MOs . . . 94
10.4 TOL2E — integral screening threshold . . . 95
10.5 VECTORS — input/output of MO vectors . . . 95
10.5.1 Superposition of fragment molecular orbitals . . . 98
10.5.2 Atomic guess orbitals with charged atoms . . . 103
10.6 Accuracy of initial guess . . . 104
10.7 THRESH — convergence threshold . . . 104
10.8 MAXITER — iteration limit . . . 105
10.9 PROFILE — performance profile . . . 105
10.10 DIIS — DIIS convergence . . . 105
10.11 DIRECT and SEMIDIRECT — recomputation of integrals . . . 106
10.11.1 Integral File Size and Format for the SCF Module . . . 107
10.12 SCF Convergence Control Options . . . 108
10.13 NR — controlling the Newton-Raphson . . . 109
10.14 LEVEL — level-shifting the orbital Hessian . . . 110
10.15 Orbital Localization . . . 111
10.16 Printing Information from the SCF Module . . . 112
10.17 Hartree-Fock or SCF, MCSCF and MP2 Gradients . . . 113

11 DFT for Molecules (DFT) 115

11.1 Specification of Basis Sets for the DFT Module . . . 118
11.2 VECTORS and MAX_OVL — KS-MO Vectors . . . 118
11.3 XC and DECOMP — Exchange-Correlation Potentials . . . 118
11.3.1 Exchange-Correlation Functionals . . . 120
11.3.2 Combined Exchange and Correlation Functionals . . . 120
11.3.3 Meta-GGA Functionals . . . 121
11.4 LB94 and CSOO — Asymptotic correction . . . 121
11.5 Sample input file . . . 122
11.6 ITERATIONS — Number of SCF iterations . . . 125

11.7 CONVERGENCE — SCF Convergence Control . . . 125
11.8 CDFT — Constrained DFT . . . 127
11.9 SMEAR — Fractional Occupation of the Molecular Orbitals . . . 128
11.10 GRID — Numerical Integration of the XC Potential . . . 129
11.10.1 Angular grids . . . 131
11.10.2 Partitioning functions . . . 133
11.10.3 Radial grids . . . 133
11.10.4 Disk usage for Grid . . . 133
11.11 TOLERANCES — Screening tolerances . . . 133
11.12 DIRECT and NOIO — Hardware Resource Control . . . 134
11.13 ODFT and MULT — Open shell systems . . . 135
11.14 SIC — Self-Interaction Correction . . . 135
11.15 MULLIKEN — Mulliken analysis . . . 136
11.16 BSSE — Basis Set Superposition Error . . . 136
11.17 Print Control . . . 136

12 Spin-Orbit DFT (SODFT) 139

13 COSMO 143

14 CIS, TDHF, and TDDFT 147
14.1 Overview . . . 147
14.2 Performance of CIS, TDHF, and TDDFT methods . . . 148
14.3 Input syntax . . . 149
14.4 Keywords of TDDFT input block . . . 150
14.4.1 CIS and RPA — the Tamm–Dancoff approximation . . . 150
14.4.2 NROOTS — the number of excited states . . . 150
14.4.3 MAXVECS — the subspace size . . . 150
14.4.4 SINGLET and NOSINGLET — singlet excited states . . . 151
14.4.5 TRIPLET and NOTRIPLET — triplet excited states . . . 151
14.4.6 THRESH — the convergence threshold of Davidson iteration . . . 151
14.4.7 MAXITER — the maximum number of Davidson iteration . . . 151
14.4.8 TARGET and TARGETSYM— the target root and its symmetry . . . 151
14.4.9 SYMMETRY — restricting the excited state symmetry . . . 152
14.4.10 ALGORITHM — algorithms for tensor contractions . . . 152

14.4.11 FREEZE — the frozen core/virtual approximation . . . 152
14.4.12 PRINT — the verbosity . . . 153
14.5 Sample input . . . 153

15 Tensor Contraction Engine Module: CI, MBPT, and CC 157

15.1 Overview . . . 157
15.2 Performance of CI, MBPT, and CC methods . . . 159
15.3 Algorithms of CI, MBPT, and CC methods . . . 160
15.3.1 Spin, spatial, and index permutation symmetry . . . 160
15.3.2 Runtime orbital range tiling . . . 160
15.3.3 Dynamic load balancing parallelism . . . 160
15.3.4 Parallel I/O schemes . . . 160
15.4 Input syntax . . . 160
15.5 Keywords of TCE input block . . . 163
15.5.1 HF, SCF, or DFT — the reference wave function . . . 163
15.5.2 CCSD,CCSDT,CCSDTQ,CISD,CISDT,CISDTQ, MBPT2,MBPT3,MBPT4, etc. — the correlation models . . . 165
15.5.3 THRESH — the convergence threshold of iterative solutions of amplitude equations . . . 167
15.5.4 MAXITER — the maximum number of iterations . . . 167
15.5.5 IO — parallel I/O scheme . . . 167
15.5.6 DIIS — the convergence acceleration . . . 168
15.5.7 FREEZE — the frozen core/virtual approximation . . . 168
15.5.8 NROOTS — the number of excited states . . . 168
15.5.9 TARGET and TARGETSYM — the target root and its symmetry . . . 168
15.5.10 SYMMETRY — restricting the excited state symmetry . . . 169
15.5.11 2EORB — alternative storage of two-electron integrals . . . 169
15.5.12 DIPOLE — the ground- and excited-state dipole moments . . . 170
15.5.13 (NO)FOCK — (not) recompute Fock matrix . . . 170
15.5.14 PRINT — the verbosity . . . 170
15.6 Sample input . . . 170
15.7 TCE Response Properties . . . 177
15.7.1 Introduction . . . 177
15.7.2 Performance . . . 177
15.7.3 Input . . . 177
15.7.4 Examples . . . 178

16 MP2 **181**

16.1 FREEZE — Freezing orbitals . . . 182
16.2 TIGHT — Increased precision . . . 183
16.3 SCRATCHDISK — Limiting I/O usage . . . 183
16.4 PRINT and NOPRINT . . . 183
16.5 VECTORS — MO vectors . . . 183
16.6 RI-MP2 fitting basis . . . 184
16.7 FILE3C — RI-MP2 3-center integral filename . . . 185
16.8 RIAPPROX — RI-MP2 Approximation . . . 185
16.9 Advanced options for RI-MP2 . . . 185
16.9.1 Control of linear dependence . . . 185
16.9.2 Reference Spin Mapping for RI-MP2 Calculations . . . 185
16.9.3 Batch Sizes for the RI-MP2 Calculation . . . 186
16.9.4 Energy Memory Allocation Mode: RI-MP2 Calculation . . . 187
16.9.5 Local Memory Usage in Three-Center Transformation . . . 187
16.10One-electron properties and natural orbitals . . . 188

17 Multiconfiguration SCF **189**

17.1 ACTIVE — Number of active orbitals . . . 189
17.2 ACTELEC — Number of active electrons . . . 190
17.3 MULTIPLICITY . . . 190
17.4 SYMMETRY — Spatial symmetry of the wavefunction . . . 190
17.5 STATE — Symmetry and multiplicity . . . 190
17.6 VECTORS — Input/output of MO vectors . . . 191
17.7 HESSIAN — Select preconditioner . . . 191
17.8 LEVEL — Level shift for convergence . . . 191
17.9 PRINT and NOPRINT . . . 191

18 Selected CI **193**

18.1 Background . . . 193
18.2 Files . . . 195
18.3 Configuration Generation . . . 195
18.3.1 Specifying the reference occupation . . . 195
18.3.2 Applying creation-annihilation operators . . . 196
18.3.3 Uniform excitation level . . . 197

18.4 Number of roots . . . 197
18.5 Accuracy of diagonalization . . . 198
18.6 Selection thresholds . . . 198
18.7 Mode . . . 198
18.8 Memory requirements . . . 198
18.9 Forcing regeneration of the MO integrals . . . 199
18.10 Disabling update of the configuration list . . . 199
18.11 Orbital locking in CI geometry optimization . . . 199

19 Coupled Cluster Calculations **201**
19.1 `MAXITER` — Maximum number of iterations . . . 201
19.2 `THRESH` — Convergence threshold . . . 202
19.3 `TOL2E` — integral screening threshold . . . 202
19.4 `DIISBAS` — DIIS subspace dimension . . . 202
19.5 `FREEZE` — Freezing orbitals . . . 202
19.6 `IPRT` — Debug printing . . . 202
19.7 PRINT and NOPRINT . . . 203
19.8 Methods (Tasks) Recognized . . . 203
19.9 Debugging and Development Aids . . . 203
19.9.1 Switching On and Off Terms . . . 203

20 Geometry Optimization with DRIVER **205**
20.1 Convergence criteria . . . 206
20.2 Available precision . . . 207
20.3 Controlling the step length . . . 207
20.4 Maximum number of steps . . . 207
20.5 Discard restart information . . . 207
20.6 Regenerate internal coordinates . . . 207
20.7 Initial Hessian . . . 207
20.8 Mode or variable to follow to saddle point . . . 208
20.9 Optimization history as XYZ files . . . 209
20.10 Print options . . . 209

21 Geometry Optimization with STEPPER **211**
21.1 `MIN` and `TS` — Minimum or transition state search . . . 211

21.2 TRACK — Mode selection . . . 212
21.3 MAXITER — Maximum number of steps . . . 212
21.4 TRUST — Trust radius . . . 212
21.5 CONVGGM, CONVGG and CONVGE — Convergence criteria . . . 212
21.6 Backstepping in STEPPER . . . 213
21.7 Initial Nuclear Hessian Options . . . 213

22 Constraints for Geometry Optimization **215**

23 Hybrid Calculations with ONIOM **217**
23.1 Real, model and intermediate geometries . . . 218
23.1.1 Link atoms . . . 219
23.1.2 Numbering of the link atoms . . . 220
23.2 High, medium and low theories . . . 220
23.2.1 Basis specification . . . 220
23.2.2 Effective core potentials . . . 220
23.2.3 General input strings . . . 220
23.3 Use of symmetry . . . 221
23.4 Molecular orbital files . . . 221
23.5 Restarting . . . 222
23.6 Examples . . . 222
23.6.1 Hydrocarbon bond energy . . . 222
23.6.2 Optimization and frequencies . . . 223
23.6.3 A three-layer example . . . 225
23.6.4 DFT with and without charge fitting . . . 226

24 Hessians **229**
24.1 Hessian Module Input . . . 229
24.1.1 Defining the wavefunction threshold . . . 229
24.1.2 Profile . . . 230
24.1.3 Print Control . . . 230

25 Vibrational frequencies **231**
25.1 Vibrational Module Input . . . 231
25.1.1 Hessian File Reuse . . . 232
25.1.2 Redefining Masses of Elements . . . 232

25.1.3 Temp or Temperature . . . 233
25.1.4 Animation . . . 233
25.1.5 An Example Input Deck . . . 235

26 DPLOT **237**

26.1 `GAUSSIAN` — Gaussian Cube format . . . 237
26.2 `TITLE` — Title directive . . . 237
26.3 `LIMITXYZ` — Plot limits . . . 237
26.4 `SPIN` — Density to be plotted . . . 238
26.5 `OUTPUT` — Filename . . . 238
26.6 `VECTORS` — MO vector file name . . . 238
26.7 `WHERE` — Density evaluation . . . 238
26.8 `ORBITAL` — Orbital sub-space . . . 238
26.9 Examples . . . 239

27 Electron Transfer Calculations with ET **241**

27.1 `VECTORS` — input of MO vectors for ET reactant and product states . . . 242
27.2 `FOCK/NOFOCK` — method for calculating the two-electron contribution to V_{RP} . . . 242
27.3 `TOL2E` — integral screening threshold . . . 242
27.4 `Example` . . . 242

28 Properties **245**

28.1 Property keywords . . . 246
28.1.1 Nbofile . . . 246

29 VSCF **247**

30 Electrostatic potentials **249**

30.1 Grid specification . . . 249
30.2 Constraints . . . 250
30.3 Restraints . . . 251

31 Prepare **253**

31.1 Default database directories . . . 255
31.2 System name and coordinate source . . . 256
31.3 Sequence file generation . . . 257
31.4 Topology file generation . . . 258

31.5 Appending to an existing topology file . . . 260
31.6 Generating a restart file . . . 261

32 Molecular dynamics **265**
32.1 Introduction . . . 265
32.1.1 Spacial decomposition . . . 265
32.1.2 Topology . . . 266
32.1.3 Files . . . 266
32.1.4 Databases . . . 267
32.1.5 Force fields . . . 268
32.2 Format of fragment files . . . 268
32.3 Creating segment files . . . 268
32.4 Creating sequence files . . . 268
32.5 Creating topology files . . . 268
32.6 Creating restart files . . . 269
32.7 Molecular simulations . . . 269
32.8 System specification . . . 269
32.9 Restarting and continuing simulations . . . 270
32.10Parameter set . . . 270
32.11Energy minimization algorithms . . . 271
32.12Multi-configuration thermodynamic integration . . . 271
32.13Time and integration algorithm directives . . . 272
32.14Ensemble selection . . . 273
32.15Velocity reassignments . . . 273
32.16Cutoff radii . . . 273
32.17Polarization . . . 274
32.18External electrostatic field . . . 274
32.19Constraints . . . 274
32.20Long range interaction corrections . . . 275
32.21Fixing coordinates . . . 275
32.22Special options . . . 275
32.23Autocorrelation function . . . 276
32.24Print options . . . 276
32.25Periodic updates . . . 277
32.26Recording . . . 278

32.27Program control options 280

33 Analysis **285**

33.1 System specification 285

33.2 Reference coordinates 285

33.3 File specification 286

33.4 Selection 287

33.5 Coordinate analysis 288

33.6 Essential dynamics analysis 290

33.7 Trajectory format conversion 290

33.8 Electrostatic potentials 292

34 Combined quantum and molecular mechanics **293**

34.1 Preparation of the restart and topology files 293

34.2 Molecular Mechanics Parameters 296

34.3 Quantum Mechanical Parameters 296

34.4 QM/MM interface parameters 297

35 File formats **301**

35.1 Format fragment file 301

35.2 Format segment file 301

35.3 Format sequence file 301

35.4 Format trajectory file 301

35.5 Format free energy file 301

35.6 Format root mean square deviation file 301

35.7 Format property file 301

36 Pseudopotential plane-wave density functional theory (NWPW) **311**

36.1 PSPW Tasks 312

36.1.1 Simulation Cell 315

36.1.2 `Unit Cell Optimization` 317

36.1.3 `DPLOT` 317

36.1.4 `Wannier` 319

36.1.5 `Self-Interaction Corrections` 319

36.1.6 `Point Charge Analysis` 320

36.1.7 `Car-Parrinello` 320

36.1.8 Adding Geometry Constraints To A Car-Parrinello Simulation 323
36.1.9 QM/MM 324
36.1.10 PSP_GENERATOR 326
36.1.11 WAVEFUNCTION_INITIALIZER 329
36.1.12 V_WAVEFUNCTION_INITIALIZER 331
36.1.13 WAVEFUNCTION_EXPANDER 332
36.1.14 STEEPEST_DESCENT 333
36.2 Band Tasks 334
36.2.1 Brillouin Zone 337
36.2.2 BAND_DPLOT 337
36.2.3 SMEAR - Fractional Occupation of the Molecular Orbitals 339
36.3 PAW Tasks 339
36.4 Pseudopotential and PAW basis Libraries 341
36.5 NWPW RTDB Entries and DataFiles 343
36.5.1 Ion Positions 343
36.5.2 Ion Velocities 343
36.5.3 Wavefunction Datafile 344
36.5.4 Velocity Wavefunction Datafile 344
36.5.5 Formatted Pseudopotential Datafile 344
36.5.6 One-Dimensional Pseudopotential Datafile 344
36.5.7 PSPW Car-Parrinello Output Datafiles 345
36.6 Car-Parrinello Scheme for Ab Initio Molecular Dynamics 346
36.6.1 Verlet Algorithm for Integration 347
36.6.2 Constant Temperature Simulations: Nose-Hoover Thermostats 348
36.7 PSPW Tutorial 1: Minimizing the geometry for a C_2 molecule 349
36.8 PSPW Tutorial 2: Running a Car-Parrinello Simulation 349
36.9 PSPW Tutorial 3: optimizing a unit cell and geometry for Silicon-Carbide 350
36.10 PSPW Tutorial 4: QM/MM simulation for CCl_4 + $64H_2O$ 351
36.11 Band Tutorial 1: Minimizing the energy of a silicon-carbide crystal by running a PSPW and Band simulation in tandem 354
36.12 BAND Tutorial 2: optimizing a unit cell and geometry for Silicon-Carbide 355
36.13 BAND Tutorial 3: optimizing a unit cell and geometry for Aluminum with fractional occupation 356
36.14 PAW Tutorial 357
36.15 PAW Tutorial 2: optimizing a unit cell and geometry for Silicon-Carbide 358

36.16PAW Tutorial 2: Running a Car-Parrinello Simulation . . . 359
36.17NWPW Capabilities and Limitations . . . 360
36.18Questions and Difficulties . . . 360

37 Controlling NWChem with Python 361
37.1 How to input and run a Python program inside NWChem . . . 361
37.2 NWChem extensions . . . 362
37.3 Examples . . . 363
37.3.1 Hello world . . . 363
37.3.2 Scanning a basis exponent . . . 363
37.3.3 Scanning a basis exponent revisited. . . . 364
37.3.4 Scanning a geometric variable . . . 365
37.3.5 Scan using the BSSE counterpoise corrected energy . . . 365
37.3.6 Scan the geometry and compute the energy and gradient . . . 366
37.3.7 Reaction energies varying the basis set . . . 367
37.3.8 Using the database . . . 368
37.3.9 Handling exceptions from NWChem . . . 368
37.3.10 Accessing geometry information — a temporary hack . . . 369
37.3.11 Scaning a basis exponent yet again — plotting and handling child processes . . . 370
37.4 Troubleshooting . . . 371

38 Interfaces to Other Programs 373
38.1 `DIRDYVTST` — DIRect Dynamics for Variational Transition State Theory . . . 373
38.1.1 Introduction . . . 374
38.1.2 Files . . . 374
38.1.3 Detailed description of the input . . . 374

39 Acknowledgments 381

A Standard Basis Sets 383

B Sample input files 399
B.1 Water SCF calculation and geometry optimization in a 6-31g basis . . . 399
B.1.1 Job 1. Single point SCF energy . . . 399
B.1.2 Job 2. Restarting and perform a geometry optimization . . . 399
B.2 Compute the polarizability of Ne using finite field . . . 400

B.2.1 Job 1. Compute the atomic energy . . . 400
B.2.2 Job 2. Compute the energy with applied field . . . 400
B.3 SCF energy of H_2CO using ECPs for C and O . . . 400
B.4 MP2 optimization and CCSD(T) on nitrogen . . . 402

C Examples of geometries using symmetry **405**
C.1 C_s methanol . . . 405
C.2 C_{2v} water . . . 405
C.3 D_{2h} acetylene . . . 406
C.4 D_{2h} ethylene . . . 406
C.5 T_d methane . . . 406
C.6 I_h buckminsterfullerene . . . 406
C.7 S_4 porphyrin . . . 407
C.8 D_{3h} iron penta-carbonyl . . . 407
C.9 D_{3d} sodium crown ether . . . 408
C.10 C_{3v} ammonia . . . 408
C.11 D_{6h} benzene . . . 408
C.12 C_{3h} BO_3H_3 . . . 408
C.13 D_{5d} ferrocene . . . 409
C.14 C_{4v} SF_5Cl . . . 409
C.15 C_{2h} trans-dichloroethylene . . . 409
C.16 D_{2d} CH_2CCH_2 . . . 410
C.17 D_{5h} cyclopentadiene anion . . . 410
C.18 D_{4h} gold tetrachloride . . . 410

D Running NWChem **411**
D.1 Sequential execution . . . 411
D.2 Parallel execution on UNIX-based parallel machines including workstation clusters using TCGMSG . . . 411
D.3 Parallel execution on UNIX-based parallel machines including workstation clusters using MPI 412
D.4 Parallel execution on MPPs . . . 413
D.5 IBM SP . . . 413
D.6 Cray T3E . . . 414
D.7 Alpha systems with Quadrics switch . . . 414
D.8 Windows 98 and NT . . . 414

D.9 Tested Platforms and O/S versions 415

Chapter 1

Introduction

NWChem is a computational chemistry package designed to run on high-performance parallel supercomputers. Code capabilities include the calculation of molecular electronic energies and analytic gradients using Hartree-Fock self-consistent field (SCF) theory, Gaussian density function theory (DFT), and second-order perturbation theory. For all methods, geometry optimization is available to determine energy minima and transition states. Classical molecular dynamics capabilities provide for the simulation of macromolecules and solutions, including the computation of free energies using a variety of force fields.

NWChem is scalable, both in its ability to treat large problems efficiently, and in its utilization of available parallel computing resources. The code uses the parallel programming tools TCGMSG and the Global Array (GA) library developed at PNNL for the High Performance Computing and Communication (HPCC) grand-challenge software program and the Environmental Molecular Sciences Laboratory (EMSL) Project. NWChem has been optimized to perform calculations on large molecules using large parallel computers, and it is unique in this regard.

This document is intended as an aid to chemists using the code for their own applications. Users are not expected to have a detailed understanding of the code internals, but some familiarity with the overall structure of the code, how it handles information, and the nature of the algorithms it contains will generally be helpful. The following sections describe the structure of the input file, and give a brief overview of the code architecture. All input directives recognized by the code are described in detail, with options, defaults, and recommended usages, where applicable. The appendices present additional information on the molecular geometry and basis function libraries included in the code.

1.1 Citation

The EMSL Software Agreement stipulates that the use of NWChem will be acknowledged in any publications which use results obtained with NWChem. The acknowledgment should be of the form:

> NWChem Version 5.1, as developed and distributed by Pacific Northwest National Laboratory, P. O. Box 999, Richland, Washington 99352 USA, and funded by the U. S. Department of Energy, was used to obtain some of these results.

The words "A modified version of" should be added at the beginning, if appropriate. *Note: Your EMSL Software Agreement contains the complete specification of the required acknowledgment.*

Please use the following citation when publishing results obtained with NWChem:

Straatsma, T.P.; Aprà, E.; Windus, T.L.; Bylaska, E.J.; de Jong, W.; Hirata, S.; Valiev, M.; Hackler, M.; Pollack, L.; Harrison, R.; Dupuis, M.; Smith, D.M.A; Nieplocha, J.; Tipparaju V.; Krishnan, M.; Auer, A.A.; Brown, E.; Cisneros, G.; Fann, G.; Früchtl, H.; Garza, J.; Hirao, K.; Kendall, R.; Nichols, J.; Tsemekhman, K.; Wolinski, K.; Anchell, J.; Bernholdt, D.; Borowski, P.; Clark, T.; Clerc, D.; Dachsel, H.; Deegan, M.; Dyall, K.; Elwood, D.; Glendening, E.; Gutowski, M.; Hess, A.; Jaffe, J.; Johnson, B.; Ju, J.; Kobayashi, R.; Kutteh, R.; Lin, Z.; Littlefield, R.; Long, X.; Meng, B.; Nakajima, T.; Niu, S.; Rosing, M.; Sandrone, G.; Stave, M.; Taylor, H.; Thomas, G.; van Lenthe, J.; Wong, A.; Zhang, Z.; *NWChem, A Computational Chemistry Package for Parallel Computers, Version 4.6* (2004), Pacific Northwest National Laboratory, Richland, Washington 99352-0999, USA.
High Performance Computational Chemistry: an Overview of NWChem a Distributed Parallel Application, Kendall, R.A.; Aprà, E.; Bernholdt, D.E.; Bylaska, E.J.; Dupuis, M.; Fann, G.I.; Harrison, R.J.; Ju, J.; Nichols, J.A.; Nieplocha, J.; Straatsma, T.P.; Windus, T.L.; Wong, A.T. Computer Phys. Comm., 2000, **128**, 260–283 .

If you use the DIRDYVTST portion of NWChem, please also use the additional citation:

DIRDYVTST, Yao-Yuan Chuang and Donald G. Truhlar, Department of Chemistry and Super Computer Institute, University of Minnesota; Ricky A. Kendall,Scalable Computing Laboratory, Ames Laboratory and Iowa State University; Bruce C. Garrett and Theresa L. Windus, Environmental Molecular Sciences Laboratory, Pacific Northwest Laboratory.

1.2 User Feedback

This software comes without warranty or guarantee of support, but we do try to meet the needs of our user community. Please send bug reports, requests for enhancement, or other comments to

`nwchem-users@emsl.pnl.gov`

When reporting problems, please provide as much information as possible, including:

- detailed description of problem
- site name
- platform you are running on, including
  - vendor name
  - computer model
  - operating system
  - compiler
- input file
- output file

Users can also subscribe to the `nwchem-users@emsl.pnl.gov` electronic mailing list itself. This is intended as a general forum through which code users can contact one another and the developers, to share experience with the code and discuss problems. Announcements of new releases and bug fixes will also be made to this list.

To subscribe to the user list, send a message to

```
majordomo@emsl.pnl.gov
```

The body of the message must contain the line

```
subscribe nwchem-users
```

The automated list manager is capable of recognizing a number of commands, including ; “subscribe”, “unsubscribe”, “get”, “index”, “which”, “who”, “info” and “lists”. The command “end” halts processing of commands. It will provide some help if the message includes the line `help` in the body.

Chapter 2

Getting Started

This section provides an overview of NWChem input and program architecture, and the syntax used to describe the input. See Sections 2.2 and 2.3 for examples of NWChem input files with detailed explanation.

NWChem consists of independent modules that perform the various functions of the code. Examples of modules include the input parser, SCF energy, SCF analytic gradient, DFT energy, etc.. Data is passed between modules and saved for restart using a disk-resident database or dumpfile (see Section 3).

The input to NWChem is composed of commands, called directives, which define data (such as basis sets, geometries, and filenames) and the actions to be performed on that data. Directives are processed in the order presented in the input file, with the exception of certain start-up directives (see Section 2.1) which provide critical job control information, and are processed before all other input. Most directives are specific to a particular module and define data that is used by that module only. A few directives (see Section 5) potentially affect all modules, for instance by specifying the total electric charge on the system.

There are two types of directives. Simple directives consist of one line of input, which may contain multiple fields. Compound directives group together multiple simple directives that are in some way related and are terminated with an `END` directive. See the sample inputs (Sections 2.2, 2.3) and the input syntax specification (Section 2.4).

All input is free format and case is ignored except for actual data (e.g., names/tags of centers, titles). Directives or blocks of module-specific directives (i.e., compound directives) can appear in any order, with the exception of the `TASK` directive (see sections 2.1 and 5.10) which is used to invoke an NWChem module. All input for a given task must precede the `TASK` directive. This input specification rule allows the concatenation of multiple tasks in a single NWChem input file.

To make the input as short and simple as possible, most options have default values. The user needs to supply input only for those items that have no defaults, or for items that must be different from the defaults for the particular application. In the discussion of each directive, the defaults are noted, where applicable.

The input file structure is described in the following sections, and illustrated with two examples. The input format and syntax for directives is also described in detail.

2.1 Input File Structure

The structure of an input file reflects the internal structure of NWChem. At the beginning of a calculation, NWChem needs to determine how much memory to use, the name of the database, whether it is a new

or restarted job, where to put scratch/permanent files, etc.. It is not necessary to put this information at the top of the input file, however. NWChem will read through the *entire* input file looking for the start-up directives. In this first pass, all other directives are ignored.

The start-up directives are

- `START`
- `RESTART`
- `SCRATCH_DIR`
- `PERMANENT_DIR`
- `MEMORY`
- `ECHO`

After the input file has been scanned for the start-up directives, it is rewound and read sequentially. Input is processed either by the top-level parser (for the directives listed in Section 5, such as `TITLE`, `SET`, ...) or by the parsers for specific computational modules (e.g., SCF, DFT, ...). Any directives that have already been processed (e.g., `MEMORY`) are ignored. Input is read until a `TASK` directive (see Section 5.10) is encountered. A `TASK` directive requests that a calculation be performed and specifies the level of theory and the operation to be performed. Input processing then stops and the specified task is executed. The position of the `TASK` directive in effect marks the end of the input for that task. Processing of the input resumes upon the successful completion of the task, and the results of that task are available to subsequent tasks in the same input file.

The name of the input file is usually provided as an argument to the execute command for NWChem. That is, the execute command looks something like the following;

```
nwchem input_file
```

The default name for the input file is `nwchem.nw`. If an input file name `input_file` is specified without an extension, the code assumes `.nw` as a default extension, and the input filename becomes `input_file.nw`. If the code cannot locate a file named either `input_file` or `input_file.nw` (or `nwchem.nw` if no file name is provided), an error is reported and execution terminates. The following section presents two input files to illustrate the directive syntax and input file format for NWChem applications.

2.2 Simple Input File — SCF geometry optimization

A simple example of an NWChem input file is an SCF geometry optimization of the nitrogen molecule, using a Dunning cc-pvdz basis set. This input file contains the bare minimum of information the user must specify to run this type of problem — fewer than ten lines of input, as follows:

```
title "Nitrogen cc-pvdz SCF geometry optimization"
geometry
  n 0 0 0
  n 0 0 1.08
end
basis
```

```
   n library cc-pvdz
 end
 task scf optimize
```

Examining the input line by line, it can be seen that it contains only four directives; `TITLE`, `GEOMETRY`, `BASIS`, and `TASK`. The `TITLE` directive is optional, and is provided as a means for the user to more easily identify outputs from different jobs. An initial geometry is specified in Cartesian coordinates and Angstrøms by means of the `GEOMETRY` directive. The Dunning cc-pvdz basis is obtained from the NWChem basis library, as specified by the `BASIS` directive input. The `TASK` directive requests an SCF geometry optimization.

The `GEOMETRY` directive (Section 6) defaults to Cartesian coordinates and Angstrøms (options include atomic units and Z-matrix format; see Section 6.4). The input blocks for the `BASIS` and `GEOMETRY` directives are structured in similar fashion, i.e., name, keyword, ..., end (In this simple example, there are no keywords). The `BASIS` input block *must* contain basis set information for every atom type in the geometry with which it will be used. Refer to Sections 7 and 8, and Appendix A for a description of available basis sets and a discussion of how to define new ones.

The last line of this sample input file (`task scf optimize`) tells the program to optimize the molecular geometry by minimizing the SCF energy. (For a description of possible tasks and the format of the `TASK` directive, refer to Section 5.10.)

If the input is stored in the file `n2.nw`, the command to run this job on a typical UNIX workstation is as follows:

```
nwchem n2
```

NWChem output is to UNIX standard output, and error messages are sent to both standard output and standard error.

2.3 Water Molecule Sample Input File

A more complex sample problem is the optimization of a positively charged water molecule using second-order Møller-Plesset perturbation theory (MP2), followed by a computation of frequencies at the optimized geometry. A preliminary SCF geometry optimization is performed using a computationally inexpensive basis set (STO-3G). This yields a good starting guess for the optimal geometry, and any Hessian information generated will be used in the next optimization step. Then the optimization is finished using MP2 and a basis set with polarization functions. The final task is to calculate the MP2 vibrational frequencies. The input file to accomplish these three tasks is as follows:

```
start h2o_freq

charge 1

geometry units angstroms
  O       0.0  0.0  0.0
  H       0.0  0.0  1.0
  H       0.0  1.0  0.0
end

basis
```

```
  H library sto-3g
  O library sto-3g
end

scf
  uhf; doublet
  print low
end

title "H2O+ : STO-3G UHF geometry optimization"

task scf optimize

basis
  H library 6-31g**
  O library 6-31g**
end

title "H2O+ : 6-31g** UMP2 geometry optimization"

task mp2 optimize

mp2; print none; end
scf; print none; end

title "H2O+ : 6-31g** UMP2 frequencies"

task mp2 freq
```

The `START` directive (Section 5.1) tells NWChem that this run is to be started from the beginning. This directive need not be at the beginning of the input file, but it is commonly placed there. Existing database or vector files are to be ignored or overwritten. The entry `h2o_freq` on the `START` line is the prefix to be used for all files created by the calculation. This convention allows different jobs to run in the same directory or to share the same scratch directory (see Section 5.2), as long as they use different prefix names in this field.

As in the first sample problem, the geometry is given in Cartesian coordinates. In this case, the units are specified as Angstrøms. (Since this is the default, explicit specification of the units is not actually necessary, however.) The `CHARGE` directive defines the total charge of the system. This calculation is to be done on an ion with charge +1.

A small basis set (STO-3G) is specified for the intial geometry optimization. Next, the multiple lines of the first `SCF` directive in the `scf ...end` block specify details about the SCF calculation to be performed. Unrestricted Hartree-Fock is chosen here (by specifying the keyword `uhf`), rather than the default, restricted open-shell high-spin Hartree-Fock (ROHF). This is necessary for the subsequent MP2 calculation, because only UMP2 is currently available for open-shell systems (see Section 4). For open-shell systems, the spin multiplicity has to be specified (using `doublet` in this case), or it defaults to `singlet`. The print level is set to `low` to avoid verbose output for the starting basis calculations.

All input up to this point affects only the settings in the runtime database. The program takes its information from this database, so the sequence of directives up to the first `TASK` directive is irrelevant. An exchange of order of the different blocks or directives would not affect the result. The `TASK` directive, however, must be specified after all relevant input for a given problem. The `TASK` directive causes the code

to perform the specified calculation using the parameters set in the preceding directives. In this case, the first task is an SCF calculation with geometry optimization, specified with the input `scf` and `optimize`. (See Section 5.10 for a list of available tasks and operations.)

After the completion of any task, settings in the database are used in subsequent tasks without change, unless they are overridden by new input directives. In this example, before the second task (`task mp2 optimize`), a better basis set (6-31G**) is defined and the title is changed. The second `TASK` directive invokes an MP2 geometry optimization.

Once the MP2 optimization is completed, the geometry obtained in the calculation is used to perform a frequency calculation. This task is invoked by the keyword `freq` in the final `TASK` directive, `task mp2 freq`. The second derivatives of the energy are calculated as numerical derivatives of analytical gradients. The intermediate energies and gradients are not of interest in this case, so output from the SCF and MP2 modules is disabled with the `PRINT` directives.

2.4 Input Format and Syntax for Directives

This section describes the input format and the syntax used in the rest of this documentation to describe the format of directives. The input format for the directives used in NWChem is similar to that of UNIX shells, which is also used in other chemistry packages, most notably GAMESS-UK. An input line is parsed into whitespace (blanks or tabs) separating tokens or fields. Any token that contains whitespace must be enclosed in double quotes in order to be processed correctly. For example, the basis set with the descriptive name `modified Dunning DZ` must appear in a directive as `"modified Dunning DZ"`, since the name consists of three separate words.

2.4.1 Input Format

A (physical) line in the input file is terminated with a newline character (also known as a 'return' or 'enter' character). A semicolon (`;`) can be also used to indicate the end of an input line, allowing a single physical line of input to contain multiple logical lines of input. For example, five lines of input for the `GEOMETRY` directive can be entered as follows;

```
geometry
 O 0  0     0
 H 0  1.430 1.107
 H 0 -1.430 1.107
end
```

These same five lines could be entered on a single line, as

```
geometry; O 0 0 0; H 0 1.430 1.107; H 0 -1.430 1.107; end
```

This one physical input line comprises five logical input lines. Each logical or physical input line must be no longer than 1023 characters.

In the input file:

- a string, token, or field is a sequence of ASCII characters (NOTE: if the string includes blanks or tabs (i.e., white space), the entire string must be enclosed in double quotes).

- \ (backslash) at the end of a line concatenates it with the next line. Note that a space character is automatically inserted at this point so that it is *not* possible to split tokens across lines. A backslash is also used to quote special characters such as whitespace, semi-colons, and hash symbols so as to avoid their special meaning (NOTE: these special symbols must be quoted with the backslash even when enclosed within double quotes).
- ; (semicolon) is used to mark the end of a logical input line within a physical line of input.
- # (the hash or pound symbol) is the comment character. All characters following # (up to the end of the physical line) are ignored.
- If *any* input line (excluding Python programs, Section 37) begins with the string INCLUDE (ignoring case) and is followed by a valid file name, then the data in that file are read as if they were included into the current input file at the current line. Up to three levels of nested include files are supported. The user should note that inputting a basis set from the standard basis library (Section 7) uses one level of include.
- Data is read from the input file until an end-of-file is detected, or until the string EOF (ignoring case) is encountered at the beginning of an input line.

2.4.2 Format and syntax of directives

Directives consist of a directive name, keywords, and optional input, and may contain one line or many. Simple directives consist of a single line of input with one or more fields. Compound directives can have multiple input lines, and can also include other optional simple and compound directives. A compound directive is terminated with an END directive. The directives START (see Section 5.1) and ECHO (see Section 5.4) are examples of simple directives. The directive GEOMETRY (see Section 6) is an example of a compound directive.

Some limited checking of the input for self-consistency is performed by the input module, but most defaults are imposed by the application modules at runtime. It is therefore usually impossible to determine beforehand whether or not all selected options are consistent with each other.

In the rest of this document, the following notation and syntax conventions are used in the generic descriptions of the NWChem input.

- a directive name always appears in all-capitals, and in computer typeface (e.g., GEOMETRY, BASIS, SCF). Note that the case of directives and keywords is ignored in the actual input.
- a keyword always appears in lower case, in computer typeface (e.g., swap, print, units, bqbq).
- variable names always appear in lower case, in computer typeface, and enclosed in angle brackets to distinguish them from keywords (e.g., <input_filename>, <basisname>, <tag>).
- $variable$ is used to indicate the substitution of the value of a variable.
- () is used to group items (the parentheses and other special symbols should not appear in the input).
- || separate exclusive options, parameters, or formats.
- [ ] enclose optional entries that have a default value.
- < > enclose a type, a name of a value to be specified, or a default value, if any.
- \ is used to concatenate lines in a description.

- `...` is used to indicate indefinite continuation of a list.

An input parameter is identified in the description of the directive by prefacing the name of the item with the type of data expected, i.e.,

- `string` – an ASCII character string
- `integer` – integer value(s) for a variable or an array
- `logical` – true/false logical variable
- `real` – real floating point value(s) for a variable or an array
- `double` – synonymous with real

If an input item is not prefaced by one of these type names, it is assumed to be of type "string".

In addition, integer lists may be specified using Fortran triplet notation, which interprets `lo:hi:inc` as `lo`, `lo+inc`, `lo+2*inc`, ..., `hi`. For example, where a list of integers is expected in the input, the following two lines are equivalent

```
7 10 21:27:2 1:3 99
7 10 21 23 25 27 1 2 3 99
```

(In Fortran triplet notation, the increment, if unstated, is 1; e.g., 1:3 = 1:3:1.)

The directive `VECTORS` (Section 10.5) is presented here as an example of an NWChem input directive. The general form of the directive is as follows:

```
VECTORS [input (<string input_movecs default atomic>) || \
                 (project <string basisname> <string filename>)] \
        [swap [(alpha||beta)] <integer vec1 vec2> ...] \
        [output <string output_movecs default $file_prefix$.movecs>]
```

This directive contains three optional keywords, as indicated by the three main sets of square brackets enclosing the keywords `input`, `swap`, and `output`. The keyword `input` allows the user to specify the source of the molecular orbital vectors. There are two mutually exclusive options for specifying the vectors, as indicated by the `||` symbol separating the option descriptions;

```
(<string input_movecs default atomic>) || \
               (project <string basisname> <string filename>) \
```

The first option, `(<string input_movecs default atomic>)`, allows the user to specify an ASCII character string for the parameter `input_movecs`. If no entry is specified, the code uses the default `atomic` (i.e., atomic guess). The second option, `(project <string basisname> <string filename>)`, contains the keyword `project`, which takes two string arguments. When this keyword is used, the vectors in file `<filename>` will be projected from the (smaller) basis `<basisname>` into the current atomic orbital (AO) basis.

The second keyword, `swap`, allows the user to re-order the starting vectors, specifying the pairs of vectors to be swapped. As many pairs as the user wishes to have swapped can be listed for `<integer vec1 vec2 ... >`. The optional keywords `alpha` and `beta` allow the user to swap the alpha or beta spin orbitals.

The third keyword, `output`, allows the user to tell the code where to store the vectors, by specifying an ASCII string for the parameter `output_movecs`. If no entry is specified for this parameter, the default is to

write the vectors back into either the user- specified MO vectors input file or, if this is not available, the file `$file_prefix$.movecs`.

A particular example of the `VECTORS` directive is shown below. It specifies both the `input` and `output` keywords, but does not use the `swap` option.

```
vectors input project "small basis" small_basis.movecs \
        output large_basis.movecs
```

This directive tells the code to generate input vectors by projecting from vectors in a smaller basis named `"small basis"`, which is stored in the file `small_basis.movecs`. The output vectors will be stored in the file `large_basis.movecs`.

The order of keyed optional entries within a directive should not matter, unless noted otherwise in the specific instructions for a particular directive.

Chapter 3

NWChem Architecture

As noted above, NWChem consists of independent modules that perform the various functions of the code. Examples include the input parser, self-consistent field (SCF) energy, SCF analytic gradient, and density functional theory (DFT) energy modules. The independent NWChem modules can share data only through a disk-resident database, which is similar to the GAMESS-UK dumpfile or the Gaussian checkpoint file. This allows the modules to share data, or to share access to files containing data.

It is not necessary for the user to be intimately familiar with the contents of the database in order to run NWChem. However, a nodding acquaintance with the design of the code will help in clarifying the logic behind the input requirements, especially when restarting jobs or performing multiple tasks within one job. Section 3.1 gives a general description of the database.

As described above (Section 2.1), all start-up directives are processed at the beginning of the job by the main program, and then the input module is invoked. Each input directive usually results in one or more entries being made in the database. When a `TASK` directive is encountered, control is passed to the appropriate module, which extracts relevant data from the database and any associated files. Upon completion of the task, the module will store significant results in the database, and may also modify other database entries in order to affect the behavior of subsequent computations.

3.1 Database Structure

Data is shared between modules of NWChem by means of the database. Three main types of information are stored in the data base: (1) arrays of data, (2) names of files that contain data, and (3) objects. Arrays are stored directly in the database, and contain the following information:

1. the name of the array, which is a string of ASCII characters (e.g., `"reference energies"`)
2. the type of the data in the array (i.e., real, integer, logical, or character)
3. the number (N) of data items in the array (Note: A scalar is stored as an array of unit length.)
4. the N items of data of the specified type

It is possible to enter data directly into the database using the `SET` directive (see Section 5.7). For example, to store a (64-bit precision) three-element real array with the name `"reference energies"` in the database, the directive is as follows:

```
set "reference energies" 0.0 1.0 -76.2
```

NWChem determines the data to be real (based on the type of the first element, `0.0`), counts the number of elements in the array, and enters the array into the database.

Much of the data stored in the database is internally managed by NWChem and should not be modified by the user. However, other data, including some NWChem input options, can be freely modified.

Objects are built in the database by storing associated data as multiple entries, using an internally consistent naming convention. This data is managed exclusively by the subroutines (or methods) that are associated with the object. Currently, the code has two main objects: basis sets and geometries. Sections 6 and 7 present a complete discussion of the input to describe these objects.

As an illustration of what comprises a geometry object, the following table contains a partial listing of the database contents for a water molecule geometry named `"test geom"`. Each entry contains the field `test geom`, which is the unique name of the object.

```
Contents of RTDB h2o.db
-----------------------

Entry                              Type[nelem]
--------------------------  ----------------------
geometry:test geom:efield             double[3]
geometry:test geom:coords             double[9]
geometry:test geom:ncenter               int[1]
geometry:test geom:charges            double[3]
geometry:test geom:tags                 char[6]
...
```

Using this convention, multiple instances of objects may be stored with different names in the same database. For example, if a user needed to do calculations considering alternative geometries for the water molecule, an input file could be constructed containing all the geometries of interest by storing them in the database under different names.

The runtime database contents for the file `h2o.db` listed above were generated from the user-specified input directive,

```
geometry "test geom"
  O     0.00000000    0.00000000    0.00000000
  H     0.00000000    1.43042809   -1.10715266
  H     0.00000000   -1.43042809   -1.10715266
end
```

The `GEOMETRY` directive allows the user to specify the coordinates of the atoms (or centers), and identify the geometry with a unique name. (Refer to Section 6 for a complete description of the `GEOMETRY` directive.)

Unless a specific name is defined for the geometry, (such as the name `"test geom"` shown in the example), the default name of `geometry` is assigned. This is the geometry name that computational modules will look for when executing a calculation. The `SET` directive can be used in the input to force NWChem to look for a geometry with a name other than `geometry`. For example, to specify use of the geometry with the name `"test geom"` in the example above, the `SET` directive is as follows:

```
set geometry "test geom"
```

NWChem will automatically check for such indirections when loading geometries. Storage of data associated with basis sets, the other database resident object, functions in a similar fashion, using the default name `"ao basis"`.

3.2 Persistence of data and restart

The database is persistent, meaning that all input data and output data (calculation results) that are not destroyed in the course of execution are permanently stored. These data are therefore available to subsequent tasks or jobs. This makes the input for restart jobs very simple, since only new or changed data must be provided. It also makes the behavior of successive restart jobs *identical* to that of multiple tasks within one job.

Sometimes, however, this persistence is undesirable, and it is necessary to return an NWChem module to its default behavior by restoring the database to its input-free state. In such a case, the `UNSET` directive (see Section 5.8) can be used to delete all database entries associated with a given module (including both inputs and outputs).

Chapter 4

Functionality

NWChem provides many methods to compute the properties of molecular and periodic systems using standard quantum mechanical descriptions of the electronic wavefunction or density. In addition, NWChem has the capability to perform classical molecular dynamics and free energy simulations. These approaches may be combined to perform mixed quantum-mechanics and molecular-mechanics simulations.

NWChem is available on almost all high performance computing platforms, workstations, PCs running LINUX, as well as clusters of desktop platforms or workgroup servers. NWChem development has been devoted to providing maximum efficiency on massively parallel processors. It achieves this performance on the 1960 processors HP Itanium2 system in the EMSL's MSCF. It has not been optimized for high performance on single processor desktop systems.

4.1 Molecular electronic structure

The following quantum mechanical methods are available to calculate energies, analytic first derivatives and second derivatives with respect to atomic coordinates.

- Self Consistent Field (SCF) or Hartree Fock (RHF, UHF).
- Gaussian Density Functional Theory (DFT), using many local, non-local (gradient-corrected), and hybrid (local, non-local, and HF) exchange-correlation potentials (spin-restricted) with formal N^3 and N^4 scaling.

The following methods are available to calculate energies and analytic first derivatives with respect to atomic coordinates. Second derivatives are computed by finite difference of the first derivatives.

- Self Consistent Field (SCF) or Hartree Fock (ROHF).
- Gaussian Density Functional Theory (DFT), using many local, non-local (gradient-corrected), and hybrid (local, non-local, and HF) exchange-correlation potentials (spin-unrestricted) with formal N^3 and N^4 scaling.
- Spin-orbit DFT (SODFT), using many local and non-local (gradient-corrected) exchange-correlation potentials (spin-unrestricted).
- MP2 including semi-direct using frozen core and RHF and UHF reference.

- Complete active space SCF (CASSCF).

The following methods are available to compute energies only. First and second derivatives are computed by finite difference of the energies.

- CCSD, CCSD(T), CCSD+T(CCSD), with RHF reference.
- Selected-CI with second-order perturbation correction.
- MP2 fully-direct with RHF reference.
- Resolution of the identity integral approximation MP2 (RI-MP2), with RHF and UHF reference.
- CIS, TDHF, TDDFT, and Tamm–Dancoff TDDFT for excited states with RHF, UHF, RDFT, or UDFT reference.
- CCSD(T) and CCSD[T] for closed- and open-shell systems (TCE module)
- UCCD, ULCCD, UCCSD, ULCCSD, UQCISD, UCCSDT, and UCCSDTQ with RHF, UHF, or ROHF reference.
- UCISD, UCISDT, and UCISDTQ with RHF, UHF, or ROHF reference.
- Non-canonical UMP2, UMP3, and UMP4 with RHF or UHF reference.
- EOM-CCSD, EOM-CCSDT, EOM-CCSDTQ for excitation energies, transition moments, and excited-state dipole moments of closed- and open-shell systems
- CCSD, CCSDT, CCSDTQ for dipole moments of closed- and open-shell systems

For all methods, the following operations may be performed:

- Single point energy
- Geometry optimization (minimization and transition state)
- Molecular dynamics on the fully *ab initio* potential energy surface
- Numerical first and second derivatives automatically computed if analytic derivatives are not available
- Normal mode vibrational analysis in cartesian coordinates
- ONIOM hybrid method of Morokuma and co-workers
- Generation of the electron density file for graphical display
- Evaluation of static, one-electron properties.
- Electrostatic potential fit of atomic partial charges (CHELPG method with optional RESP restraints or charge constraints)

For closed and open shell SCF and DFT:

- COSMO energies - the continuum solvation 'COnductor-like Screening MOdel' of A. Klamt and G. Schüürmann to describe dielectric screening effects in solvents.

In addition, automatic interfaces are provided to

- Python
- the POLYRATE direct dynamics software

4.2 Relativistic effects

The following methods for including relativity in quantum chemistry calculations are available:

- Spin-free and spin-orbit one-electron Douglas-Kroll and zeroth-order regular approximations (ZORA) are available for all quantum mechanical methods and their gradients.
- Dyall's spin-free Modified Dirac Hamiltonian approximation is available for the Hartree-Fock method and its gradients.
- One-electron spin-orbit effects can be included via spin-orbit potentials. This option is available for DFT and its gradients, but has to be run without symmetry.

4.3 Pseudopotential plane-wave electronic structure

Two modules are available to compute the energy, optimize the geometry, numerical second derivatives, and perform ab initio molecular dynamics using pseudopotential plane-wave DFT.

- PSPW - (Pseudopotential plane-wave) A gamma point code for calculating molecules, liquids, crystals, and surfaces.
- Band - A prototype band structure code for calculating crystals and surfaces with small band gaps (e.g. semi-conductors and metals)

With

- Conjugate gradient and limited memory BFGS minimization
- Car-Parrinello (extended Lagrangian dynamics)
- Constant energy and constant temperature Car-Parrinello simulations
- Fixed atoms in cartesian and SHAKE constraints in Car-Parrinello
- Pseudopotential libraries
- Hamann and Troullier-Martins norm-conserving pseudopotentials with optional semicore corrections
- Automated wavefunction initial guess, now with LCAO
- Vosko and PBE96 exchange-correlation potentials (spin-restricted and unrestricted)
- Orthorhombic simulation cells with periodic and free space boundary conditions.
- Modules to convert between small and large plane-wave expansions
- Interface to DRIVER, STEPPER, and VIB modules
- Polarization through the use of point charges
- Mulliken, point charge, DPLOT (wavefunction, density and electrostatic potential plotting) analysis

4.4 Molecular dynamics

The following functionality is available for classical molecular simulations:

- Single configuration energy evaluation
- Energy minimization
- Molecular dynamics simulation
- Free energy simulation (multistep thermodynamic perturbation (MSTP) or multiconfiguration thermodynamic integration (MCTI) methods with options of single and/or dual topologies, double wide sampling, and separation-shifted scaling)

The classical force field includes:

- Effective pair potentials (functional form used in AMBER, GROMOS, CHARMM, etc.)
- First order polarization
- Self consistent polarization
- Smooth particle mesh Ewald (SPME)
- Twin range energy and force evaluation
- Periodic boundary conditions
- SHAKE constraints
- Consistent temperature and/or pressure ensembles

NWChem also has the capability to combine classical and quantum descriptions in order to perform:

- Mixed quantum-mechanics and molecular-mechanics (QM/MM) minimizations and molecular dynamics simulation , and
- Quantum molecular dynamics simulation by using any of the quantum mechanical methods capable of returning gradients.

By using the DIRDYVTST module of NWChem, the user can write an input file to the POLYRATE program, which can be used to calculate rate constants including quantum mechanical vibrational energies and tunneling contributions.

4.5 Python

The Python programming language has been embedded within NWChem and many of the high level capabilities of NWChem can be easily combined and controlled by the user to perform complex operations.

4.6 Parallel tools and libraries (ParSoft)

- Global arrays (GA)
- Agregate Remote Memory Copy Interface (ARMCI)
- Linear Algebra (PeIGS) and FFT
- ParIO
- Memory allocation (MA)

Chapter 5

Top-level directives

Top-level directives are directives that can affect all modules in the code. Some specify molecular properties (e.g., total charge) or other data that should apply to all subsequent calculations with the current database. However, most top-level directives provide the user with the means to manage the resources for a calculation and to start computations. As the first step in the execution of a job, NWChem scans the entire input file looking for start-up directives, which NWChem must process before all other input. The input file is then rewound and processed sequentially, and each directive is processed in the order in which it is encountered. In this second pass, start-up directives are ignored.

The following sections describe each of the top-level directives in detail, noting all keywords, options, required input, and defaults.

5.1 START and RESTART — Start-up mode

A START or RESTART directive is optional. If one of these two directives is not specified explicitly, the code will infer one, based upon the name of the input file and the availability of the database. When allowing NWChem to infer the start-up directive, the user must be quite certain that the contents of the database will result in the desired action. It is usually more prudent to specify the directive explicitly, using the following format:

```
(RESTART || START)   \
            [<string file_prefix default $input_file_prefix$>] \
            [rtdb <string rtdb_file_name default $file_prefix$.db>]
```

The START directive indicates that the calculation is one in which a new database is to be created. Any relevant information that already exists in a previous database of the same name is destroyed. The string variable <file_prefix> will be used as the prefix to name any files created in the course of the calculation.

E.g., to start a new calculation on water, one might specify

```
start water
```

which will make all files begin with "water.".

If the user does not specify an entry for <file_prefix> on the START directive (or omits the START directive altogether), the code uses the base-name of the input file as the file prefix. That is, the variable

<file_prefix> is assigned the name of the input file (not its full pathname), but without the last "dot-suffix". For example, the input file name /home/dave/job.2.nw yields job.2 as the file prefix, if a name is not assigned explicitly using the START directive.

The user also has the option of specifying a unique name for the database, using the keyword rtdb. When this keyword is entered, the string entered for rtdb_file_name is used as the database name. If the keyword rtbd is omitted, the name of the database defaults to $<file_prefix>$.db in the directory for permanent files.

If a calculation is to start from a previous calculation and go on using the existing database, the RESTART directive must be used. In such a case, the previous database must already exist. The name specified for <file_prefix> usually should not be changed when restarting a calculation. If it is changed, NWChem will not be able to find needed files when going on with the calculation.

In the most common situation, the previous calculation was completed (with or without an error condition), and it is desired to perform a new task or restart the previous one, perhaps with some input changes. In these instances, the RESTART directive should be used. This reuses the previous database and associated files, and reads the input file for new input and task information.

The RESTART directive looks immediately for new input and task information, deleting information about previous incomplete tasks. For example, when doing a RESTART there is no need to specify geometry or basis set declaration because the program will detect this information since it is stored in the run-time database.

If a calculation runs out of time, for example because it is on a queuing system, this is another instance where doing a RESTART is advisable. Simply include nothing after the RESTART directive except those tasks that are unfinished.

NOTE: Due to changes in the runtime database structure, RESTART will not work on database files generated by NWChem versions 4.0.1 and older.

To summarize the default options for this start-up directive, if the input file does *not* contain a START or a RESTART directive, then

- the variable <file_prefix> is assigned the name of the input file for the job, without the suffix (which is usually .nw)
- the variable <rtdb_file_name> is assigned the default name, $file_prefix$.db

If the database with name $file_prefix$.db does *not* already exist, the calculation is carried out as if a START directive had been encountered. If the database with name $file_prefix$.db *does* exist, then the calculation is performed as if a RESTART directive had been encountered.

For example, NWChem can be run using an input file with the name water.nw by typing the UNIX command line,

```
nwchem water.nw
```

If the NWChem input file water.nw does not contain a START or RESTART directive, the code sets the variable <file_prefix> to water. Files created by the job will have this prefix, and the database will be named water.db. If the database water.db does *not* exist already, the code behaves as if the input file contains the directive,

```
start water
```

If the database water.db *does* exist, the code behaves as if the input file contained the directive,

```
restart water
```

5.2 SCRATCH_DIR and PERMANENT_DIR — File directories

These are start-up directives that allow the user to specify the directory location of scratch and permanent files created by NWChem. NWChem distinguishes between permanent (or persistent) files and scratch (or temporary) files, and allows the user the option of putting them in different locations. In most installations, however, permanent and scratch files are all written to the current directory by default. What constitutes "local" disk space may also differ from machine to machine.

The conventions for file storage are at the discretion of the specific installation, and are quite likely to be different on different machines. When assigning locations for permanent and scratch files, the user must be cognizant of the characteristics of the installation on a particular platform. To consider just a few examples, on clusters, machine-specific or process-specific names must be supplied for both local and shared file systems, while on SMPs it is useful to specify scratch file directories with automated striping across processors with round-robin allocation. On SMP clusters (a.k.a. constellations), both of these specifications are required.

The SCRATCH_DIR and PERMANENT_DIR directives are identical in format and capability, and enable the user to specify a single directory for all processes, or different directories for different processes. The general form of the directive is as follows:

```
(PERMANENT_DIR || SCRATCH_DIR) [(<string host>||<integer process>):] \
                                    <string directory> \
                               [...]
```

Directories are extracted from the user input by executing the following steps, in sequence:

1. Look for a directory qualified by the process ID number of the invoking process. Processes are numbered from zero. Else,
2. If there is a list of directories qualified by the name of the host machine[1], then use round-robin allocation from the list for processes executing on the given host. Else,
3. If there is a list of directories unqualified by any hostname or process ID, then use round-robin allocation from this list.

If directory allocation directive(s) are not specified in the input file, or if no match is found to the directory names specified by input using these directives, then the steps above are executed using the installation-specific defaults. If the code cannot find a valid directory name based on the input specified in either the directive(s) or the system defaults, files are automatically written to the current working directory (`"."`).

The following is a list of examples of specific allocations of scratch directory locations:

- Put scratch files from all processes in the local scratch directory (Warning: the definition of "local scratch directory" may change from machine to machine):

  ```
  scratch_dir /localscratch
  ```

- Put scratch files from Process 0 in `/piofs/rjh`, but put all other scratch files in `/scratch`:

[1] As returned by `util_hostname()` which maps to the output of the command `hostname` on Unix workstations.

```
scratch_dir /scratch 0:/piofs/rjh
```

- Put scratch files from Process 0 in directory `scr1`, those from Process 1 in `scr2`, and so forth, in a round-robin fashion, using the given list of directories:

```
scratch_dir /scr1 /scr2 /scr3 /scr4 /scr5
```

- Allocate files in a round-robin fashion from host-specific lists for processes distributed across two SGI multi-processor machines (node names *coho* and *bohr*):

```
scratch_dir coho:/xfs1/rjh coho:/xfs2/rjh coho:/xfs3/rjh \
    bohr:/disk01/rjh bohr:/disk02/rjh bohr:/disk13/rjh
```

5.3 MEMORY — Control of memory limits

This is a start-up directive that allows the user to specify the amount of memory that NWChem can use for the job. If this directive is not specified, memory is allocated according to installation-dependent defaults. *The defaults should generally suffice for most calculations, since the defaults usually correspond to the total amount of memory available on the machine. It should usually be unnecessary to provide a memory directive!!!*

The general form of the directive is as follows:

```
MEMORY [[total] <integer total_size>] \
       [stack <integer stack_size>] \
       [heap <integer heap_size>] \
       [global <integer global_size>] \
       [units <string units default real>] \
       [(verify||noverify)] \
       [(nohardfail||hardfail)] \
```

NWChem recognizes the following memory units:

- `real` and `double` (synonyms)
- `integer`
- `byte`
- `kb` (kilobytes)
- `mb` (megabytes)
- `mw` (megawords, 64-bit word)

In most cases, the user need specify only the total memory limit to adjust the amount of memory used by NWChem. The following specifications all provide for eight megabytes of total memory (assuming 64-bit floating point numbers), which will be distributed according to the default partitioning:

```
memory 1048576
memory 1048576 real
memory 1 mw
memory 8 mb
memory total 8 mb
memory total 1048576
```

In NWChem there are three distinct regions of memory: stack, heap, and global. Stack and heap are node-private, while the union of the global region on all processors is used to provide globally-shared memory. The allowed limits on each category are determined from a default partitioning (currently 25% heap, 25% stack, and 50% global). Alternatively, the keywords `stack`, `heap`, and `global` can be used to define specific allocations for each of these categories. If the user sets only one of the stack, heap, or global limits by input, the limits for the other two categories are obtained by partitioning the remainder of the total memory available in proportion to the weight of those two categories in the default memory partitioning. If two of the category limits are given, the third is obtained by subtracting the two given limits from the total limit (which may have been specified or may be a default value). If all three category limits are specified, they determine the total memory allocated. However, if the total memory is also specified, it must be larger than the sum of all three categories. The code will abort if it detects an inconsistent memory specification.

The following memory directives also allocate 8 megabytes, but specify a complete partitioning as well:

```
memory total 8 stack 2 heap 2 global 4 mb
memory stack 2 heap 2 global 4 mb
```

The optional keywords `verify` and `noverify` in the directive give the user the option of enabling or disabling automatic detection of corruption of allocated memory. The default is `verify`, which enables the feature. This incurs some overhead (which can be around 10% increase in walltime on some platforms), which can be eliminated by specifying `noverify`.

The keywords `hardfail` and `nohardfail` give the user the option of forcing (or not forcing) the local memory management routines to generate an internal fatal error if any memory operation fails. The default is `nohardfail`, which allows the code to continue past any memory operation failure, and perhaps generate a more meaningful error message before terminating the calculation. Forcing a hard-fail can be useful when poorly coded applications do not check the return status of memory management routines.

When assigning the specific memory allocations using the keywords `stack`, `heap`, and `global` in the `MEMORY` directive, the user should be aware that some of the distinctions among these categories of memory have been blurred in their actual implementation in the code. The memory allocator (MA) allocates both the heap and the stack from a single memory region of size `heap+stack`, without enforcing the partition. The heap vs. stack partition is meaningful only to applications developers, and can be ignored by most users. Further complicating matters, the global array (GA) toolkit is allocated from within the MA space on distributed memory machines, while on shared-memory machines it is separate[2].

On distributed memory platforms, the MA region is actually the total size of

```
stack+heap+global
```

All three types of memory allocation compete for the same pool of memory, with no limits except on the total available memory. This relaxation of the memory category definitions usually benefits the user, since it can allow allocation requests to succeed where a stricter memory model would cause the directive to fail.

[2]This is because on true shared-memory machines there is no choice but to allocate GAs from within a shared-memory segment, which is managed differently by the operating system.

These implementation characteristics must be kept in mind when reading program output that relates to memory usage.

Standard default for memory is currently 400 MB.

5.4 ECHO — Print input file

This start-up directive is provided as a convenient way to include a listing of the input file in the output of a calculation. It causes the entire input file to be printed to Fortran unit six (standard output). It has no keywords, arguments, or options, and consists of the single line:

```
ECHO
```

The ECHO directive is processed only once, by Process 0 when the input file is read.

5.5 TITLE — Specify job title

This top-level directive allows the user to identify a job or series of jobs that use a particular database. It is an optional directive, and if omitted, the character string containing the input title will be empty. Multiple TITLE directives may appear in the input file (e.g., the example file in Section 2.3) in which case a task will use the one most recently specified. The format for the directive is as follows:

```
TITLE <string title>
```

The character string <title> is assigned to the contents of the string following the TITLE directive. If the string contains white space, it must be surrounded by double quotes. For example,

```
title "This is the title of my NWChem job"
```

The title is stored in the database and will be used in all subsequent tasks/jobs until redefined in the input.

5.6 PRINT and NOPRINT — Print control

The PRINT and NOPRINT directives allow the user to control how much output NWChem generates. These two directives are special in that the compound directives for *all* modules are supposed to recognize them. Each module can control both the overall print level (general verbosity) and the printing of individual items which are identified by name (see below). The standard form of the PRINT directive is as follows:

```
PRINT [(none || low || medium || high || debug) default medium] \
      [<string list_of_names ... >]

NOPRINT <string list_of_names ... >
```

The default print level is medium.

Every output that is printed by NWChem has a print threshold associated with it. If this threshold is equal to or lower than the print level requested by the user, then the output is generated. For example, the threshold for printing the SCF energy at convergence is `low` (Section 10.16). This means that if the user-specified print level on the `PRINT` directive is `low`, `medium`, `high`, or `debug`, then the SCF energy will be printed at convergence.

The overall print level specified using the `PRINT` directive is a convenient tool for controlling the verbosity of NWChem. Setting the print level to `high` might be helpful in diagnosing convergence problems. The print level of `debug` might also be of use in evaluating problem cases, but the user should be aware that this can generate a huge amount of output. Setting the print level to `low` might be the preferable choice for geometry optimizations that will perform many steps which are in themselves of little interest to the user.

In addition, it is possible to enable the printing of specific items by naming them in the `PRINT` directive in the `<list_of_names>`. Items identified in this way will be printed, regardless of the overall print level specified. Similarly, the `NOPRINT` directive can be used to suppress the printing of specific items by naming them in its `<list_of_names>`. These items will *not* be printed, regardless of the overall print level, or the specific print level of the individual items.

The list of items that can be printed for each module is documented as part of the input instructions for that module. The items recognized by the top level of the code, and their thresholds, are:

Name	**Print Level**	**Description**
"total time"	medium	Print cpu and wall time at job end
"task time"	high	Print cpu and wall time for each task
"rtdb"	high	Print names of RTDB entries
"rtdbvalues"	high	Print name and values of RTDB entries
"ga summary"	medium	Summarize GA allocations at job end
"ga stats"	high	Print GA usage statistics at job end
"ma summary"	medium	Summarize MA allocations at job end
"ma stats"	high	Print MA usage statistics at job end
"version"	debug	Print version number of all compiled routines
"tcgmsg"	never	Print TCGMSG debug information

Table 5.1: Top Level Print Control Specifications

The following example shows how a `PRINT` directive for the top level process can be used to limit printout to only essential information. The directive is

```
print none "ma stats" rtdb
```

This directive instructs the NWChem main program to print nothing, except for the memory usage statistics (`ma stats`) and the names of all items stored in the database at the end of the job.

The print level within a module is inherited from the calling layer. For instance, by specifying the print to be low within the MP2 module will cause the SCF, CPHF and gradient modules when invoked from the MP2 to default to low print. Explicit user input of print thresholds overrides the inherited value.

5.7 SET — Enter data in the RTDB

This top-level directive allows the user to enter data directly into the run-time database (see Section 3.1 for a description of the database). The format of the directive is as follows:

```
SET <string name> [<string type default automatic>] <$type$ data>
```

The entry for variable `<name>` is the name of data to be entered into the database. This must be specified; there is no default. The variable `<type>`, which is optional, allows the user to define a string specifying the type of data in the array `<name>`. The data type can be explicitly specified as `integer`, `real`, `double`, `logical`, or `string`. If no entry for `<type>` is specified on the directive, its value is inferred from the data type of the *first* datum. In such a case, floating-point data entered using this directive must include either an exponent or a decimal point, to ensure that the correct default type will be inferred. The correct default type will be inferred for logical values if logical-true values are specified as `.true.`, `true`, or `t`, and logical-false values are specified as `.false.`, `false`, or `f`. One exception to the automatic detection of the data type is that the data type **must** be explicitly stated to input integer ranges, unless the first element in the list is an integer that is not a range (c.f., 2.4). For example,

```
set atomid 1 3:7 21
```

will be interpreted as a list of integers. However,

```
set atomid 3:7 21
```

will not work since the first element will be interpreted as a string and not an integer. To work around this feature, use instead

```
set atomid integer 3:7 21
```

which says to write three through seven, as well as twenty-one.

The `SET` directive is useful for providing indirection by associating the name of a basis set or geometry with the standard object names (such as `"ao basis"` or `geometry`) used by NWChem. The following input file shows an example using the `SET` directive to direct different tasks to different geometries. The required input lines are as follows:

```
title "Ar dimer BSSE corrected MP2 interaction energy"
geometry "Ar+Ar"
  Ar1 0 0 0
  Ar2 0 0 2
end

geometry "Ar+ghost"
  Ar1 0 0 0
  Bq2 0 0 2
end

basis
  Ar1 library aug-cc-pvdz
  Ar2 library aug-cc-pvdz
```

```
  Bq2 library Ar aug-cc-pvdz
end

set geometry "Ar+Ar"
task mp2

scf; vectors atomic; end

set geometry "Ar+ghost"
task mp2
```

This input tells the code to perform MP2 energy calculations on an argon dimer in the first task, and then on the argon atom in the presence of the "ghost" basis of the other atom.

The SET directive can also be used as an indirect means of supplying input to a part of the code that does not have a separate input module (e.g., the atomic SCF, Section 10.5.2). Additional examples of applications of this directive can be found in the sample input files (see Section 2.3), and its usage with basis sets (Section 7) and geometries (Section 6). Also see Section 3.1 for an example of how to store an array in the database.

5.8 UNSET — Delete data in the RTDB

This directive gives the user a way to delete simple entries from the database. The general form of the directive is as follows:

```
UNSET <string name>[*]
```

This directive cannot be used with complex objects such as geometries and basis sets[3]. A wild-card (*) specified at the end of the string <name> will cause *all* entries whose name begins with that string to be deleted. This is very useful as a way to reset modules to their default behavior, since modules typically store information in the database with names that begin with module:. For example, the SCF program can be restored to its default behavior by deleting all database entries beginning with scf:, using the directive

```
unset scf:*
```

Section 10.5.1 has an example using unset on a water dimer calculation.

The following example makes an entry in the database using the SET directive, and then immediately deletes it using the UNSET directive:

```
set mylist 1 2 3 4
unset mylist
```

5.9 STOP — Terminate processing

This top-level directive provides a convenient way of verifying an input file without actually running the calculation. It consists of the single line,

[3]Complex objects are stored using a structured naming convention that is not matched by a simple wild card.

```
STOP
```

As soon as this directive is encountered, all processing ceases and the calculation terminates with an error condition.

5.10 TASK — Perform a task

The TASK directive is used to tell the code what to do. The input directives are parsed sequentially until a TASK directive is encountered, as described in Section 2.1. At that point, the calculation or operation specified in the TASK directive is performed. When that task is completed, the code looks for additional input to process until the next TASK directive is encountered, which is then executed. This process continues to the end of the input file. NWChem expects the last directive before the end-of-file to be a TASK directive. If it is not, a warning message is printed. Since the database is persistent, multiple tasks within one job behave *exactly* the same as multiple restart jobs with the same sequence of input.

There are four main forms of the the TASK directive. The most common form is used to tell the code at what level of theory to perform an electronic structure calculation, and which specific calculations to perform. The second form is used to specify tasks that do not involve electronic structure calculations or tasks that have not been fully implemented at all theory levels in NWChem, such as simple property evaluations. The third form is used to execute UNIX commands on machines having a Bourne shell. The fourth form is specific to combined quantum-mechanics and molecular-mechanics (QM/MM) calculations.

By default, the program terminates when a task does not complete successfully. The keyword ignore can be used to prevent this termination, and is recognized by all forms of the TASK directive. When a TASK directive includes the keyword ignore, a warning message is printed if the task fails, and code execution continues with the next task. An example of this feature is given in the sample input file in Section 11.5.

The input options, keywords, and defaults for each of these four forms for the TASK directive are discussed in the following sections.

5.10.1 TASK Directive for Electronic Structure Calculations

This is the most commonly used version of the TASK directive, and it has the following form:

```
TASK <string theory> [<string operation default energy>] [ignore]
```

The string <theory> specifies the level of theory to be used in the calculations for this task. NWChem currently supports ten different options. These are listed below, with the corresponding entry for the variable <theory>:

- scf — Hartree-Fock
- dft — Density functional theory for molecules
- sodft — Spin-Orbit Density functional theory
- mp2 — MP2 using a semi-direct algorithm
- direct_mp2 — MP2 using a full-direct algorithm
- rimp2 — MP2 using the RI approximation

- ccsd — Coupled-cluster single and double excitations
- ccsd(t) — Coupled-cluster linearized triples approximation
- ccsd+t(ccsd) — Fourth order triples contribution
- mcscf — Multiconfiguration SCF
- selci — Selected configuration interaction with perturbation correction
- md — Classical molecular dynamics simulation
- pspw — Pseudopotential plane-wave density functional theory for molecules and insulating solids using NWPW
- band — Pseudopotential plane-wave density functional theory for solids using NWPW
- tce — Tensor Contraction Engine (please see Section 15.4 for a complete description of this task directive

The string <operation> specifies the calculation that will be performed in the task. The default operation is a single point energy evaluation. The following list gives the selection of operations currently available in NWChem:

- energy — Evaluate the single point energy.
- gradient — Evaluate the derivative of the energy with respect to nuclear coordinates.
- optimize — Minimize the energy by varying the molecular structure. By default, this geometry optimization is presently driven by the Driver module (see Section 20), but the Stepper module (see Section 21) may also be used.
- saddle — Conduct a search for a transition state (or saddle point) using either Driver (Section 20, the default) or Stepper (Section 21).
- hessian — Compute second derivatives. See Section 24 for analytic hessians.
- frequencies or freq — Compute second derivatives and print out an analysis of molecular vibrations. See Section 25 for controls for vibration calculations.
- property — Calculate the properties for the wave function.
- dynamics — Perform classical molecular dynamics.
- thermodynamics — Perform multi-configuration thermodynamic integration using classical MD

NOTE: See Section 36.1 for the complete list of operations that accompany the NWPW module.

The user should be aware that some of these operations (gradient, optimize, dynamics, thermodynamics) require computation of derivatives of the energy with respect to the molecular coordinates. If analytical derivatives are not available (Section 4), they must be computed numerically, which can be very computationally intensive.

Here are some examples of the TASK directive, to illustrate the input needed to specify particular calculations with the code. To perform a single point energy evaluation using any level of theory, the directive is very simple, since the energy evaluation is the default for the string operation. For an SCF energy calculation, the input line is simply

```
task scf
```

Equivalently, the operation can be specified explicitly, using the directive

```
task scf energy
```

Similarly, to perform a geometry optimization using density functional theory, the `TASK` directive is

```
task dft optimize
```

The optional keyword `ignore` can be used to allow execution to continue even if the task fails, as discussed above. An example with the keyword `ignore` can be found in Section 11.5.

5.10.2 `TASK` Directive for Special Operations

This form of the `TASK` directive is used in instances where the task to be performed does not fit the model of the previous version (such as execution of a Python program, Section 37), or if the operation has not yet been implemented in a fashion that applies to a wide range of theories (e.g., property evaluation). Instead of requiring `theory` and `operation` as input, the directive needs only a string identifying the task. The form of the directive in such cases is as follows:

```
TASK <string task> [ignore]
```

The supported tasks that can be accessed with this form of the `TASK` directive are listed below, with the corresponding entries for string variable `<task>`.

- `python` — Execute a Python program (Section 37).
- `rtdbprint` — Print the contents of the database.
- `cphf` — Invoke the CPHF module.
- `property` — Perform miscellaneous property calculations.
- `dplot` — Execute a DPLOT run (Section 26)

This directive also recognizes the keyword `ignore`, which allows execution to continue after a task has failed.

5.10.3 `TASK` Directive for the Bourne Shell

This form of the `TASK` directive is supported only on machines with a fully UNIX-style operating system. This directive causes specified processes to be executed using the Bourne shell. This form of the task directive is:

```
TASK shell [(<integer-range process = 0>||all)] \
           <string command>
```

The keyword shell is required for this directive. It specifies that the given command will be executed in the Bourne shell. The user can also specify which process(es) will execute this command by entering values for process on the directive. The default is for only process zero to execute the command. A range of processes may be specified, using Fortran triplet notation[4]. Alternatively, all processes can be specified simply by entering the keyword all. The input entered for command must form a single string, and must consist of valid UNIX command(s). If the string includes white space, it must be enclosed in double quotes.

For example, the TASK directive to tell process zero to copy the molecular orbitals file to a backup location /piofs/save can be input as follows:

```
task shell "cp *.movecs /piofs/save"
```

The TASK directive to tell all processes to list the contents of their /scratch directories is as follows:

```
task shell all "ls -l /scratch"
```

The TASK directive to tell processes 0 to 10 to remove the contents of the current directory is as follows:

```
task shell 0:10:1 "/bin/rm -f *"
```

Note that NWChem's ability to quote special input characters is *very* limited when compared with that of the Bourne shell. To execute all but the simplest UNIX commands, it is usually much easier to put the shell script in a file and execute the file from within NWChem.

5.10.4 TASK Directive for QM/MM simulations

This is very similar to the most commonly used version of the TASK directive described in Section 5.10.1, and it has the following form;

```
TASK QMMM <string theory> [<string operation default energy>] [ignore]
```

The string <theory> specifies the QM theory to be used in the QM/MM simulation[5]. The level of theory may be any QM method that can compute gradients but those algorithms in NWChem that do not support analytic gradients should be avoided (c.f., Section 4).

The string <operation> is used to specify the calculation that will be performed in the QM/MM task. The default operation is a single point energy evaluation. The following list gives the selection of operations currently available in the NWChem QM/MM module;

- energy — single point energy evaluation
- optimize — minimize the energy by variation of the molecular structure.
- dynamics — molecular dynamics using nwARGOS

Here are some examples of the TASK directive for QM/MM simulations. To perform a single point energy of a QM/MM system using any QM level of theory, the directive is very simple. As with the general task directive, the QM/MM energy evaluation is the default. For a DFT energy calculation the task directive input is,

[4]The notation lo:hi:inc denotes the integers lo, lo+inc, lo+2*inc, . . . , hi

[5]If theory is "md" this is not a QM/MM simulation and will result in an appropriate error

```
task qmmm dft
```

or completely as

```
task qmmm dft energy
```

To do a molecular dynamics simulation of a QM/MM system using the SCF level of theory the task directive input would be

```
task qmmm scf dynamics
```

The optional keyword `ignore` can be used to allow execution to continue even if the task fails, as discussed above.

5.10.5 `TASK` Directive for BSSE calculations

NWChem computes the basis set superposition error (BSSE) when two or more fragments are interacting by using the counterpoise method. This directive is performed if the `BSSE` section is present. Single point energies, energy gradients, geometry optimizations, Hessians and frequencies, at the level of theory that allows these tasks, can be obtained with the BSSE correction. The input options for the BSSE section are:

```
BSSE
  MON <string monomer name> <integer natoms> \
   [INPUT  [<string input>]] \
   [INPUT_WGHOST[<string input>]] \
   [CHARGE [< real charge>]] \
  [OFF] \
  [ON] \
END
```

`MON` defines the monomer's name and its atoms; ¡string monomer name¿ defines the name of the monomer, ¡integer atoms¿ is the list of atoms corresponding to the monomer (where such a list is relative to the initial geometry). This information is needed for each monomer. With the tag `INPUT` the user can modify any calculation attributes for each monomer without ghost. For example, the iterations number and the grid can be changed in a DFT calculation (see the example of the interaction between Zn^{2+} and water). `INPUT_WGHOST` is the same than `INPUT` but for the monomer with ghost. The input changes will be applied within this and for the following calculations, you should be cautious reverting the changes for the next monomers. `CHARGE` assigns a charge to a monomer and it must be consistent with the total charge in the whole system (see Section 5.11). The options `OFF` and `ON` turns off and on any BSSE calculation.

The energy evaluation involves 1 + 2N calculations, i.e. one for the supermolecule and two for the N monomers. [S. Simon, M. Duran, J. J. Dannenberg, J. Chem. Phys., 105, 11024 (1996)] NWChem stores the vector files for each calculation (`<string monomer name>.bsse.movecs`), and one hessian file (`<string monomer name>.bsse.hess`). The code does not assign automatically the basis set for the ghost atoms, you must assign the corresponding bqX for each element, instead.

Examples

The dimer $(FH)_2$

```
title dimer
start dimer
geometry units angstrom
symmetry c1
  F        1.47189        2.47463       -0.00000
  H        1.47206        3.29987        0.00000
  F        1.46367       -0.45168        0.00000
  H        1.45804        0.37497       -0.00000
end

basis "ao basis"
 F library 6-31G
 H library 6-31G
 bqF library F 6-31G
 bqH library H 6-31G
end
dft; xc slater 1.0 vwn_5 1.0; direct; end
bsse
  mon first 1 2
  mon second 3 4
end

task dft energy
```

Changing `maxiter` for a specific monomer: $Zn^{2+}(H_2O)$

```
title znwater
start znwater

echo
geometry noautoz units angstrom
symmetry c1
  Zn      -1.89334       -0.72741       -0.00000
  O       -0.20798        0.25012        0.00000
  H       -0.14200        1.24982       -0.00000
  H        0.69236       -0.18874       -0.00000
end

basis "ao basis"
 O library 6-31G
 Zn library 6-31G
 H library 6-31G
 bqO library O 6-31G
 bqZn library Zn 6-31G
 bqH library H 6-31G
end
charge 2
scf; direct; end
mp2; end
```

```
bsse
  mon metal 1
    charge 2
    input_wghost "scf\;  maxiter 200\; end"
  mon water 2 3 4
end

task mp2 optimize
```

5.11 CHARGE — Total system charge

This is an optional top-level directive that allows the user to specify the total charge of the system. The form of the directive is as follows:

```
CHARGE <real charge default 0>
```

The default charge[6] is zero if this directive is omitted. An example of a case where the directive would be needed is for a calculation on a doubly charged cation. In such a case, the directive is simply,

```
charge 2
```

If centers with fractional charge have been specified (Section 6) the net charge of the system should be adjusted to ensure that there are an integral number of electrons.

The charge may be changed between tasks, and is used by all wavefunction types. For instance, in order to compute the first two vertical ionization energies of LiH, one might optimize the geometry of LiH using a UHF SCF wavefunction, and then perform energy calculations at the optimized geometry on LiH^{+} and LiH^{2+} in turn. This is accomplished with the following input:

```
geometry; Li 0 0 0; H  0 0 1.64; end
basis; Li library 3-21g; H library 3-21g; end

scf; uhf; singlet; end
task scf optimize

charge 1
scf; uhf; doublet; end
task scf

charge 2
scf; uhf; singlet; end
task scf
```

The GEOMETRY, BASIS, and SCF directives are described below (Sections 6, 7 and 10 respectively) but their intent should be clear. The TASK directive is described above (Section 5.10).

[6] The charge directive, in conjunction with the charges of atomic nuclei (which can be changed via the geometry input, cf. Section 6.3), determines the total number of electrons in the chemical system. Therefore, a `charge n` specification removes "n" electrons from the chemical system. Similarly, `charge -n` adds "n" electrons.

5.12 ECCE_PRINT — Print information for Ecce

The ECCE_PRINT directive allows the user to print out a file, usually called ecce.out, that will allow the calculation and its results to be imported into Ecce.

```
ECCE_PRINT <string name>
```

The entry for variable <name> is the name of the file that will contain the Ecce import information and should include the full path to the directory where you want that file. For example

```
ecce_print /home/user/job/ecce.out
```

If the full path is not given and only the file name is given, the file will be located in whatever directory the job is started in. For example, if the line

```
ecce_print ecce.out
```

is in the input file, the file could end up in the scratch directory if the user is using a batch script that copies the input file to a local scratch directory and then launches NWChem from there. If the system then automatically removes files in the scratch space at the end of the job, the ecce.out file will be lost. So, the best practice is to include the full path name for the file.

Chapter 6

Geometries

The GEOMETRY directive is a compound directive that allows the user to define the geometry to be used for a given calculation. The directive allows the user to specify the geometry with a relatively small amount of input, but there are a large number of optional keywords and additional subordinate directives that the user can specify, if needed. The directive therefore appears to be rather long and complicated when presented in its general form, as follows:

```
GEOMETRY [<string name default geometry>] \
         [units <string units default angstroms>] \
         [(angstrom_to_au || ang2au) \
                <real angstrom_to_au default 1.8897265>] \
         [print [xyz] || noprint] \
         [center || nocenter] \
         [bqbq] \
         [autosym [real tol default 1d-2]] \
         [autoz || noautoz] \
         [adjust] \
         [(nuc || nucl || nucleus) <string nucmodel>]


  [SYMMETRY [group] <string group_name> [print] \
         [tol <real tol default 1d-2>]]



  <string tag> <real x y z> [vx vy vz] [charge <real charge>] \
         [mass <real mass>] \
         [(nuc || nucl || nucleus) <string nucmodel>]
  ... ]

  [ZMATRIX || ZMT || ZMAT
       <string tagn> <list_of_zmatrix_variables>
       ...

       [VARIABLES
            <string symbol> <real value>
```

```
            ... ]

        [CONSTANTS
            <string symbol> <real value>
            ... ]

    (END || ZEND)]

        [ZCOORD
            CVR_SCALING <real value>
            BOND    <integer i> <integer j> \
                    [<real value>] [<string name>] [constant]
            ANGLE   <integer i> <integer j> \
                    [<real value>] [<string name>] [constant]
            TORSION <integer i> <integer j> <integer k> <integer l> \
                    [<real value>] [<string name>] [constant]
         END]

         [SYSTEM surface  <molecule polymer surface crystal default molecule>
              lat_a <real lat_a> lat_b <real lat_b> lat_c <real lat_c>
              alpha <real alpha> beta <real beta> gamma <real gamma>
         END]

END
```

The three main parts of the GEOMETRY directive are:

- keywords on the first line of the directive (to specify such optional input as the geometry name, input units, and print level for the output)
- symmetry information
- Cartesian coordinates or Z-matrix input to specify the locations of the atoms and centers
- lattice parameters (needed only for periodic systems)

The following sections present the input for this compound directive in detail, describing the options available and the usages of the various keywords in each of the three main parts.

6.1 Keywords on the GEOMETRY directive

This section presents the options that can be specified using the keywords and optional input on the main line of the GEOMETRY directive. As described above, the first line of the directive has the general form,

```
GEOMETRY [<string name default geometry>] \
         [units <string units default angstroms>] \
         [bqbq] \
         [print [xyz] || noprint] \
```

```
[center || nocenter] \
[autosym [real tol default 1d-2]] \
[autoz || noautoz] \
[adjust] \
[(nuc || nucl || nucleus) <string nucmodel>]
```

All of the keywords and input on this line are optional. The following list describes all options and their defaults.

- `<name>` – user-supplied name for the geometry; the default name is `geometry`, and all NWChem modules look for a geometry with this name. However, multiple geometries may be specified by using a different name for each. Subsequently, the user can direct a module to a named geometry by using the `SET` directive (see the example in Section 5.7) to associate the default name of `geometry` with the alternate name.

- `units` – keyword specifying that a value will be entered by the user for the string variable `<units>`. The default units for the geometry input are Angstrøms (Note: atomic units or Bohr are used within the code, regardless of the option specified for the input units. The default conversion factor used in the code to convert from Angstrøms to Bohr is 1.8897265 which may be overidden with the `angstrom_to_au` keyword described below.). The code recognizes the following possible values for the string variable `<units>`:

  - `angstroms` or `an` — Angstroms (Å), the default (converts to A.U. using the Åto A.U. conversion factor)
  - `au` or `atomic` or `bohr` — Atomic units (A.U.)
  - `nm` or `nanometers` — nanometers (converts to A.U. using a conversion factor computed as 10.0 times the Å to A.U. conversion factor)
  - `pm` or `picometers` — picometers (converts to A.U. using a conversion factor computed as 0.01 times the Å to A.U. conversion factor)

- `angstrom_to_au` – may also be specified as `ang2au`. This enables the user to modify the conversion factors used to convert between Å and A.U.. The default value is 1.8897265.

- `bqbq` – keyword to specify the treatment of interactions between dummy centers. The default in NWChem is to ignore such interactions when computing energies or energy derivatives. These interactions will be included if the keyword `bqbq` is specified.

- `print` and `noprint` – complementary keyword pair to enable or disable printing of the geometry. The default is to print the output associated with the geometry. In addition, the keyword `print` may be qualified by the additional keyword `xyz`, which specifies that the coordinates should be printed in the XYZ format of molecular graphics program XMol.

- `center` and `nocenter` – complementary keyword pair to enable or disable translation of the center of nuclear charge to the origin. With the origin at this position, all three components of the nuclear dipole are zero. The default is to move the center of nuclear charge to the origin.

- `autosym` – keyword to specify that the symmetry of the geometric system should be automatically determined. This option is on by default. Only groups up to and including O_h are recognized. Occasionally NWChem will be unable to determine the full symmetry of a molecular system, but will find a proper subgroup of the full symmetry. The default tolerance is set to work for most cases, but may need to be decreased to find the full symmetry of a geometry. Note that autosym will be turned off if the `SYMMETRY` group input is given (See section 6.2).

- `noautoz` – by default NWChem (release 3.3 and later) will generate redundant internal coordinates from user input Cartesian coordinates. The internal coordinates will be used in geometry optimizations. The `noautoz` keyword disables use of internal coordinates. The `autoz` keyword is provided only for backward compatibility. See Section 6.5 for a more detailed description of redundant internal coordinates, including how to force the definition of specific internal variables in combination with automatically generated variables.
- `adjust` – This indicates that an existing geometry is to be adjusted. Only new input for the redundant internal coordinates may be provided (Section 6.5). It is not possible to define new centers or to modify the point group using this keyword. See Section 6.5 for an example of its usage.
- `nucleus` – keyword to specify the default model for the nuclear charge distribution. The following values are recognized:
  - `point` or `pt` — point nuclear charge distribution. This is the default.
  - `finite` or `fi` — finite nuclear charge distribution with a Gaussian shape. The RMS radius of the Gaussian is determined from the nuclear mass number A by the expression $r_{\mathrm{RMS}} = 0.836 * A^{1/3} + 0.57$ fm.

  NOTE: If you specify a finite nuclear size, you should ensure that the basis set you use is contracted for a finite nuclear size. See the Section 7 for more information.

The following examples illustrate some of the various options that the user can specify on the first input line of the `GEOMETRY` directive, using the keywords and input options described above.

The following directives all specify the same geometry for H_2 (a bond length of 0.732556 Å):

```
geometry
  h 0 0 0
  h 0 0 0.732556
end

geometry units pm
  h 0 0 0
  h 0 0 73.2556
end
```

```
geometry units nm
  h 0 0 0
  h 0 0 0.0732556
end

geometry units atomic
  h 0 0 0
  h 0 0 1.3843305
end
```

6.2 SYMMETRY — Symmetry Group Input

The `SYMMETRY` directive is used (optionally) within the compound `GEOMETRY` directive to specify the point group for the molecular geometry. The general form of the directive, as described above within the general form of the `GEOMETRY` directive, is as follows:

```
[SYMMETRY [group] <string group_name> [print] \
       [tol <real tol default 1d-2>]]
```

The keyword `group` is optional, and can be omitted without affecting how the input for this directive is processed[1]. However, if the `SYMMETRY` directive is used, a group name must be specified by supplying an entry for the string variable `<group_name>`. The group name should be specified as the standard Schöflies symbol. Examples of expected input for the variable `group_name` include such entries as:

[1]For periodic systems, there are additional keywords within this directive (not yet documented), so having a keyword for the group name is useful.

- `c2v` – for molecular symmetry C_{2v}
- `d2h` – for molecular symmetry D_{2h}
- `Td` – for molecular symmetry T_d
- `d6h` – for molecular symmetry D_{6h}

The `SYMMETRY` directive is optional. The default is no symmetry (i.e., C_1 point group). Automatic detection of point group symmetry is available through the use of `autosym` in the `GEOMETRY` directive main line (discussed in Section 6.1). Note: if the `SYMMETRY` directive is present the `autosym` keyword is ignored.

If only symmetry-unique atoms are specified, the others will be generated through the action of the point group operators, but the user if free to specify all atoms. The user must know the symmetry of the molecule being modeled, and be able to specify the coordinates of the atoms in a suitable orientation relative to the rotation axes and planes of symmetry. Appendix C lists a number of examples of the `GEOMETRY` directive input for specific molecules having symmetry patterns recognized by NWChem. The exact point group symmetry will be forced upon the molecule, and atoms within 10^{-3} A.U. of a symmetry element (e.g., a mirror plane or rotation axis) will be forced onto that element. Thus, it is not necessary to specify to a high precision those coordinates that are determined solely by symmetry.

The keyword `print` gives information concerning the point group generation, including the group generators, a character table, the mapping of centers, and the group operations.

The keyword `tol` relates to the accuracy with which the symmetry-unique atoms should be specified. When the atoms are generated, those that are within the tolerance, `tol`, are considered the same.

6.3 Cartesian coordinate input

The default in NWChem is to specify the geometry information entirely in Cartesian coordinates, and examples of this format have appeared above (e.g, Section 2.3). Each center (usually an atom) is identified on a line of the following form:

```
<string tag> <real x y z> [vx vy vz] \
    [charge <real charge>] [mass <real mass>] \
    [(nuc || nucl || nucleus) <string nucmodel>]
```

The string `<tag>` is the name of the atom or center, and its case (upper or lower) is important. The tag is limited to 16 characters and is interpreted as follows:

- If the entry for `<tag>` begins with either the symbol or name of an element (regardless of case), then the center is treated as an atom of that type. The default charge is the atomic number (adjusted for the presence of ECPs by the ECP `NELEC` directive ; see Section 8). Additional characters can be added to the string, to distinguish between atoms of the same element (For example, the tags `oxygen`, `O`, `o34`, `olonepair`, and `Oxygen-ether`, will all be interpreted as oxygen atoms.).
- If the entry for `<tag>` begins with the characters `bq` or `x` (regardless of case), then the center is treated as a dummy center with a default zero charge (Note: a tag beginning with the characters `xe` will be interpreted as a xenon atom rather than as a dummy center.). Dummy centers may optionally have basis functions or non-zero charge. See Section B.2 for a sample input using dummy centers with charges.

It is *important* to be aware of the following points regarding the definitions and usage of the values specified for the variable <tag> to describe the centers in a system:

- If the tag begins with characters that cannot be matched against an atom, and those characters are not BQ or X, then a fatal error is generated.
- The tag of a center is used in the BASIS (Section 7) and ECP (Section 8) directives to associate functions with centers.
- All centers with the same tag will have the same basis functions.
- When using automatic symmetry detection, only centers with the same tag will be candidates for testing for symmetry equivalence.
- The user-specified charges (of all centers, atomic and dummy) and any net total charge of the system (Section 5.11) are used to determine the number of electrons in the system.

The Cartesian coordinates of the atom in the molecule are specified as real numbers supplied for the variables x, y, and z following the characters entered for the tag. The values supplied for the coordinates must be in the units specified by the value of the variable <units> on the first line of the GEOMETRY directive input.

After the Cartesian coordinate input, optional velocities may be entered as real numbers for the variables vx, vy, and vz. The velocities should be given in atomic units and are used in QMD and PSPW calculations.

The Cartesian coordinate input line also contains the optional keywords charge, mass and nucleus, which allow the user to specify the charge of the atom (or center) and its mass (in atomic mass units), and the nuclear model. The default charge for an atom is its atomic number, adjusted for the presence of ECPs (see Section 8). In order to specify a different value for the charge on a particular atom, the user must enter the keyword charge, followed by the desired value for the variable <charge>.

The default mass for an atom is taken to be the mass of its most abundant naturally occurring isotope or of the isotope with the longest half-life. To model some other isotope of the element, its mass must be defined explicitly by specifying the keyword mass, followed by the value (in atomic mass units) for the variable <mass>.

The default nuclear model is a point nucleus. The keyword nucleus (or nucl or nuc) followed by the model name <nucmodel> overrides this default. Allowed values of <nucmodel> are point or pt and finite or fi. The finite option is a nuclear model with a Gaussian shape. The RMS radius of the Gaussian is determined by the atomic mass number via the formula $r_{\mathrm{RMS}} = 0.836 * A^{1/3} + 0.57$ fm. The mass number A is derived from the variable <mass>.

The geometry of the system can be specified entirely in Cartesian coordinates by supplying a <tag> line of the type described above for each atom or center. The user has the option, however, of supplying the geometry of some or all of the atoms or centers using a Z-matrix description. In such a case, the user supplies the input tag line described above for any centers to be described by Cartesian coordinates, and then specifies the remainder of the system using the optional ZMATRIX directive described below in Section 6.4.

6.4 ZMATRIX — Z-matrix input

The ZMATRIX directive is an optional directive that can be used within the compound GEOMETRY directive to specify the structure of the system with a Z-matrix, which can include both internal and Cartesian

coordinates. The ZMATRIX directive is itself a compound directive that can include the VARIABLES and CONSTANTS directives, depending on the options selected. The general form of the compound ZMATRIX directive is as follows:

```
[ZMATRIX || ZMT || ZMAT
     <string tagn> <list_of_zmatrix_variables>
     ...

     [VARIABLES
          <string symbol> <real value>
          ... ]

     [CONSTANTS
          <string symbol> <real value>
          ... ]

(END || ZEND)]
```

The input module recognizes three possible spellings of this directive name. It can be invoked with ZMATRIX, ZMT, or ZMAT. The user can specify the molecular structure using either Cartesian coordinates or internal coordinates (bond lengths, bond angles and dihedral angles. The Z-matrix input for a center defines connectivity, bond length, and bond or torsion angles. Cartesian coordinate input for a center consists of three real numbers defining the x,y,z coordinates of the atom.

Within the Z-matrix input, bond lengths and Cartesian coordinates must be input in the user-specified units, as defined by the value specified for the variable <units> on the first line of the GEOMETRY directive. All angles are specified in degrees.

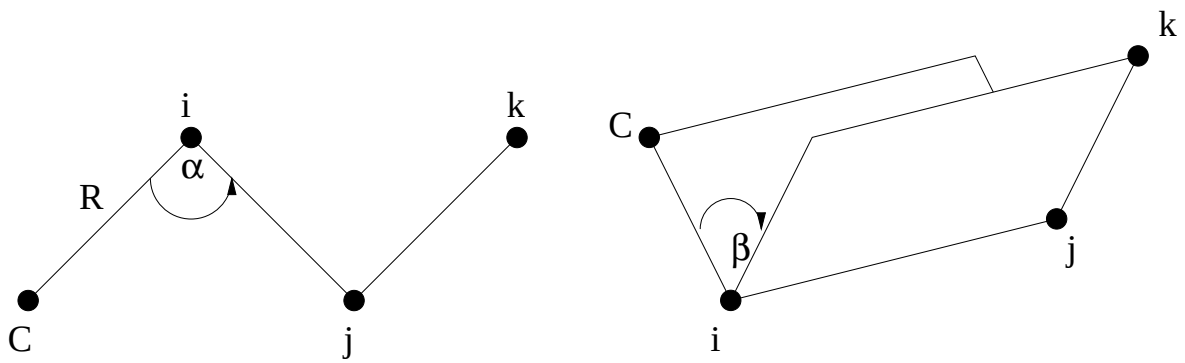
The individual centers (denoted as i, j, and k below) used to specify Z-matrix connectivity may be designated either as integers (identifying each center by number) or as tags (*If tags are used, the tag must be unique for each center.*) The use of "dummy" atoms is possible, by using X or BQ at the start of the tag.

Bond lengths, bond angles and dihedral angles (denoted below as R, alpha, and beta, respectively) may be specified either as numerical values or as symbolic strings that must be subsequently defined using the VARIABLES or CONSTANTS directives. The numerical values of the symbolic strings labeled VARIABLES may be subject to changes during a geometry optimization say, while the numerical values of the symbolic strings labeled CONSTANTS will stay frozen to the value given in the input. The same symbolic string can be used more than once, and any mixture of numeric data and symbols is acceptable. Bond angles (α) must be in the range $0 < \alpha < 180$.

The Z-matrix input is specified sequentially as follows:

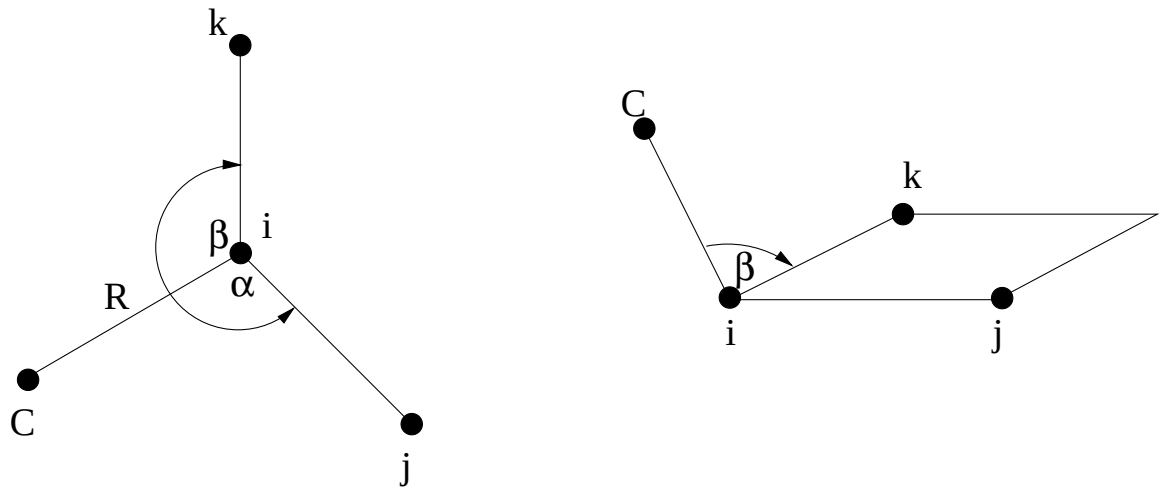
```
tag1
tag2 i R
tag3 i R j alpha
tag4 i R j alpha k beta [orient]
...
```

The structure of this input is described in more detail below. In the following discussion, the tag or number of the center being currently defined is labeled as C ("C" for current). The values entered for these tags for centers defined in the Z-matrix input are interpreted in the same way as the <tag> entries for Cartesian coordinates described above (see Section 6.3). Figures 6.1, 6.2 and 6.3 display the relationships between the input data and the definitions of centers and angles.



Input line: C i R j alpha k beta

Figure 6.1: Relationships between the centers, bond angle and dihedral angle in Z-matrix input.



Input line: C i R j alpha k beta +1

Figure 6.2: Relationships between the centers and two bond angles in Z-matrix input with optional parameter specified as +1.

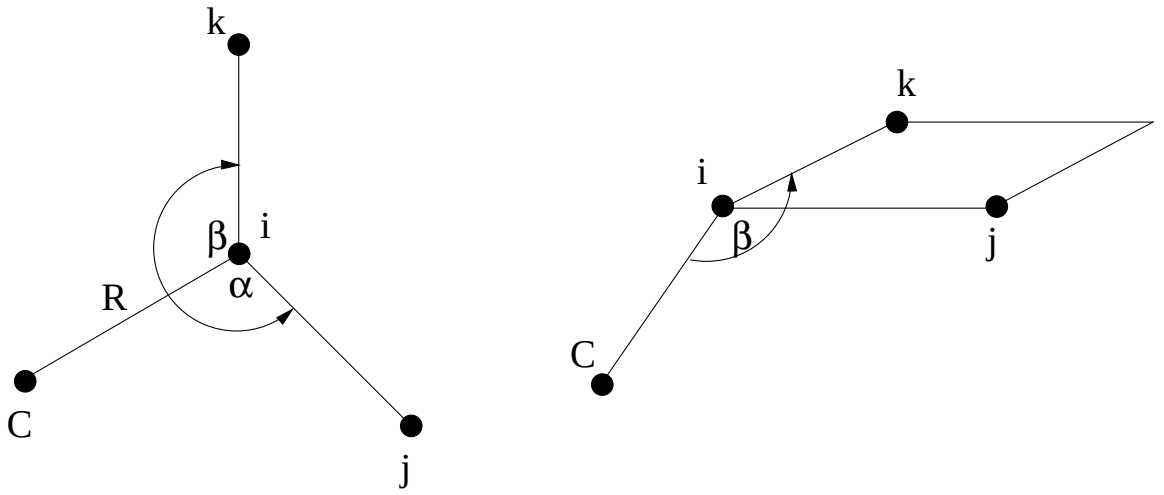


Figure 6.3: Relationships between the centers and two bond angles in Z-matrix input with optional parameter specified as −1.

The Z-matrix input shown above is interpreted as follows:

1. `tag1`

   Only a tag is required for the first center.

2. `tag2 i R`

   The second center requires specification of its tag and the bond length (R_{Ci}) distance to a previous atom, which is identified by `i`.

3. `tag3 i R j alpha`

   The third center requires specification of its tag, its bond length distance (R_{Ci}) to one of the two previous centers (identified by the value of `i`), and the bond angle $\alpha = \widehat{Cij}$.

4. `tag i R j alpha k beta [<integer orient default 0>]`

   The fourth, and all subsequent centers, require the tag, a bond length (R_{Ci}) relative to center `i`, the bond angle with centers `i` and `j` ($\alpha = \widehat{Cij}$), and *either*

   (a) the dihedral angle (β) between the current center and centers `i`, `j`, and `k` (Figure 6.1), or

   (b) a second bond angle $\beta = \widehat{Cik}$ and an orientation to the plane containing the other three centers (Figure 6.2 and 6.3).

   By default, β is interpreted as a dihedral angle (see Figure 6.1), but if the optional final parameter (`<orient>`) is specified with the value ± 1, then β is interpreted as the angle $\widehat{Cik}$. The sign of `<orient>` specifies the direction of the bond angle relative to the plane containing the three reference atoms. If `<orient>` is +1, then the new center (`C`) is above the plane (Figure 6.2); and if `<orient>` is −1, then `C` is below the plane (Figure 6.3).

Following the Z-matrix center definitions described above, the user can specify initial values for any symbolic variables used to define the Z-matrix tags. This is done using the optional `VARIABLES` directive, which has the general form:

```
VARIABLES
  <string symbol>  <real value>
  ...
```

Each line contains the name of a variable followed by its value. Optionally, an equals sign (`=`) can be included between the symbol and its value, for clarity in reading the input file.

Following the `VARIABLES` directive, the `CONSTANTS` directive may be used to define any Z-matrix symbolic variables that remain unchanged during geometry optimizations. To freeze the Cartesian coordinates of an atom, refer to Section 6.6. The general form of this directive is as follows:

```
CONSTANTS
  <string symbol>  <real value>
  ...
```

Each line contains the name of a variable followed by its value. As with the `VARIABLES` directive, an equals sign (`=`) can be included between the symbol and its value.

The end of the Z-matrix input using the compound `ZMATRIX` directive is signaled by a line containing either `END` or `ZEND`, following all input for the directive itself and its associated optional directives.

A simple example is presented for water. All Z-matrix parameters are specified numerically, and symbolic tags are used to specify connectivity information. This requires that all tags be unique, and therefore different tags are used for the two hydrogen atoms, which may or may not be identical.

```
geometry
  zmatrix
    O
    H1 O 0.95
    H2 O 0.95 H1 108.0
  end
end
```

The following example illustrates the Z-matrix input for the molecule CH_3CF_3. This input uses the numbers of centers to specify the connectivity information (`i`, `j`, and `k`), and uses symbolic variables for the Z-matrix parameters `R`, `alpha`, and `beta`, which are defined in the inputs for the `VARIABLES` and `CONSTANTS` directives.

```
geometry
 zmatrix
   C
   C 1 CC
   H 1 CH1 2 HCH1
   H 1 CH2 2 HCH2 3  TOR1
   H 1 CH3 2 HCH3 3 -TOR2
   F 2 CF1 1 CCF1 3  TOR3
   F 2 CF2 1 CCF2 6  FCH1
```

```
   F 2 CF3 1 CCF3 6  -FCH1
   variables
     CC    1.4888
     CH1   1.0790
     CH2   1.0789
     CH3   1.0789
     CF1   1.3667
     CF2   1.3669
     CF3   1.3669
   constants
     HCH1  104.28
     HCH2  104.74
     HCH3  104.7
     CCF1  112.0713
     CCF2  112.0341
     CCF3  112.0340
     TOR1  109.3996
     TOR2  109.3997
     TOR3  180.0000
     FCH1  106.7846
 end
end
```

The input for any centers specified with Cartesian coordinates must be specified using the format of the <tag> lines described in Section 6.3 above. However, in order to correctly specify these Cartesian coordinates within the Z-matrix, the user must understand the orientation of centers specified using internal coordinates. These are arranged as follows:

- The first center is placed at the origin.
- The second center is placed along the positive z-axis.
- The third center is placed in the z-x plane.

6.5 ZCOORD — Forcing internal coordinates

By default redundant internal coordinates are generated for use in geometry optimizations. Connectivity is inferred by comparing inter-atomic distances with the sum of the van der Waals radii of the two atoms involved in a possible bond, times a scaling factor. The scaling factor is an input parameter of ZCOORD which maybe changed from its default value of 1.3. Under some circumstances (unusual bonding, bond dissociation, ...) it will be necessary to augment the automatically generated list of internal coordinates to force some specific internal coordinates to be included in among the internal coordinates. This is accomplished by including the optional directive ZCOORD within the geometry directive. The general form of the ZCOORD directive is as follows:

```
  ZCOORD
     CVR_SCALING <real value>
     BOND    <integer i> <integer j> \
             [<real value>] [<string name>] [constant]
     ANGLE   <integer i> <integer j> <integer k> \
```

```
            [<real value>] [<string name>] [constant]
    TORSION <integer i> <integer j> <integer k> <integer l> \
            [<real value>] [<string name>] [constant]
END
```

The centers `i`, `j`, `k` and `l` *must* be specified using the numbers of the centers, as supplied in the input for the Cartesian coordinates. The `ZCOORD` input parameters are defined as follows:

- `cvr_scaling` — scaling factor applied to van der Waals radii.
- `bond` — a bond between the two centers.
- `angle` — a bond angle $\widehat{ijk}$.
- `torsion` — a torsion (or dihedral) angle. The angle between the planes `i-j-k` and `j-k-l`.

A value may be specified for a user-defined internal coordinate, in which case it is forced upon the input Cartesian coordinates while attempting to make only small changes in the other internal coordinates. If no value is provided the value implicit in the input coordinates is kept. If the keyword `constant` is specified, then that internal variable is not modified during a geometry optimization with DRIVER (Section 20). Each internal coordinate may also be named either for easy identification in the output, or for the application of constraints (Section 6.6).

If the keyword `adjust` is specified on the main `GEOMETRY` directive, only `ZCOORD` data may be specified and it can be used to change the user-defined internal coordinates, including adding/removing constraints and changing their values.

6.6 Applying constraints in geometry optimizations

Internal coordinates specified as constant in a `ZCOORD` directive or in the constants section of a `ZMATRIX` directive, will be frozen at their initial values if a geometry optimization is performed with DRIVER (Section 20).

If internal coordinates have the same name (give or take an optional sign for torsions) then they are forced to have the same value. This may be used to force bonds or angles to be equal even if they are not related by symmetry.

When atoms have been specified by their Cartesian coordinates, *and* internal coordinates are not being used, it is possible to freeze the cartesian position of selected atoms. This is useful for such purposes as optimizing a molecule absorbed on the surface of a cluster with fixed geometry. Only the gradients associated with the active atoms are computed. This can result in a big computational saving, since gradients associated with frozen atoms are forced to zero (Note, however, that this destroys the translational and rotational invariance of the gradient. This is not yet fully accommodated by the STEPPER geometry optimization software, and can sometimes result in slower convergence of the optimization. The DRIVER optimization package does not suffer from this problem).

The `SET` directive (Section 5.7) is used to freeze atoms, by specifying a directive of the form:

```
set geometry:actlist <integer list_of_center_numbers>
```

This defines only the centers in the list as active. All other centers will have zero force assigned to them, and will remain frozen at their starting coordinates during a geometry optimization.

For example, the following directive specifies that atoms numbered 1, 5, 6, 7, 8, and 15 are active and all other atoms are frozen:

```
set geometry:actlist 1 5:8 15
```

or equivalently,

```
set geometry:actlist 1 5 6 7 8 15
```

If this option is not specified by entering a SET directive, the default behavior in the code is to treat all atoms as active. To revert to this default behavior after the option to define frozen atoms has been invoked, the UNSET directive must be used (since the database is persistent, see Section 3.2). The form of the UNSET directive is as follows:

```
unset geometry:actlist
```

6.7 SYSTEM — Lattice parameters for periodic systems

This keyword is needed only for for 1-, 2-, and 3-dimensional periodic systems.

The system keyword can assume the following values

- polymer — system with 1-d translational symmetry.
- surface — system with 2-d translational symmetry.
- crystal — system with 3-d translational symmetry.
- molecule — no translational symmetry (this is the default)

When the system possess translational symmetry, **fractional** coordinates are used in the directions where translational symmetry exists. This means that for crystals x, y and z are fractional, for surfaces x and y are fractional, whereas for polymers only z is fractional. For example, in the following H_2O layer input (a 2-d periodic system), x and y coordinates are fractional, whereas z is expressed in Å.

```
geometry units angstrom
  O     0.353553    0.353553         2.100000000
  H     0.263094    0.353553         2.663590000
  H     0.444007    0.353553         2.663590000
```

Since no space group symmetry is available yet other than $P1$, input of cell parameters is relative to the primitive cell. For example, this is the input required for the cubic face-centered type structure of bulk MgO.

```
system crystal
 lat_a 2.97692 lat_b 2.97692 lat_c 2.97692
 alpha 60.00 beta 60.00 gamma 60.00
end
```

Chapter 7

Basis sets

NWChem currently supports basis sets consisting of generally contracted[1] Cartesian Gaussian functions up to a maximum angular momentum of six (h functions), and also sp (or L) functions[2] . The `BASIS` directive is used to define these, and also to specify use of an effective core potential (ECP) that is associated with a basis set; see Section 8.

The basis functions to be used for a given calculation can be drawn from a standard set in the EMSL basis set library that is included in the release of NWChem (See Appendix A for a list of the standard basis sets currently supplied with the release of the code). Alternatively, the user can specify particular functions explicitly in the input, to define a particular basis set.

The general form of the `BASIS` directive is as follows:

```
BASIS [<string name default "ao basis">] \
      [(spherical || cartesian) default cartesian] \
      [(segment || nosegment) default segment] \
      [(print || noprint) default print]
      [rel]

   <string tag> library [<string tag_in_lib>] \
                <string standard_set> [file <filename>] \
                [except <string tag list>] [rel]

      ...

   <string tag> <string shell_type> [rel]
      <real exponent> <real list_of_coefficients>
      ...

END
```

Examining the keywords on the first line of the `BASIS` directive:

[1] Generally contracted meaning that the same primitive, Gaussian functions are contracted into multiple contracted functions using different contraction coefficients. Reuse of the radial functions increases the efficiency of integral generation.

[2] An sp shell is two-component general contraction. However, the first component specifies an s shell and the second a p shell. Again, reuse of the radial functions increases the efficiency of integral generation.

- `name`

  By default, the basis set is stored in the database with the name `"ao basis"`. Another name may be specified in the `BASIS` directive, thus, multiple basis sets may be stored simultaneously in the database. Also, the DFT (Section 11) and RI-MP2 (Section 16) modules and the Dyall-modified-Dirac relativistic method (Section 9.3) require multiple basis sets with specific names.

  The user can associate the `"ao basis"` with another named basis using the `SET` directive (see Section 5.7).

- `SPHERICAL` or `CARTESIAN`

  The keywords `spherical` and `cartesian` offer the option of using either spherical-harmonic (5 d, 7 f, 9 g, ...) or Cartesian (6 d, 10 f, 15 g, ...) angular functions. The default is Cartesian.

  Note that the correlation-consistent basis sets were designed using spherical harmonics and to use these, the `spherical` keyword should be present in the `BASIS` directive. The use of spherical functions also helps eliminate problems with linear dependence.

- `SEGMENT` or `NOSEGMENT`

  By default, NWChem forces all basis sets to be segmented, even if they are input with general contractions or L or sp shells. This is because the current derivative integral program cannot handle general contractions. If a calculation is computing energies only, a performance gain can result from exploiting generally contracted basis sets, in which case `NOSEGMENT` should be specified.

- `PRINT` or `NOPRINT`

  The default is for the input module to print all basis sets encountered. Specifying the keyword `noprint` allows the user to suppress this output.

- `REL`

  This keyword marks the entire basis as a relativistic basis for the purposes of the Dyall-modified-Dirac relativistic integral code. The marking of the basis set is necessary for the code to make the proper association between the relativistic shells in the ao basis and the shells in the large and/or small component basis. This is only necessary for basis sets which are to be used as the ao basis. The user is referred to Section 9.3 for more details.

Basis sets are associated with centers by using the tag of a center in a geometry that has either been input by the user (Section 6) or is available elsewhere. Each atom or center with the same `tag` will have the same basis set. All atoms must have basis functions assigned to them — only dummy centers (X or Bq) may have no basis functions. To facilitate the specification of the geometry and the basis set for any chemical system, the matching process of a basis set tag to a geometry tag first looks for an exact match. If no match is found, NWChem will attempt to match, ignoring case, the name or symbol of the element. E.g., all hydrogen atoms in a system could be labeled "H1", "H2", ..., in the geometry but only one basis set specification for "H" or "hydrogen" is necessary. If desired, a special basis may be added to one or more centers (e.g., "H1") by providing a basis for that tag. If the matching mechanism fails then NWChem stops with an appropriate error message.

A special set of tags, "*" and tags ending with a "*" (E.g. "H*") can be used in combination with the keyword `library` (see section below). These tags facilitate the definition of a certain type of basis set of all atoms, or a group of atoms, in a geometry using only a single or very few basis set entries. The "*" tag will not place basis sets on dummy atoms, Bq* can be used for that if necessary.

Examined next is how to reference standard basis sets in the basis set library, and finally, how to define a basis set using exponents and coefficients.

7.1 Basis set library

The keyword `library` associated with each specific `tag` entry specifies that the calculation will use the standard basis set in NWChem for that center. The variable `<standard_set>` is the name that identifies the functions in the library. The names of standard basis sets are not case sensitive. See Appendix A for a complete list of the basis sets in the NWChem library and their specifications.

The general form of the input line requesting basis sets from the NWChem basis set library is:

```
  <string tag> library [<string tag_in_lib>] \
               <string standard set> [file < filename> \
               [except <string tag list>] [rel]
     ...
```

For example, the NWChem basis set library contains the Dunning cc-pvdz basis set. These may be used as follows

```
basis
  oxygen library cc-pvdz
  hydrogen library cc-pvdz
end
```

A default path of the NWChem basis set libraries is provided on installation of the code, but a different path can be defined by specifying the keyword `file`, and one can explicitly name the file to be accessed for the basis functions. For example,

```
basis
  o  library 3-21g file /usr/d3g681/nwchem/library
  si library 6-31g file /usr/d3g681/nwchem/libraries/
end
```

This directive tells the code to use the basis set `3-21g` in the file `/usr/d3g681/nwchem/library` for atom `o` and to use the basis set `6-31g` in the directory `/usr/d3g681/nwchem/libraries/` for atom `si`, rather than look for them in the default libraries. When a directory is defined the code will search for the basis set in a file with the name `6-31g`.

The "*" tag can be used to efficiently define basis set input directives for large numbers of atoms. An example is:

```
basis
  *  library 3-21g
end
```

This directive tells the code to assign the basis sets `3-21g` to all the atom tags defined in the geometry. If one wants to place a different basis set on one of the atoms defined in the geometry, the following directive can be used:

```
basis
  *  library 3-21g except H
end
```

This directive tells the code to assign the basis sets `3-21g` to all the atoms in the geometry, except the hydrogen atoms. Remember that the user will have to explicitly define the hydrogen basis set in this directive! One may also define tags that end with a "*":

```
basis
  oxy*  library 3-21g
end
```

This directive tells the code to assign the basis sets `3-21g` to all atom tags in the geometry that start with "oxy".

If standard basis sets are to be placed upon a dummy center, the variable `<tag_in_lib>` must also be entered on this line, to identify the correct atom type to use from the basis function library (see the ghost atom example in Section 5.7 and below). For example: To specify the cc-pvdz basis for a calculation on the water monomer in the dimer basis, where the dummy oxygen and dummy hydrogen centers have been identified as `bqo` and `bqh` respectively, the `BASIS` directive is as follows:

```
basis
  o   library cc-pvdz
  h   library cc-pvdz
  bqo library o cc-pvdz
  bqh library h cc-pvdz
end
```

A special dummy center tag is `bq*`, which will assign the same basis set to all bq centers in the geometry. Just as with the "*" tag, the `except` list can be used to assign basis sets to unique dummy centers.

The library basis sets can also be marked as relativistic by adding the `rel` keyword to the tag line. See Section 9.3 for more details. The correlation consistent basis sets have been contracted for relativistic effects and are included in the standard library.

There are also contractions in the standard library for both a point nucleus and a finite nucleus of Gaussian shape. These are usually distinguished by the suffixex `_pt` and `_fi`. It is the user's responsibility to ensure that the contraction matches the nuclear type specified in the geometry object. The specification of a finite nucleus basis set does NOT automatically set the nuclear type for that atom to be finite. See Section 6 for information.

7.2 Explicit basis set definition

If the basis sets in the library or available in other external files are not suitable for a given calculation, the basis set may be explicitly defined. A generally contracted Gaussian basis function is associated with a center using an input line of the following form:

```
<string tag> <string shell_type> [rel]
   <real exponent> <real list_of_coefficients>
   ...
```

The variable `<shell_type>` identifies the angular momentum of the shell, s, p, d, ... NWChem is configured to handle up to h shells. The keyword `rel` marks the shell as relativistic — see Section 9.3 for more details. Subsequent lines define the primitive function exponents and contraction coefficients. General contractions are specified by including multiple columns of coefficients.

The following example defines basis sets for the water molecule:

```
basis spherical nosegment
  oxygen s
    11720.0000    0.000710  -0.000160
     1759.0000    0.005470  -0.001263
      400.8000    0.027837  -0.006267
      113.7000    0.104800  -0.025716
       37.0300    0.283062  -0.070924
       13.2700    0.448719  -0.165411
        5.0250    0.270952  -0.116955
        1.0130    0.015458   0.557368
        0.3023   -0.002585   0.572759
  oxygen s
        0.3023    1.000000
  oxygen p
       17.7000    0.043018
        3.8540    0.228913
        1.0460    0.508728
        0.2753    0.460531
  oxygen p
        0.2753    1.000000
  oxygen d
        1.1850    1.000000
  hydrogen s
       13.0100    0.019685
        1.9620    0.137977
        0.4446    0.478148
        0.1220    0.501240
  hydrogen s
        0.1220    1.000000
  hydrogen p
        0.7270    1.000000
  oxygen s
        0.01      1.0
  hydrogen s
        0.02974   1.0
  hydrogen p
        0.141      1.0
end
```

7.3 Combinations of library and explicit basis set input

The user can use a mixture of library basis and explicit basis set input to define the basis sets used on the various atoms.

For example, the following `BASIS` directive augments the Dunning cc-pvdz basis set for the water molecule with a diffuse s-shell on oxygen and adds the aug-cc-pVDZ diffuse functions onto the hydrogen.

```
basis spherical nosegment
```

```
  oxygen library cc-pvdz
  hydrogen library cc-pvdz
  oxygen s
    0.01 1.0
  hydrogen library "aug-cc-pVDZ Diffuse"
end
```

The resulting basis set defined is identical to the one defined above in the explicit basis set input.

Chapter 8

Effective Core Potentials

Effective core potentials (ECPs) are a useful means of replacing the core electrons in a calculation with an effective potential, thereby eliminating the need for the core basis functions, which usually require a large set of Gaussians to describe them. In addition to replacing the core, they may be used to represent relativistic effects, which are largely confined to the core. In this context, both the scalar (spin-free) relativistic effects and spin-orbit (spin-dependent) relativistic effects may be included in effective potentials. NWChem has the facility to use both, and these are described in the next two sections.

A brief recapitulation of the development of RECPs is given here, following Pacios and Christiansen[1]. The process can be viewed as starting from an atomic Dirac-Hartree-Fock calculation, done in *jj* coupling, and producing relativistic effective potentials (REPs) for each l and j value, $U_{lj}^{\rm REP}$. From these, a local potential is extracted, which for example contains the Coulomb potential of the core electrons balanced by the part of the nuclear attraction which cancels the core electron charge. The residue is expressed in a semi-local form,

$$U^{\rm REP} = U_{LJ}^{\rm REP}(r) + \sum_{l=0}^{L-1} \sum_{j=|l-1/2}^{l+1/2} \left[U_{lj}^{\rm REP}(r) - U_{LJ}^{\rm REP}(r)\right] \sum_{m} |ljm\rangle\langle ljm| \tag{8.1}$$

where L is one larger than the maximum angular momentum in the atom. The scalar potential is obtained by averaging the REPs for each j for a given l to give an averaged relativistic effective potential, or AREP,

$$U_l^{\rm AREP}(r) = \frac{1}{2l+1}\left[lU_{l-1/2}^{\rm REP}(r) + (l+1)U_{l+1/2}^{\rm REP}(r)\right]. \tag{8.2}$$

These are summed into the full potential.

The spin-orbit potential is obtained from the difference between the REPs for the two j values for a given l, and may be represented in terms of an effective spin-orbit operator,

$$H^{\rm SO} = \mathbf{s}\cdot\sum_{l=1}^{L-1}\frac{2}{2l+1}\Delta U_l^{\rm REP}\sum_{mm'}|lm\rangle\langle lm|\hat{l}|lm'\rangle\langle lm'|. \tag{8.3}$$

where

$$\Delta U_l^{\rm REP} = U_{l+1/2}^{\rm REP}(r) - U_{l-1/2}^{\rm REP}(r). \tag{8.4}$$

[1] l. F. Pacios and P. A. Christiansen, J. Chem. Phys. **82**, 2664 (1985)

The spin-orbit integrals generated by NWChem are the integrals over the sum, including the factor of $2/(2l+1)$, so that they may be treated as an effective spin-orbit operator without further factors introduced.

The effective potentials, both scalar and spin-orbit, are fitted to Gaussians with the form

$$r^2 U_l(r) = \sum_k A_{lk} r^{n_{lk}} e^{-B_{lk} r^2}$$

where A_{lk} is the contraction coefficient, n_{lk} is the exponent of the "r" term (r-exponent), and B_{lk} is the Gaussian exponent. The n_{lk} is shifted by 2, in accordance with most of the ECP literature and implementations, i.e., an $n_{lk} = 0$ implies r^{-2}. The current implementation allows n_{lk} values of only 0, 1, or 2.

8.1 Scalar ECPs

The optional directive `ECP` allows the user to describe an effective core potential (ECP) in terms of contracted Gaussian functions as given above. Potentials using these functions must be specified explicitly by user input in the `ECP` directive. This directive has essentially the same form and properties as the standard `BASIS` directive, except for essential differences required for ECPs. Because of this, the ECP is treated internally as a basis set. The form of the input for the `ECP` directive is as follows:

```
ECP [<string name default "ecp basis">] \
      [print || noprint default print]

   <string tag> library [<string tag_in_lib>] \
                <string standard_set> [file <filename>] \
                [except <string tag list>]

   <string tag> [nelec] <integer number_of_electrons_replaced>

      ...

   <string tag> <string shell_type>
   <real r-exponent> <real Gaussian-exponent> <real list_of_coefficients>
      ...

END
```

ECPs are automatically segmented, even if general contractions are input. The projection operators defined in an ECP are spherical by default, so there is no need to include the `CARTESIAN` or `SPHERICAL` keyword as there is for a standard basis set. ECPs are associated with centers in geometries through tags or names of centers. These tags must match in the same manner as for basis sets the tags in a `GEOMETRY` and `ECP` directives, and are limited to sixteen (16) characters. Each center with the same tag will have the same ECP. By default, the input module prints each ECP that it encounters. The `NOPRINT` option can be used to disable printing. There can be only one active ECP, even though several may exist in the input deck. The ECP modules load "ecp basis" inputs along with any "ao basis" inputs present. ECPs may be used in both energy and gradient calculations.

ECPs are named in the same fashion as geometries or regular basis sets, with the default name being `"ecp basis"`. It should be clear from the above discussion on geometries and database entries how indirection

is supported. All directives that are in common with the standard Gaussian basis set input have the same function and syntax.

As for regular basis sets, ECPs may be obtained from the standard library. The names of the sets of ECPs available in the standard library (their coverage is described in Appendix A) are

- "Hay-Wadt MB (n+1) ECP"
- "Hay-Wadt VDZ (n+1) ECP"
- "LANL2DZ ECP"
- "SBKJC VDZ ECP"
- "Stuttgart RLC ECP"
- "Stuttgart RSC ECP"
- "CRENBL ECP"
- "CRENBS ECP"

The keyword `nelec` allows the user to specify the number of core electrons replaced by the ECP. Additional input lines define the specific coefficients and exponents. The variable `<shell_type>` is used to specify the components of the ECP. The keyword `ul` entered for `<shell_type>` denotes the local part of the ECP. This is equivalent to the highest angular momentum functions specified in the literature for most ECPs. The standard entries (`s, p, d`, etc.) for `shell_type` specify the angular momentum projector onto the local function. The shell type label of `s` indicates the `ul-s` projector input, `p` indicates the `ul-p`, etc.

For example, the Christiansen, Ross and Ermler ARECPs are available in the standard basis set libary named `{crenbl_ecp}`. To perform a calculation on uranyl (UO_2^{2+}) with all-electron oxygen (aug-cc-pvdz basis), and uranium with an ARECP and using the corresponding basis the following input can be used

```
geometry
  U 0 0  0
  O 0 0  1.65
  O 0 0 -1.65
end
basis
  U library crenbl_ecp
  O library aug-cc-pvdz
end
ecp
  U library crenbl_ecp
end
```

The following is an example of explicit input of an ECP for H_2CO. It defines an ECP for the carbon and oxygen atoms in the molecule.

```
ecp
  C nelec 2 # ecp replaces 2 electrons on C
  C ul      # d
          1       80.0000000       -1.60000000
          1       30.0000000       -0.40000000
```

```
          2        0.5498205       -0.03990210
  C s       # s - d
          0        0.7374760        0.63810832
          0      135.2354832       11.00916230
          2        8.5605569       20.13797020
   C p      # p - d
          2       10.6863587       -3.24684280
          2       23.4979897        0.78505765
   O nelec 2 # ecp replaces 2 electrons on O
   O ul     # d
          1       80.0000000       -1.60000000
          1       30.0000000       -0.40000000
          2        1.0953760       -0.06623814
   O s      # s - d
          0        0.9212952        0.39552179
          0       28.6481971        2.51654843
          2        9.3033500       17.04478500
   O p      # p - s
          2       52.3427019       27.97790770
          2       30.7220233      -16.49630500
end
```

Various ECPs without a local function are available, including those of the Stuttgart group. For those, no "ul" part needs to be defined. To define the absence of the local potential, simply specify one contraction with a zero coefficient:

```
    <string tag> ul
    2     1.00000     0.00000
```

8.2 Spin-orbit ECPs

The Spin-orbit ECPs can be used with the Density Functional Approach, but one has to run the calculations without symmetry. Note: when a Hartree-Fock method is specified the spin-orbit input will be ignored.

Spin-orbit ECPs are fitted in precisely the same functional form as the scalar RECPs and have the same properties, with the exception that there is no local potential ul, no s potential and no effective charge has to be defined. Spin-orbit potentials are specified in the same way as ECPs except that the directive `SO` is used instead of `ECP`. Note that there currently are no spin-orbit ECPs defined in the standard NWChem library. The `SO` directive is as follows:

```
SO [<string name default "so basis">] \
      [print || noprint default print]

   <string tag> library [<string tag_in_lib>] \
                <string standard_set> [file <filename>]
                [except <string tag list>]
      ...

   <string tag> <string shell_type>
```

```
    <real r-exponent> <real Gaussian-exponent> <real list_of_coefficients>
       ...

END
```

Note: in the literature the coefficients of the spin-orbit potentials are NOT always defined in the same manner. The NWChem code assumes that the spin-orbit potential defined in the input is of the form:

$$\Delta U_l^{\mathrm{NWChem}} = \frac{2}{2l+1}\Delta U_l \tag{8.5}$$

For example, in the literature the Stuttgart potentials are defined as ΔU_l and, hence, have to be multiplied by $2/(2l+1)$. On the other hand, the CRENBL potentials in the published papers are defined as $\frac{l}{2l+1}\Delta U_l$ and, hence, have to be multiplied by $2/l$ (Warning: on the CRENBL website the spin-orbit potentials already have been corrected with the $2/l$ factor).

Chapter 9

Relativistic All-electron Approximations

All methods which include treatment of relativistic effects are ultimately based on the Dirac equation, which has a four component wave function. The solutions to the Dirac equation describe both positrons (the "negative energy" states) and electrons (the "positive energy" states), as well as both spin orientations, hence the four components. The wave function may be broken down into two-component functions traditionally known as the large and small components; these may further be broken down into the spin components.

The implementation of approximate all-electron relativistic methods in quantum chemical codes requires the removal of the negative energy states and the factoring out of the spin-free terms. Both of these may be achieved using a transformation of the Dirac Hamiltonian known in general as a Foldy-Wouthuysen transformation. Unfortunately this transformation cannot be represented in closed form for a general potential, and must be approximated. One popular approach is that originally formulated by Douglas and Kroll[1] and developed by Hess[2]. This approach decouples the positive and negative energy parts to second order in the external potential (and also fourth order in the fine structure constant, α). Other approaches include the Zeroth Order Regular Approximation (ZORA)[3] and modification of the Dirac equation by Dyall[4], and involves an exact FW transformation on the atomic basis set level[5].

Since these approximations only modify the integrals, they can in principle be used at all levels of theory. At present the Douglas-Kroll and ZORA implementations can be used at all levels of theory whereas Dyall's approach is currently available at the Hartree-Fock level. The derivatives have been implemented, allowing both methods to be used in geometry optimizations and frequency calculations.

The `RELATIVISTIC` directive provides input for the implemented relativistic approximations and is a compound directive that encloses additional directives specific to the approximations:

```
RELATIVISTIC
 [DOUGLAS-KROLL [<string (ON||OFF) default ON> \
               <string (FPP||DKH||DKFULL||DK3||DK3FULL) default DKH>]  ||
  ZORA [ (ON || OFF) default ON ] ||
```

[1] M. Douglas and N. M. Kroll, Ann. Phys. (N.Y.) **82**, 89 (1974)

[2] B.A. Hess, Phys. Rev. A **32**, 756 (1985); **33**, 3742 (1986)

[3] C. Chang, M. Pelissier, M. Durand, Physica Scripta **34**, 294 (1986); E. van Lenthe, *The ZORA Equation*, doctoral thesis, Vrije Universiteit, Amsterdam (1996); S. Faas, J.G. Snijders, J.H. van Lenthe, E. van Lenthe, and E.J. Baerends, Chem. Phys. Lett. **246**, 632 (1995).

[4] K. G. Dyall, J. Chem. Phys. **100**, 2118 (1994)

[5] K. G. Dyall, J. Chem. Phys. **106**, 9618 (1997); K. G. Dyall and T. Enevoldsen, J. Chem. Phys. **111**, 10000 (1999).

```
  DYALL-MOD-DIRAC [ (ON || OFF) default ON ]
                  [ (NESC1E || NESC2E) default NESC1E ] ]
 [CLIGHT <real clight default 137.0359895>]
END
```

Only one of the methods may be chosen at a time. If both methods are found to be on in the input block, NWChem will stop and print an error message. There is one general option for both methods, the definition of the speed of light in atomic units:

```
CLIGHT <real clight default 137.0359895>
```

The following sections describe the optional sub-directives that can be specified within the `RELATIVISTIC` block.

9.1 Douglas-Kroll approximation

The spin-free and spin-orbit one-electron Douglas-Kroll approximation have been implemented. The use of relativistic effects from this Douglas-Kroll approximation can be invoked by specifying:

```
DOUGLAS-KROLL [<string (ON||OFF) default ON> \
               <string (FPP||DKH||DKFULL|DK3|DK3FULL) default DKH>]
```

The `ON|OFF` string is used to turn on or off the Douglas-Kroll approximation. By default, if the `DOUGLAS-KROLL` keyword is found, the approximation will be used in the calculation. If the user wishes to calculate a non-relativistic quantity after turning on Douglas-Kroll, the user will need to define a new `RELATIVISTIC` block and turn the approximation `OFF`. The user could also simply put a blank `RELATIVISTIC` block in the input file and all options will be turned off.

The `FPP` is the approximation based on free-particle projection operators[6] whereas the `DKH` and `DKFULL` approximations are based on external-field projection operators[7]. The latter two are considerably better approximations than the former. `DKH` is the Douglas-Kroll-Hess approach and is the approach that is generally implemented in quantum chemistry codes. `DKFULL` includes certain cross-product integral terms ignored in the `DKH` approach (see for example Häberlen and Rösch[8]). The third-order Douglas-Kroll approximation has been implemented by T. Nakajima and K. Hirao[9]. This approximation can be called using `DK3` (DK3 without cross-product integral terms) or `DK3FULL` (DK3 with cross-product integral terms).

The contracted basis sets used in the calculations should reflect the relativistic effects, i.e. one should use contracted basis sets which were generated using the Douglas-Kroll Hamiltonian. Basis sets that were contracted using the non-relativistic (Schödinger) Hamiltonian WILL PRODUCE ERRONEOUS RESULTS for elements beyond the first row. See appendix A for available basis sets and their naming convention.

NOTE: we suggest that spherical basis sets are used in the calculation. The use of high quality cartesian basis sets can lead to numerical inaccuracies.

In order to compute the integrals needed for the Douglas-Kroll approximation the implementation makes use of a fitting basis set (see literature given above for details). The current code will create this fitting basis

[6] B.A. Hess, Phys. Rev. A **32**, 756 (1985)
[7] B.A. Hess, Phys. Rev. A **33**, 3742 (1986)
[8] O.D. Häberlen, N. Rösch, Chem. Phys. Lett. **199**, 491 (1992)
[9] T. Nakajima and K. Hirao, Chem. Phys. Lett. **329**, 5111 (2000); T. Nakajima and K. Hirao, J. Chem. Phys. **113**, 7786 (2000)

set based on the given "ao basis" by simply uncontracting that basis. This again is what is commonly implemented in quantum chemistry codes that include the Douglas-Kroll method. Additional flexibility is available to the user by explicitly specifying a Douglas-Kroll fitting basis set. This basis set must be named "D-K basis" (see Chapter 7).

9.2 Zeroth Order regular approximation (ZORA)

The spin-free and spin-orbit one-electron zeroth-order regular approximation (ZORA) have been implemented. The use of relativistic effects with ZORA can be invoked by specifying:

```
ZORA [<string (ON||OFF) default ON>
```

The ON|OFF string is used to turn on or off ZORA. By default, if the ZORA keyword is found, the approximation will be used in the calculation. If the user wishes to calculate a non-relativistic quantity after turning on ZORA, the user will need to define a new RELATIVISTIC block and turn the approximation OFF. The user can also simply put a blank RELATIVISTIC block in the input file and all options will be turned off.

9.3 Dyall's Modified Dirac Hamitonian approximation

The approximate methods described in this section are all based on Dyall's modified Dirac Hamiltonian. This Hamiltonian is entirely equivalent to the original Dirac Hamiltonian, and its solutions have the same properties. The modification is achieved by a transformation on the small component, extracting out $\sigma \cdot \mathbf{p}/2mc$. This gives the modified small component the same symmetry as the large component, and in fact it differs from the large component only at order α^2. The advantage of the modification is that the operators now resemble the operators of the Breit-Pauli Hamiltonian, and can be classified in a similar fashion into spin-free, spin-orbit and spin-spin terms. It is the spin-free terms which have been implemented in NWChem, with a number of further approximations.

The first is that the negative energy states are removed by a normalized elimination of the small component (NESC), which is equivalent to an exact Foldy-Wouthuysen (EFW) transformation. The number of components in the wave function is thereby effectively reduced from 4 to 2. NESC on its own does not provide any advantages, and in fact complicates things because the transformation is energy-dependent. The second approximation therefore performs the elimination on an atom-by-atom basis, which is equivalent to neglecting blocks which couple different atoms in the EFW transformation. The advantage of this approximation is that all the energy dependence can be included in the contraction coefficients of the basis set. The tests which have been done show that this approximation gives results well within chemical accuracy. The third approximation neglects the commutator of the EFW transformation with the two-electron Coulomb interaction, so that the only corrections that need to be made are in the one-electron integrals. This is the equivalent of the Douglas-Kroll(-Hess) approximation as it is usually applied.

The use of these approximations can be invoked with the use of the DYALL-MOD-DIRAC directive in the RELATIVISTIC directive block. The syntax is as follows.

```
DYALL-MOD-DIRAC [ (ON || OFF) default ON ]
                [ (NESC1E || NESC2E) default NESC1E ]
```

The ON|OFF string is used to turn on or off the Dyall's modified Dirac approximation. By default, if the DYALL-MOD-DIRAC keyword is found, the approximation will be used in the calculation. If the user wishes to

calculate a non-relativistic quantity after turning on Dyall's modified Dirac, the user will need to define a new `RELATIVISTIC` block and turn the approximation `OFF`. The user could also simply put a blank `RELATIVISTIC` block in the input file and all options will be turned off.

Both one- and two-electron approximations are available `NESC1E || NESC2E`, and both have analytic gradients. The one-electron approximation is the default. The two-electron approximation specified by `NESC2E` has some sub options which are placed on the same logical line as the `DYALL-MOD-DIRAC` directive, with the following syntax:

```
NESC2E [ (SS1CENT [ (ON || OFF) default ON ] || SSALL) default SSALL ]
       [ (SSSS [ (ON || OFF) default ON ] || NOSSSS) default SSSS ]
```

The first sub-option gives the capability to limit the two-electron corrections to those in which the small components in any density must be on the same center. This reduces the $(LL|SS)$ contributions to at most three-center integrals and the $(SS|SS)$ contributions to two centers. For a case with only one relativistic atom this option is redundant. The second controls the inclusion of the $(SS|SS)$ integrals which are of order α^4. For light atoms they may safely be neglected, but for heavy atoms they should be included.

In addition to the selection of this keyword in the `RELATIVISTIC` directive block, it is necessary to supply basis sets in addition to the `ao basis`. For the one-electron approximation, three basis sets are needed: the atomic FW basis set, the large component basis set and the small component basis set. The atomic FW basis set should be included in the `ao basis`. The large and small components should similarly be incorporated in basis sets named `large component` and `small component`, respectively. For the two-electron approximation, only two basis sets are needed. These are the large component and the small component. The large component should be included in the `ao basis` and the small component is specified separately as `small component`, as for the one-electron approximation. This means that the two approximations can *not* be run correctly without changing the `ao basis`, and it is up to the user to ensure that the basis sets are correctly specified.

There is one further requirement in the specification of the basis sets. In the `ao basis`, it is necessary to add the `rel` keyword either to the `basis` directive or the library tag line (See below for examples). The former marks the basis functions specified by the tag as relativistic, the latter marks the whole basis as relativistic. The marking is actually done at the unique shell level, so that it is possible not only to have relativistic and nonrelativistic atoms, it is also possible to have relativistic and nonrelativistic shells on a given atom. This would be useful, for example, for diffuse functions or for high angular momentum correlating functions, where the influence of relativity was small. The marking of shells as relativistic is necessary to set up a mapping between the ao basis and the large and/or small component basis sets. For the one-electron approximation the large and small component basis sets MUST be of the same size and construction, i.e. differing only in the contraction coefficients.

It should also be noted that the relativistic code will NOT work with basis sets that contain sp shells, nor will it work with ECPs. Both of these are tested and flagged as an error.

Some examples follow. The first example sets up the data for relativistic calculations on water with the one-electron approximation and the two-electron approximation, using the library basis sets.

```
start h2o-dmd

geometry units bohr
symmetry c2v
  O       0.000000000    0.000000000   -0.009000000
  H       1.515260000    0.000000000   -1.058900000
  H      -1.515260000    0.000000000   -1.058900000
```

```
end

basis "fw" rel
  oxygen library cc-pvdz_pt_sf_fw
  hydrogen library cc-pvdz_pt_sf_fw
end

basis "large"
  oxygen library cc-pvdz_pt_sf_lc
  hydrogen library cc-pvdz_pt_sf_lc
end

basis "large2" rel
  oxygen library cc-pvdz_pt_sf_lc
  hydrogen library cc-pvdz_pt_sf_lc
end

basis "small"
  oxygen library cc-pvdz_pt_sf_sc
  hydrogen library cc-pvdz_pt_sf_sc
end

set "ao basis" fw
set "large component" large
set "small component" small

relativistic
  dyall-mod-dirac
end

task scf

set "ao basis" large2
unset "large component"
set "small component" small

relativistic
  dyall-mod-dirac nesc2e
end

task scf
```

The second example has oxygen as a relativistic atom and hydrogen nonrelativistic.

```
start h2o-dmd2

geometry units bohr
symmetry c2v
  O       0.000000000    0.000000000   -0.009000000
  H       1.515260000    0.000000000   -1.058900000
  H      -1.515260000    0.000000000   -1.058900000
```

```
end

basis "ao basis"
  oxygen library cc-pvdz_pt_sf_fw rel
  hydrogen library cc-pvdz
end

basis "large component"
  oxygen library cc-pvdz_pt_sf_lc
end

basis "small component"
  oxygen library cc-pvdz_pt_sf_sc
end

relativistic
  dyall-mod-dirac
end

task scf
```

Chapter 10

Hartree-Fock or Self-consistent Field

The NWChem self-consistent field (SCF) module computes closed-shell restricted Hartree-Fock (RHF) wavefunctions, restricted high-spin open-shell Hartree-Fock (ROHF) wavefunctions, and spin-unrestricted Hartree-Fock (UHF) wavefunctions.

The `SCF` directive provides input to the SCF module and is a compound directive that encloses additional directives specific to the SCF module:

```
SCF
  ...
END
```

10.1 Wavefunction type

A spin-restricted, closed shell RHF calculation is performed by default. An error results if the number of electrons is inconsistent with this assumption. The number of electrons is inferred from the total charge on the system and the sum of the effective nuclear charges of all centers (atoms and dummy atoms, Section 6). The total charge on the system is zero by default, unless specified at some value by input on the `CHARGE` directive (Section 5).

The options available to define the SCF wavefunction and multiplicity are as follows:

```
SINGLET
DOUBLET
TRIPLET
QUARTET
QUINTET
SEXTET
SEPTET
OCTET
NOPEN <integer nopen default 0>
RHF
ROHF
UHF
```

The optional keywords SINGLET, DOUBLET, ..., OCTET and NOPEN allow the user to specify the number of singly occupied orbitals for a particular calculation. SINGLET is the default, and specifies a closed shell; DOUBLET specifies one singly occupied orbital; TRIPLET specifies two singly occupied orbitals; and so forth. If there are more than seven singly occupied orbitals, the keyword NOPEN must be used, with the integer nopen defining the number of singly occupied orbitals (sometimes referred to as open shells).

If the multiplicity is any value other than SINGLET, the default calculation will be a spin-restricted, high-spin, open-shell SCF calculation (keyword ROHF). The open-shell orbitals must be the highest occupied orbitals. If necessary, any starting vectors may be rearranged through the use of the SWAP keyword on the VECTORS directive (see Section 10.5) to accomplish this.

A spin-unrestricted solution can also be performed by specifying the keyword UHF. In UHF calculations, it is assumed that the number of singly occupied orbitals corresponds to the difference between the number of alpha-spin and beta-spin orbitals. For example, a UHF calculation with 2 more alpha-spin orbitals than beta-spin orbitals can be obtained by specifying

```
scf
   triplet ; uhf    # (Note: two logical lines of input)
   ...
end
```

The user should be aware that, by default, molecular orbitals are symmetry adapted in NWChem. This may not be desirable for fully unrestricted wavefunctions. In such cases, the user has the option of defeating the defaults by specifying the keywords ADAPT OFF (see Section 10.3) and SYM OFF (see Section 10.2).

The keywords RHF and ROHF are provided in the code for completeness. It may be necessary to specify these in order to modify the behavior of a previous calculation (see Section 3.2 for restart behavior).

10.2 SYM — use of symmetry

```
SYM <string (ON||OFF) default ON>
```

This directive enables/disables the use of symmetry to speed up Fock matrix construction (via the petite-list or skeleton algorithm) in the SCF, if symmetry was used in the specification of the geometry. Symmetry adaptation of the molecular orbitals is not affected by this option. The default is to use symmetry if it is specified in the geometry directive (Section 6).

For example, to disable use of symmetry in Fock matrix construction:

```
sym off
```

10.3 ADAPT – symmetry adaptation of MOs

```
ADAPT <string (ON||OFF) default ON>
```

The default in the SCF module calculation is to force symmetry adaption of the molecular orbitals. This does not affect the speed of the calculation, but without explicit adaption the resulting orbitals may

be symmetry contaminated for some problems. This is especially likely if the calculation is started using orbitals from a distorted geometry.

The underlying assumption in the use of symmetry in Fock matrix construction is that the density is totally symmetric. If the orbitals are symmetry contaminated, this assumption may not be valid — which could result in incorrect energies and poor convergence of the calculation. It is thus advisable when specifying `ADAPT OFF` to also specify `SYM OFF` (Section 10.2).

10.4 TOL2E — integral screening threshold

```
TOL2E <real tol2e default min(10e-7 , 0.01*$thresh$)>
```

The variable `tol2e` is used in determining the integral screening threshold for the evaluation of the energy and related Fock-like matrices. The Schwarz inequality is used to screen the product of integrals and density matrices in a manner that results in an accuracy in the energy and Fock matrices that approximates the value specified for `tol2e`.

It is generally not necessary to set this parameter directly. Specify instead the required precision in the wavefunction, using the `THRESH` directive (Section 10.7). The default threshold is the minimum of 10^{-7} and 0.01 times the requested convergence threshold for the SCF calculation (Section 10.7).

The input to specify the threshold explicitly within the `SCF` directive is, for example:

```
tol2e 1e-9
```

For very diffuse basis sets, or for high-accuracy calculations it might be necessary to set this parameter. A value of 10^{-12} is sufficient for nearly all such purposes.

10.5 VECTORS — input/output of MO vectors

```
VECTORS [[input] (<string input_movecs default atomic>) || \
                 (project <string basisname> <string filename>) || \
                 (fragment <string file1> [<string file2> ...])] \
        [swap [alpha||beta] <integer vec1 vec2> ...] \
        [reorder <integer atom1 atom2> ...] \
        [output <string output_filename default input_movecs>] \
        [lock]
        [rotate  <string input_geometry> <string input_movecs>]
```

The `VECTORS` directive allows the user to specify the source and destination of the molecular orbital vectors. In a startup calculation (see Section 5.1), the default source for guess vectors is a diagonalized Fock matrix constructed from a superposition of the atomic density matrices for the particular problem. This is usually a very good guess. For a restarted calculation, the default is to use the previous MO vectors.

The optional keyword `INPUT` allows the user to specify the source of the input molecular orbital vectors as any of the following:

- `ATOMIC` — eigenvectors of a Fock-like matrix formed from a superposition of the atomic densities (the default guess). See Sections 10.5.2 and 10.6.

- `HCORE` — eigenvectors of the bare-nucleus Hamiltonian or the one-electron Hamiltonian.
- `filename` — the name of a file containing the MO vectors from a previous calculation. Note that unless the path is fully qualified, or begins with a dot (“.”), then it is assumed to reside in the directory for permanent files (see Section 5.2).
- `PROJECT basisname filename` — projects the existing MO vectors in the file `filename` from the smaller basis with name `basisname` into the current basis. The definition of the basis `basisname` must be available in the current database, and the basis must be smaller than the current basis. In addition, the geometry used for the previous calculations must have the atoms in the same order and in the same orientation as the current geometry.
- `FRAGMENT file1 ...` — assembles starting MO vectors from previously performed calculations on fragments of the system and is described in more detail in Section 10.5.1. Even though there are some significant restrictions in the use of the initial implementation of this method (see Section 10.5.1), this is the most powerful initial guess option within the code. It is particularly indispensable for open shell metallic systems.
- `ROTATE input_geometry input_movecs` — rotates MO vectors generated at a previous geometry to the current active geometry.

The molecular orbitals are saved every iteration if more than 600 seconds have elapsed, and also at the end of the calculation. At completion (converged or not), the SCF module always canonically transforms the molecular orbitals by *separately* diagonalizing the closed–closed, open–open, and virtual–virtual blocks of the Fock matrix.

The name of the file used to store the MO vectors is determined as follows:

- if the `OUTPUT` keyword was specified on the `VECTORS` directive, then the filename that follows this keyword is used, or
- if the input vectors were read from a file, this file is reused for the output vectors (overwriting the input vectors); else,
- a default file name is generated in the directory for permanent files (Section 5.2) by prepending `".movecs"` with the file prefix, i.e., `"<file_prefix>.movecs"`.

The name of this file is stored in the database so that a subsequent SCF calculation will automatically restart from these MO vectors.

Applications of this directive are illustrated in the following examples.

Example 1:

```
vectors output h2o.movecs
```

Assuming a start-up calculation, this directive will result in use of the default atomic density guess, and will output the vectors to the file `h2o.movecs`.

Example 2:

```
vectors input initial.movecs output final.movecs
```

This directive will result in the initial vectors being read from the file `"initial.movecs"`. The results will be written to the file `final.movecs`. The contents of `"initial.movecs"` will not be changed.

Example 3:

```
vectors input project "small basis" small.movecs
```

This directive will cause the calculation to start from vectors in the file "small.movecs" which are in a basis named "small basis". The output vectors will be written to the default file "<file_prefix.movecs>".

Once starting vectors have been obtained using any of the possible options, they may be reordered through use of the SWAP keyword. This optional keyword requires a list of orbital pairs that will be swapped. For UHF calculations, separate SWAP keywords may be provided for the alpha and beta orbitals, as necessary.

An example of use of the SWAP directive:

```
vectors input try1.movecs swap 173 175 174 176 output try2.movecs
```

This directive will cause the initial orbitals to be read from the file "try1.movecs". The vectors for the orbitals within the pairs 173–175 will be swapped with those within 174–176, so the resulting order is 175, 176, 173, 174. The final orbitals obtained in the calculation will be written to the file "try2.movecs".

The swapping of orbitals occurs as a sequential process in the order (left to right) input by the user. Thus, regarding each pair as an elementary transposition it is possible to construct arbitrary permutations of the orbitals. For instance, to apply the permutation (6789)[1] we note that this permutation is equal to (67)(78)(89), and thus may be specified as

```
vectors swap 8 9  7 8  6 7
```

Another example, now illustrating this feature for a UHF calculation, is the directive

```
vectors swap beta 4 5 swap alpha 5 6
```

This input will result in the swapping of the 5–6 alpha orbital pair and the 4–5 beta orbital pair. (All other items in the input use the default values.)

The LOCK keyword allows the user to specify that the ordering of orbitals will be locked to that of the initial vectors, insofar as possible. The default is to order by ascending orbital energies within each orbital space. One application where locking might be desirable is a calculation where it is necessary to preserve the ordering of a previous geometry, despite flipping of the orbital energies. For such a case, the LOCK directive can be used to prevent the SCF calculation from changing the ordering, even if the orbital energies change.

The mapping of the MO's to the nuclei can be changed using the REORDER keyword. Once starting vectors have been obtained using any of the possible options, the REORDER keyword moves the MO coefficients between atoms listed in the integer list. This keyword is particularly useful for calculating localized electron and hole states.

This optional keyword requires a list containing the new atom ordering. It is not necessary to provide separate lists for alpha and beta orbitals.

An example of use of the REORDER keyword:

```
vectors input try1.movecs reorder 2 1 output try2.movecs
```

This directive will cause the initial orbitals to be read from the file "try1.movecs". The MO coefficients for the basis functions on atom 2 will be swapped with those on atom 1. The final orbitals obtained in the calculation will be written to the file "try2.movecs".

[1] The cyclic permutation (6789) maps the ordered list 6 7 8 9 into 9 6 7 8.

The following example shows how the ROTATE keyword can be used to rotate MO vectors calculated at geometry geom1 to geometry geom2, which has a different rotational orientation:

```
set geometry geom1
dft
 vectors input atomic output geom1.mo
end
task dft

set geometry geom2
dft
 vectors input rotate geom1 geom1.mo output geom2.mo
end
task dft
```

10.5.1 Superposition of fragment molecular orbitals

The fragment initial guess is particularly useful in the following instances:

- The system naturally decomposes into molecules that can be treated individually, e.g., a cluster.
- One or more fragments are particularly hard to converge and therefore much time can be saved by converging them independently.
- A fragment (e.g., a metal atom) must be prepared with a specific occupation. This can often be readily accomplished with a calculation on the fragment using dummy charges to model a ligand field.
- The molecular occupation predicted by the atomic initial guess is often wrong for systems with heavy metals which may have partially occupied orbitals with lower energy than some doubly occupied orbitals. The fragment initial guess avoids this problem.

```
VECTORS [input] fragment <string file1> [<string file2> ...]
```

The molecular orbitals are formed by superimposing the previously generated orbitals of fragments of the molecule being studied. These fragment molecular orbitals must be in the same basis as the current calculation. The input specifies the files containing the fragment molecular orbitals. For instance, in a calculation on the water dimer, one might specify

```
vectors fragment h2o1.movecs h2o2.movecs
```

where h2o1.movecs contains the orbitals for the first fragment, and h2o2.movecs contains the orbitals for the second fragment.

A complete example of the input for a calculation on the water dimer using the fragment guess is as follows:

```
start dimer

title "Water dimer SCF using fragment initial guess"
```

```
geometry dimer
  O   -0.595   1.165  -0.048
  H    0.110   1.812  -0.170
  H   -1.452   1.598  -0.154
  O    0.724  -1.284   0.034
  H    0.175  -2.013   0.348
  H    0.177  -0.480   0.010
end

geometry h2o1
  O   -0.595   1.165  -0.048
  H    0.110   1.812  -0.170
  H   -1.452   1.598  -0.154
end

geometry h2o2
  O    0.724  -1.284   0.034
  H    0.175  -2.013   0.348
  H    0.177  -0.480   0.010
end

basis
  o library 3-21g
  h library 3-21g
end

set geometry h2o1
scf; vectors input atomic output h2o1.movecs; end
task scf

set geometry h2o2
scf; vectors input atomic output h2o2.movecs; end
task scf

set geometry dimer
scf
vectors input fragment h2o1.movecs h2o2.movecs \
        output dimer.movecs
end
task scf
```

First, the geometry of the dimer and the two monomers are specified and given names. Then, after the basis specification, calculations are performed on the fragments by setting the geometry to the appropriate fragment (Section 5.7) and redirecting the output molecular orbitals to an appropriately named file. Note also that use of the atomic initial guess is forced, since the default initial guess is to use any existing MOs which would not be appropriate for the second fragment calculation. Finally, the dimer calculation is performed by specifying the dimer geometry, indicating use of the fragment guess, and redirecting the output MOs.

The following points are important in using the fragment initial guess:

1. The fragment calculations must be in the same basis set as the full calculation.

2. The order of atoms in the fragments and the order in which the fragment files are specified must be such that when the fragment basis sets are concatenated all the basis functions are in the same order as in the full system. This is readily accomplished by first generating the full geometry with atoms for each fragment contiguous, splitting this into numbered fragments and specifying the fragment MO files in the correct order on the `VECTORS` directive.

3. The occupation of orbitals is preserved when they are merged from the fragments to the full molecule and the resulting occupation must match the requested occupation for the full molecule. E.g., a triplet ROHF calculation must be comprised of fragments that have a total of exactly two open-shell orbitals.

4. Because of these restrictions, it is not possible to introduce additional atoms (or basis functions) into fragments for the purpose of cleanly breaking real bonds. However, it is possible, and highly recommended, to introduce additional point charges to simulate the presence of other fragments.

5. MO vectors of partially occupied or strongly polarized systems are very sensitive to orientation. While it is possible to specify the same fragment MO vector file multiple times in the `VECTORS` directive, it is usually much better to do a separate calculation for each fragment.

6. Linear dependencies which were present in a fragment calculation may be magnified in the full calculation. When this occurs, some of the fragment's highest virtual orbitals will not be copied to the full system, and a warning will be printed.

A more involved example is now presented. We wish to model the sextet state of Fe(III) complexed with water, imidazole and a heme with a net unit positive charge. The default atomic guess does not give the correct d^5 occupation for the metal and also gives an incorrect state for the double anion of the heme. The following performs calculations on all of the fragments. Things to note are:

1. The use of a dummy +2 charge in the initial guess on the heme which in part simulates the presence of the metal ion, and also automatically forces an additional two electrons to be added to the system (the default net charge being zero).

2. The iron fragment calculation (charge +3, d^5, sextet) will yield the correct open-shell occupation for the full system. If, instead, the *d*-orbitals were partially occupied (e.g., the doublet state) it would be useful to introduce dummy charges around the iron to model the ligand field and thereby lift the degeneracy to obtain the correct occupation.

3. C_s symmetry is used for all of the calculations. It is not necessary that the same symmetry be used in all of the calculations, provided that the order and orientation of the atoms is preserved.

4. The `unset scf:*` directive is used immediately before the calculation on the full system so that the default name for the output MO vector file can be used, rather than having to specify it explicitly.

```
start heme6a1
title  "heme-H2O (6A1) from M.Dupuis"

############################################################
# Define the geometry of the full system and the fragments #
############################################################

geometry full-system
   symmetry cs

   H     0.438   -0.002    4.549
```

```
   C     0.443   -0.001    3.457
   C     0.451   -1.251    2.828
   C     0.452    1.250    2.828
   H     0.455    2.652    4.586
   H     0.461   -2.649    4.586
   N1    0.455   -1.461    1.441
   N1    0.458    1.458    1.443
   C     0.460    2.530    3.505
   C     0.462   -2.530    3.506
   C     0.478    2.844    1.249
   C     0.478    3.510    2.534
   C     0.478   -2.848    1.248
   C     0.480   -3.513    2.536
   C     0.484    3.480    0.000
   C     0.485   -3.484    0.000
   H     0.489    4.590    2.664
   H     0.496   -4.592    2.669

   H     0.498    4.573    0.000
   H     0.503   -4.577    0.000
   H    -4.925    1.235    0.000
   H    -4.729   -1.338    0.000
   C    -3.987    0.685    0.000
   N    -3.930   -0.703    0.000
   C    -2.678    1.111    0.000
   C    -2.622   -1.076    0.000
   H    -2.284    2.126    0.000
   H    -2.277   -2.108    0.000
   N    -1.838    0.007    0.000

   Fe    0.307    0.000    0.000

   O     2.673   -0.009    0.000
   H     3.238   -0.804    0.000
   H     3.254    0.777    0.000
end

geometry ring-only
   symmetry cs
   H     0.438   -0.002    4.549
   C     0.443   -0.001    3.457
   C     0.451   -1.251    2.828
   C     0.452    1.250    2.828
   H     0.455    2.652    4.586
   H     0.461   -2.649    4.586
   N1    0.455   -1.461    1.441
   N1    0.458    1.458    1.443
   C     0.460    2.530    3.505
   C     0.462   -2.530    3.506
   C     0.478    2.844    1.249
   C     0.478    3.510    2.534
```

```
   C     0.478   -2.848    1.248
   C     0.480   -3.513    2.536
   C     0.484    3.480    0.000
   C     0.485   -3.484    0.000
   H     0.489    4.590    2.664
   H     0.496   -4.592    2.669

   Bq    0.307    0.0      0.0    charge 2  # simulate the iron
end

geometry imid-only
   symmetry cs
   H     0.498    4.573    0.000
   H     0.503   -4.577    0.000
   H    -4.925    1.235    0.000
   H    -4.729   -1.338    0.000
   C    -3.987    0.685    0.000
   N    -3.930   -0.703    0.000
   C    -2.678    1.111    0.000
   C    -2.622   -1.076    0.000
   H    -2.284    2.126    0.000
   H    -2.277   -2.108    0.000
   N    -1.838    0.007    0.000
end

geometry fe-only
   symmetry cs
   Fe    .307    0.000    0.000
end

geometry water-only
   symmetry cs
   O     2.673   -0.009    0.000
   H     3.238   -0.804    0.000
   H     3.254    0.777    0.000
end

############################
# Basis set for everything #
############################

basis nosegment
  O  library 6-31g*
  N  library 6-31g*
  C  library 6-31g*
  H  library 6-31g*
 Fe  library "Ahlrichs pVDZ"
end

#########################################################
# SCF on the fragments for initial guess for full system #
```

```
#########################################################

scf; thresh 1e-2; end

set geometry ring-only
scf; vectors atomic swap 80 81 output ring.mo; end
task scf

set geometry water-only
scf; vectors atomic output water.mo; end
task scf

set geometry imid-only
scf; vectors atomic output imid.mo; end
task scf

charge 3
set geometry fe-only
scf; sextet; vectors atomic output fe.mo; end
task scf

#########################
# SCF on the full system #
#########################

unset scf:*     # This restores the defaults

charge 1

set geometry full-system

scf
 sextet
 vectors fragment ring.mo imid.mo fe.mo water.mo
 maxiter 50
end

task scf
```

10.5.2 Atomic guess orbitals with charged atoms

As noted above, the default guess vectors are based on superimposing the density matrices of the neutral atoms. If some atoms are significantly charged, this default guess may be improved upon by modifying the atomic densities. This is done by setting parameters that add fractional charges to the occupation of the valence atomic orbitals. Since the atomic SCF program does not have its own input block, the SET directive (Section 5.7) must be used to set these parameters.

The input specifies a list of tags (i.e., names of atoms in a geometry, see Section 6) and the charges to be added to those centers. Two parameters must be set as follows:

```
set atomscf:tags_z <string list_of_tags>
```

```
set atomscf:z      <real list_of_charges>
```

The array of strings `atomscf:tags_z` should be set to the list of tags, and the array `atomscf:z` should be set to the list of charges which must be real numbers (not integers). All atoms that have a tag specified in the list of tags will be assigned the corresponding charge from the list of charges.

For example, the following specifies that all oxygen atoms with tag `O` be assigned a charge of `-1` and all iron atoms with tag `Fe` be assigned a charge of `+2`

```
set atomscf:z        -1  2.0
set atomscf:tags_z    O  Fe
```

There are some limitations to this feature. It is not possible to add electrons to closed shell atoms, nor is it possible to remove all electrons from a given atom. Attempts to do so will cause the code to report an error, and it will not report further errors in the input for modifying the charge even when they are detected.

Finally, recall that the database is persistent (Section 3.2) and that the modified settings will be used in subsequent atomic guess calculations unless the data is deleted from the database with the `UNSET` directive (Section 5.8).

10.6 Accuracy of initial guess

For SCF, the initial Fock-matrix construction from the atomic guess is now (staring from version 3.3) performed to a default precision of 1e-7. However, other wavefunctions, notably DFT, use a lower precision. In charged, or diffuse basis sets, this precision may not be sufficient and could result in incorrect ordering of the initial orbitals. The accuracy may be increased with the following directive which should be inserted in the top-level of input (i.e., outside of the SCF input block) and before the `TASK` directive.

```
set tolguess 1e-7
```

10.7 THRESH — convergence threshold

```
THRESH  <real thresh default 1.0e-4>
```

This directive specifies the convergence threshold for the calculation. The convergence threshold is the norm of the orbital gradient, and has a default value in the code of 10^{-4}.

The norm of the orbital gradient corresponds roughly to the precision available in the wavefunction, and the energy should be converged to approximately the square of this number. It should be noted, however, that the precision in the energy will not exceed that of the integral screening tolerance. This tolerance (Section 10.4) is automatically set from the convergence threshold, so that sufficient precision is usually available by default.

The default convergence threshold suffices for most SCF energy and geometry optimization calculations, providing about 6–8 decimal places in the energy, and about four significant figures in the density and energy derivative with respect to nuclear coordinates. However, greater precision may be required for calculations involving weakly interacting systems, floppy molecules, finite-difference of gradients to compute the Hessian, and for post-Hartree-Fock calculations. A threshold of 10^{-6} is adequate for most such purposes, and a threshold of 10^{-8} might be necessary for very high accuracy or very weak interactions. A threshold of 10^{-10} should be regarded as the best that can be attained in most circumstances.

10.8 MAXITER — iteration limit

```
MAXITER <integer maxiter default 8>
```

The maximum number of iterations for the SCF calculation defaults to 20 for both ROHF/RHF and UHF calculations. For most molecules, this number of iterations is more than sufficient for the quadratically convergent SCF algorithm to obtain a solution converged to the default threshold (see Section 10.7 above). If the SCF program detects that the quadratically convergent algorithm is not efficient, then it will resort to a linearly convergent algorithm and increase the maximum number of iterations by 10.

Convergence may not be reached in the maximum number of iterations for many reasons, including input error (e.g., an incorrect geometry or a linearly dependent basis), a very low convergence threshold, a poor initial guess, or the fact that the system is intrinsically hard to converge due to the presence of many states with similar energies.

The following sets the maximum number of SCF iterations to 50:

```
maxiter 50
```

10.9 PROFILE — performance profile

This directive allows the user to obtain timing and parallel execution information about the SCF module. It is specified by the simple keyword

```
PROFILE
```

This option can be helpful in understanding the computational performance of an SCF calculation. However, it can introduce a significant overhead on machines that have expensive timing routines, such as the SUN.

10.10 DIIS — DIIS convergence

This directive allows the user to specify DIIS convergence rather than second-order convergence for the SCF calculation. The form of the directive is as follows:

```
DIIS
```

The implementation of this option is currently fairly rudimentary. It does not have level-shifting and damping, and does not support open shells or UHF. It is provided on an "as is" basis, and should be used with caution.

When the DIIS directive is specified in the input, the user has the additional option of specifying the size of the subspace for the DIIS extrapolation. This is accomplished with the DIISBAS directive, which is of the form:

```
DIISBAS <integer diisbas default 5>
```

The default of 5 should be adequate for most applications, but may be increased if convergence is poor. On large systems, it may be necessary to specify a lower value for diisbas, to conserve memory.

10.11 DIRECT and SEMIDIRECT — recomputation of integrals

In the context of SCF calculations direct means that all integrals are recomputed as required and none are stored. The other extreme are disk- or memory-resident (sometimes termed conventional) calculations in which all integrals are computed once and stored. Semi-direct calculations are between these two extremes with some integrals being precomputed and stored, and all other integrals being recomputed as necessary.

The default behavior of the SCF module is

- If enough memory is available, the integrals are computed once and are cached in memory.
- If there is not enough memory to store all the integrals at once, then 95% of the available disk space in the scratch directory (see Section 5.2) is assumed to be available for this purpose, and as many integrals as possible are cached on disk (with no memory being used for caching). Some attempt is made to store the most expensive integrals in the cache.
- If there is not enough room in memory or on disk for all the integrals, then the ones that are not cached are recomputed in a semidirect fashion.

The integral file is deleted at the end of a calculation, so it is not possible to restart a semidirect calculation when the integrals are cached in memory or on disk. Many computer systems (e.g., the EMSL IBM SP) clear the fast scratch space at the end of each job, adding a further complication to the problem of restarting a *parallel* semidirect calculation.

On the IBM SP or any other computer with fast disks local to each processor, semidirect calculation offers the best behavior. It can result in *quadratic speedup* as more processors are added.

A fully direct calculation (with recomputation of the integrals at each iteration) is forced by specifying the directive

```
DIRECT
```

Alternatively, the `SEMIDIRECT` directive can be used to control the default semidirect calculation by defining the amount of disk space and the cache memory size. The form of this directive is as follows:

```
SEMIDIRECT [filesize <integer filesize default disksize>]
           [memsize  <integer memsize default available>]
           [filename <string filename default $file_prefix.aoints$>]
```

The keyword `FILESIZE` allows the user to specify the amount of disk space to be used per process for storing the integrals in 64-bit words. Similarly, the keyword `MEMSIZE` allows the user to specify the number of 64-bit words to be used per process for caching integrals in memory. (Note: If the amount of storage space specified by the entry for `memsize` is not available, the code cuts the value in half and checks again for available space. This process is repeated until the request is satisfied.)

By default, the integral files are placed into the scratch directory (see Section 5.2). Specifying the keyword `FILENAME` overrides this default. The user-specified name entered in the string `filename` has the process number appended to it, so that each process has a distinct file but with a common base-name and directory. Therefore, it is not possible to use this keyword to specify different disks for different processes. The `SCRATCH_DIR` directive (see Section 5.2) can be used for this purpose.

For example, to force full recomputation of all integrals:

```
direct
```

Exactly the same result could be obtained by entering the directive:

```
semidirect filesize 0 memsize 0
```

To disable the use of memory for caching integrals and limit disk usage by each process to 100 megawords (MW):

```
semidirect memsize 0 filesize 100000000
```

The integral records are typically 32769 words long and any non-zero value for `filesize` or `memsize` should be enough to hold at least one record.

10.11.1 Integral File Size and Format for the SCF Module

The file format is rather complex, since it accommodates a variety of packing and compression options and the distribution of data. This section presents some information that may help the user understand the output, and illustrates how to use the output information to estimate file sizes.

If integrals are stored with a threshold of greater than 10^{-10}, then the integrals are stored in a 32-bit fixed-point format (with appropriate treatment for large values to retain precision). If integrals are stored with a threshold less than 10^{-10}, however, the values are stored in 64-bit floating-point format. If a replicated-data calculation is being run, then 8 bits are used for each basis function label, unless there are more than 256 functions, in which case 16 bits are used. If distributed data is being used, then the labels are always packed to 8 bits (the distributed blocks always being less than 256; labels are relative to the start of the block).

Thus, the number (W) of 64-bit words required to store N integrals, may be computed as

$$W = \begin{cases} N \text{ , 8-bit labels and 32-bit values} \\ \frac{3}{2}N \text{ , 16-bit labels and 32-bit values} \\ \frac{3}{2}N \text{ , 8-bit labels and 64-bit values} \\ 2N \text{ , 16-bit labels and 64-bit values} \end{cases}$$

The actual number of words required can exceed this computed value by up to one percent, due to bookkeeping overhead, and because the file itself is organized into fixed-size records.

With at least the default print level, all semidirect (not direct) calculations will print out information about the integral file and the number of integrals computed. The form of this output is as follows:

```
 Integral file          = ./c6h6.aoints.0
 Record size in doubles =  32769        No. of integs per rec  =  32768
 Max. records in memory =      3        Max. records in file   =      5
 No. of bits per label  =      8        No. of bits per value  =     32

 #quartets = 2.0D+04  #integrals = 7.9D+05  direct = 63.6%  cached = 36.4%
```

The file information above relates only to process 0. The line of information about the number of quartets, integrals, etc., is a sum over all processes.

When the integral file is closed, additional information of the following form is printed:

```
------------------------------------------------------------
EAF file 0: "./c6h6.aoints.0" size=262152 bytes
------------------------------------------------------------
               write      read    awrite     aread      wait
               -----      ----    ------     -----      ----
     calls:        6        12         0         0         0
   data(b): 1.57e+06  3.15e+06  0.00e+00  0.00e+00
   time(s): 1.09e-01  3.12e-02                    0.00e+00
rate(mb/s): 1.44e+01  1.01e+02
------------------------------------------------------------

 Parallel integral file used       4 records with       0 large values
```

Again, the detailed file information relates just to process 0, but the final line indicates the total number of integral records stored by all processes.

This information may be used to optimize subsequent calculations, for instance by assigning more memory or disk space.

10.12 SCF Convergence Control Options

Note to users: It is desired that the SCF program converge reliably with the default options for a wide variety of molecules. In addition, it should be guaranteed to converge for any system, with sufficient iterations. Please report significant convergence problems to `nwchem-users@emsl.pnl.gov`, and include the input file.

The SCF program uses a preconditioned conjugate gradient (PCG) method that is unconditionally convergent. Basically, a search direction is generated by multiplying the orbital gradient (the derivative of the energy with respect to the orbital rotations) by an approximation to the inverse of the level-shifted orbital Hessian. In the initial iterations (see Section 10.13), an inexpensive one-electron approximation to the inverse orbital Hessian is used. Closer to convergence, the full orbital Hessian is used, which should provide quadratic convergence. For both the full or one-electron orbital Hessians, the inverse-Hessian matrix-vector product is formed iteratively. Subsequently, an approximate line search is performed along the new search direction. If the exact Hessian is being employed, then the line search should require a single step (of unity). Preconditioning with approximate Hessians may require additional steps, especially in the initial iterations. It is the (approximate) line search that provides the convergence guarantee. The iterations required to solve the linear equations are referred to as micro-iterations. A macro-iteration comprises both the iterative solution and a line search.

Level-shifting plays the same role in this algorithm as it does in the conventional iterative solution of the SCF equations. The approximate Hessian used for preconditioning should be positive definite. If this is not the case, then level-shifting by a positive constant (Δ) serves to make the preconditioning matrix positive definite, by adding Δ to all of its eigenvalues. The level-shifts employed for the RHF orbital Hessian should be approximately four times (only twice for UHF) the value that one would employ in a conventional SCF[2]. Level-shifting is automatically enabled in the early iterations, and the default options suffice for most test cases.

So why do things go wrong and what can be done to fix convergence problems? Most problems encountered so far arise either poor initial guesses or from small or negative eigenvalues of the orbital Hessian. The atomic orbital guess is usually very good. However, in calculations on charged systems, especially with open

[2]This can be seen by considering a one-electron approximation to the closed-shell RHF Hessian in canonical orbitals, $A_{ia,jb} = 4\delta_{ij}\delta_{ab}(\epsilon_a - \epsilon_i)$. Similarly, the level shift should be twice as large for UHF.

shells, incorrect initial occupations may result. The SCF might then converge very slowly since very large orbital rotations might be required to achieve the correct occupation or move charge large distances in the molecule. Possible actions are

- Modify the atomic guess by assigning charges to the atoms known to carry substantial charges (Section 10.5.2)
- Examining an analysis of the initial orbitals (Section 10.16) and then swapping them to attain the desired occupation (Section 10.5).
- Converging the calculation in a minimal basis set, which is usually easier, and then projecting into a larger basis set (Section 10.5).
- Using the fragment orbital initial guess (Section 10.5.1).

Small or negative Hessian eigenvalues can occur even though the calculation seem to be close to convergence (as measured by the gradient norm, or the off-diagonal Fock matrix elements). Small eigenvalues will cause the iterative linear equation solver to converge slowly, resulting in an excessive number of micro-iterations. This makes the SCF expensive in terms of computation time, and it is possible to exceed the maximum number of iterations without achieving the accuracy required for quadratic convergence — which causes more macro-iterations to be performed.

Two main options are available when a problem will not converge: Newton-Raphson can be disabled temporarily or permanently (see Section 10.13), and level-shifting can be applied to the matrix (see Section 10.14). In some cases, both options may be necessary to achieve final convergence.

If there is reason to suspect a negative eigenvalue, the first course is to disable the Newton-Raphson iteration until the solution is closer to convergence. It may be necessary to disable it completely. At some point close to convergence, the Hessian will be positive definite, so disabling Newton-Raphson should yield a solution with approximately the same convergence rate as DIIS.

If temporarily disabling Newton-Raphson is not sufficient to achieve convergence, it may be necessary to disable it entirely and apply a small level-shift to the approximate Hessian. This should improve the convergence rate of the micro-iterations and stabilize the macro-iterations. The level-shifting will destroy exact quadratic convergence, but the optimization process is automatically adjusted to reflect this by enforcing conjugacy and reducing the accuracy to which the linear equations are solved. The net result of this is that the solution will do more macro-iterations, but each one should take less time than it would with the unshifted Hessian.

The following sections describe the directives needed to disable the Newton-Raphson iteration and specify level-shifting.

10.13 NR — controlling the Newton-Raphson

```
NR <real nr_switch default 0.1>
```

The exact orbital Hessian is adopted as the preconditioner when the maximum element of the orbital gradient is below the value specified for `nr_switch`. The default value is 0.1, which means that Newton-Raphson will be disabled until the maximum value of the orbital gradient (twice the largest off-diagonal Fock matrix element) is less than 0.1. To disable the Newton-Raphson entirely, the value of `nr_switch` must be set to zero. The directive to accomplish this is as follows:

```
nr 0
```

10.14 LEVEL — level-shifting the orbital Hessian

This directive allows the user to specify level-shifting to obtain a positive-definite preconditioning matrix for the SCF solution procedure. Separate level shifts can be set for the first-order convergent one-electron approximation to the Hessian used with the preconditioned conjugate gradient (PCG) method, and for the full Hessian used with the Newton-Raphson (NR) approach. It is also possible to change the level-shift automatically as the solution attains some specified accuracy. The form of the directive is as follows:

```
LEVEL [pcg <real initial default 20.0> \
        [<real tol default 0.5> <real final default 0.0>]] \
      [nr <real initial default 0.0> \
        [<real tol default 0.0> <real final default 0.0>]]
```

This directive contains only two keywords: one for the PCG method and the other for the exact Hessian (Newton Raphson, or NR). Use of PCG or NR is determined by the input specified for `nr_switch` on the `NR` directive, Section 10.13 above.

Specifying the keyword `pcg` on the `LEVEL` directive allows the user to define the level shifting for the approximate (i.e., PCG) method. Specifying the keyword `nr` allows the user to define the level shifting for the exact Hessians. In both options, the initial level shift is defined by the value specified for the variable `initial`. Optionally, `tol` can be specified independently with each keyword to define the level of accuracy that must be attained in the solution before the level shifting is changed to the value specified by input in the real variable `final`. Level shifts and gradient thresholds are specified in atomic units.

For the PCG method (as specified using the keyword `pcg`), the defaults for this input are 20.0 for `initial`, 0.5 for `tol`, and 0.0 for `final`. This means that the approximate Hessian will be shifted by 20.0 until the maximum element of the gradient falls below 0.5, at which point the shift will be set to zero.

For the exact Hessian (as specified using the keyword `nr`), the defaults are all zero. The exact Hessian is usually not shifted since this destroys quadratic convergence. An example of an input directive that applies a shift of 0.2 to the exact Hessian is as follows:

```
level nr 0.2
```

To apply this shift to the exact Hessian only until the maximum element of the gradient falls below 0.005, the required input directive is as follows:

```
level nr 0.2 0.005 0
```

Note that in both of these examples, the parameters for the PCG method are at the default values. To obtain values different from the defaults, the keyword `pcg` must also be specified. For example, to specify the level shifting in the above example for the exact Hessian *and* non-default shifting for the PCG method, the directive would be something like the following:

```
level pcg 20 0.3 0.0 nr 0.2 0.005 0.0
```

This input will cause the PCG method to be level-shifted by 20.0 until the maximum element of the gradient falls below 0.3, then the shift will be zero. For the exact Hessian, the level shifting is initially 0.2, until the maximum element falls below 0.005, after which the shift is zero.

The default options correspond to

```
level pcg 20 0.5 0 nr 0 0 0
```

10.15 Orbital Localization

The SCF module includes an *experimental* implementation of orbital localization, including Foster-Boys and Pipek-Mezey which only works for closed-shell (RHF) wavefunctions. There is currently no input in the SCF block to control this so the `SET` directive (Section 5.7) must be used.

The directive

```
set scf:localize t
```

will separately localize the core, valence, and virtual orbital spaces using the Pipek-Mezey algorithm. If the additional directive

```
set scf:loctype FB
```

is included, then the Foster-boys algorithm is used. The partitioning of core-orbitals is performed using the atomic information described in Section 16.1.

In the next release, this functionality will be extended to included all wavefunctions using molecular orbitals.

10.16 Printing Information from the SCF Module

All output from the SCF module is controlled using the `PRINT` directive described in Section 5.6. The following list describes the items from SCF that are currently under direct print control, along with the print level for each one.

Name	**Print Level**	**Description**
"atomic guess density"	debug	guess density matrix
"atomic scf"	debug	details of atomic SCF
"mo guess"	default	brief info from mo guess
"information"	low	results
"initial vectors"	debug	
"intermediate vectors"	debug	
"final vectors"	debug	
"final vectors analysis"	default	
"initial vectors analysis"	never	
"intermediate evals"	debug	
"final evals"	default	
"schwarz"	high	integral screening info & stats at completion
"screening statistics"	debug	display stats after every Fock build
"geometry"	high	
"symmetry"	debug	detailed symmetry info
"basis"	high	
"geombas"	debug	detailed basis map info
"vectors i/o"	default	report vectors I/O
"parameters"	default	convergence parameters
"convergence"	default	info each iteration
"mulliken ao"	never	Mulliken population of basis functions

Table 10.1: SCF Print Control Specifications

10.17 Hartree-Fock or SCF, MCSCF and MP2 Gradients

The input for this directive allows the user to adjust the print control for the SCF, UHF, ROHF, MCSCF and MP2 gradients. The form of the directive is as follows:

```
GRADIENTS
  [print || noprint] ...
END
```

The complementary keyword pair `print` and `noprint` allows the user some additional control on the information that can be included in the print output from the SCF calculation. Currently, only a few items can be explicitly invoked via print control. These are as follows:

Name	**Print Level**	**Description**
"information"	low	calculation info
"geometry"	high	geometry information
"basis"	high	basis set(s) used
"forces"	low	details of force components
"timing"	default	timing for each phase

Table 10.2: Gradient Print Control Specifications

Chapter 11

DFT for Molecules (DFT)

The NWChem density functional theory (DFT) module uses the Gaussian basis set approach to compute closed shell and open shell densities and Kohn-Sham orbitals in the:

- local density approximation (LDA),
- non-local density approximation (NLDA),
- local spin-density approximation (LSD),
- non-local spin-density approximation (NLSD),
- non-local meta-GGA approximation (metaGGA),
- any empirical mixture of local and non-local approximations (including exact exchange), and
- asymptotically corrected exchange-correlation potentials.

The formal scaling of the DFT computation can be reduced by choosing to use auxiliary Gaussian basis sets to fit the charge density (CD) and/or fit the exchange-correlation (XC) potential.

DFT input is provided using the compound `DFT` directive

```
DFT
  ...
END
```

The actual DFT calculation will be performed when the input module encounters the `TASK` directive (Section 5.10).

```
TASK DFT
```

Once a user has specified a geometry and a Kohn-Sham orbital basis set the DFT module can be invoked with no input directives (defaults invoked throughout). There are sub-directives which allow for customized application; those currently provided as options for the DFT module are:

```
VECTORS [[input] (<string input_movecs default atomic>) || \
                 (project <string basisname> <string filename>)] \
        [swap [alpha||beta] <integer vec1 vec2> ...] \
        [output <string output_filename default input_movecs>] \


XC [[acm] [b3lyp] [beckehandh] [pbe0]\
   [becke97]  [becke97-1] [becke97-2] [becke97-3] [becke98] [hcth] [hcth120] [hcth147]\
    [hcth407] [becke97gga1]  [hcth407p]\
    [mpw91] [mpw1k] [xft97] [cft97] [ft97] [op] [bop] [pbeop]\
    [xpkzb99] [cpkzb99] [xtpss03] [ctpss03] [xctpssh]\
    [b1b95] [bb1k] [mpw1b95] [mpwb1k] [pw6b95] [pwb6k] [m05] [m05-2x] [vs98] \
    [m06] [m06-hf] [m06-L] [m06-2x] \
    [HFexch <real prefactor default 1.0>] \
    [becke88 [nonlocal] <real prefactor default 1.0>] \
    [xperdew91 [nonlocal] <real prefactor default 1.0>] \
    [xpbe96 [nonlocal] <real prefactor default 1.0>] \
    [gill96 [nonlocal] <real prefactor default 1.0>] \
    [lyp <real prefactor default 1.0>] \
    [perdew81 <real prefactor default 1.0>] \
    [perdew86 [nonlocal] <real prefactor default 1.0>] \
    [perdew91 [nonlocal] <real prefactor default 1.0>] \
    [cpbe96 [nonlocal] <real prefactor default 1.0>] \
    [pw91lda <real prefactor default 1.0>] \
    [slater <real prefactor default 1.0>] \
    [vwn_1 <real prefactor default 1.0>] \
    [vwn_2 <real prefactor default 1.0>] \
    [vwn_3 <real prefactor default 1.0>] \
    [vwn_4 <real prefactor default 1.0>] \
    [vwn_5 <real prefactor default 1.0>] \
    [vwn_1_rpa <real prefactor default 1.0>] \
    [xtpss03 [nonlocal] <real prefactor default 1.0>] \
    [ctpss03 [nonlocal] <real prefactor default 1.0>] \
    [bc95 [nonlocal] <real prefactor default 1.0>] \
    [xpw6b95 [nonlocal] <real prefactor default 1.0>] \
    [xpwb6k [nonlocal] <real prefactor default 1.0>] \
    [xm05 [nonlocal] <real prefactor default 1.0>] \
    [xm05-2x [nonlocal] <real prefactor default 1.0>] \
    [cpw6b95 [nonlocal] <real prefactor default 1.0>] \
    [cpwb6k [nonlocal] <real prefactor default 1.0>] \
    [cm05 [nonlocal] <real prefactor default 1.0>] \
    [cm05-2x [nonlocal] <real prefactor default 1.0>]] \
    [xvs98 [nonlocal] <real prefactor default 1.0>]] \
    [cvs98 [nonlocal] <real prefactor default 1.0>]] \
    [xm06-L [nonlocal] <real prefactor default 1.0>]] \
    [xm06-hf [nonlocal] <real prefactor default 1.0>]] \
    [xm06 [nonlocal] <real prefactor default 1.0>]] \
    [xm06-2x [nonlocal] <real prefactor default 1.0>]] \
    [cm06-L [nonlocal] <real prefactor default 1.0>]] \
    [cm06-hf [nonlocal] <real prefactor default 1.0>]] \
    [cm06 [nonlocal] <real prefactor default 1.0>]] \
```

```
    [cm06-2x [nonlocal] <real prefactor default 1.0>]]


CONVERGENCE [[energy <real energy default 1e-7>] \
             [density <real density default 1e-5>] \
             [gradient <real gradient default 5e-4>] \
             [dampon <real dampon default 0.0>] \
             [dampoff <real dampoff default 0.0>] \
             [diison <real diison default 0.0>] \
             [diisoff <real diisoff default 0.0>] \
             [levlon <real levlon default 0.0>] \
             [levloff <real levloff default 0.0>] \
             [ncydp <integer ncydp default 2>] \
             [ncyds <integer ncyds default 30>] \
             [ncysh <integer ncysh default 30>] \
             [damp <integer ndamp default 0>] [nodamping] \
             [diis [nfock <integer nfock default 10>]] \
             [nodiis] [lshift <real lshift default 0.5>] \
             [nolevelshifting] \
             [hl_tol <real hl_tol default 0.1>] \
             [rabuck [n_rabuck <integer n_rabuck default 25>]]


GRID [(xcoarse||coarse||medium||fine||xfine) default medium] \
     [(gausleg||lebedev ) default lebedev ] \
     [(becke||erf1||erf2||ssf) default erf1] \
     [(euler||mura||treutler) default mura] \
     [rm <real rm default 2.0>] \
     [nodisk]


TOLERANCES [[tight] [tol_rho <real tol_rho default 1e-10>] \
            [accCoul <integer accCoul default 8>] \
            [radius <real radius default 25.0>]]


[(LB94||CS00 <real shift default none>)]

DECOMP
ODFT
DIRECT
INCORE
ITERATIONS <integer iterations default 30>
MAX_OVL
MULLIKEN
MULT <integer mult default 1>
NOIO
PRINT||NOPRINT
```

The following sections describe these keywords and optional sub-directives that can be specified for a `DFT` calculation in NWChem.

11.1 Specification of Basis Sets for the DFT Module

The DFT module requires at a minimum the basis set for the Kohn-Sham molecular orbitals. This basis set must be in the default basis set named `"ao basis"`, or it must be assigned to this default name using the `SET` directive (see Section 5.7).

In addition to the basis set for the Kohn-Sham orbitals, the charge density fitting basis set can also be specified in the input directives for the DFT module. This basis set is used for the evaluation of the Coulomb potential in the Dunlap scheme[1]. The charge density fitting basis set must have the name `"cd basis"`. This can be the actual name of a basis set, or a basis set can be assigned this name using the `SET` directive, as described in Section 5.7. If this basis set is not defined by input, the $O(N^4)$ exact Coulomb contribution is computed.

The user also has the option of specifying a third basis set for the evaluation of the exchange-correlation potential. This basis set must have the name `"xc basis"`. If this basis set is not specified by input, the exchange contribution (XC) is evaluated by numerical quadrature. In most applications, this approach is efficient enough, so the `"xc basis"` basis set is not generally required.

For the DFT module, the input options for defining the basis sets in a given calculation can be summarized as follows;

- `"ao basis"` – Kohn-Sham molecular orbitals; required for all calculations
- `"cd basis"` – charge density fitting basis set; optional, but recommended for evaluation of the Coulomb potential
- `"xc basis"` – exchange-correlation (XC) fitting basis set; optional, and usually not recommended

11.2 VECTORS and MAX_OVL — KS-MO Vectors

The `VECTORS` directive is the same as that in the SCF module (Section 10.5). Currently, the `LOCK` keyword is not supported by the DFT module, however the directive

```
MAX_OVL
```

has the same effect.

11.3 XC and DECOMP — Exchange-Correlation Potentials

```
XC [[acm] [b3lyp] [beckehandh] [pbe0]\
   [becke97]  [becke97-1] [becke97-2] [becke97-3] [becke98] [hcth] [hcth120] [hcth147] \
    [hcth407] [becke97gga1] [hcth407p] \
    [optx] [hcthp14] [mpw91] [mpw1k] [xft97] [cft97] [ft97] [op] [bop] [pbeop]\
    [HFexch <real prefactor default 1.0>] \
```

[1] B.I. Dunlap, J.W.D. Connolly and J.R. Sabin, J. Chem. Phys. **71**, 4993 (1979)

```
[becke88 [nonlocal] <real prefactor default 1.0>] \
[xperdew91 [nonlocal] <real prefactor default 1.0>] \
[xpbe96 [nonlocal] <real prefactor default 1.0>] \
[gill96 [nonlocal] <real prefactor default 1.0>] \
[lyp <real prefactor default 1.0>] \
[perdew81 <real prefactor default 1.0>] \
[perdew86 [nonlocal] <real prefactor default 1.0>] \
[perdew91 [nonlocal] <real prefactor default 1.0>] \
[cpbe96 [nonlocal] <real prefactor default 1.0>] \
[pw91lda <real prefactor default 1.0>] \
[slater <real prefactor default 1.0>] \
[vwn_1 <real prefactor default 1.0>] \
[vwn_2 <real prefactor default 1.0>] \
[vwn_3 <real prefactor default 1.0>] \
[vwn_4 <real prefactor default 1.0>] \
[vwn_5 <real prefactor default 1.0>] \
[vwn_1_rpa <real prefactor default 1.0>]]
```

The user has the option of specifying the exchange-correlation treatment in the DFT Module (see table 11.1). The default exchange-correlation functional is defined as the local density approximation (LDA) for closed shell systems and its counterpart the local spin-density (LSD) approximation for open shell systems. Within this approximation the exchange functional is the Slater $\rho^{1/3}$ functional (from J.C. Slater, *Quantum Theory of Molecules and Solids, Vol. 4: The Self-Consistent Field for Molecules and Solids* (McGraw-Hill, New York, 1974)), and the correlation functional is the Vosko-Wilk-Nusair (VWN) functional (functional V) (S.J. Vosko, L. Wilk and M. Nusair, Can. J. Phys. **58**, 1200 (1980)). The parameters used in this formula are obtained by fitting to the Ceperley and Alder[2] Quantum Monte-Carlo solution of the *homogeneous electron gas*.

These defaults can be invoked explicitly by specifying the following keywords within the DFT module input directive, `XC slater vwn_5`.

That is, this statement in the input file

```
dft
  XC slater vwn_5
end
task dft
```

is equivalent to the simple line

```
task dft
```

The `DECOMP` directive causes the components of the energy corresponding to each functional to be printed, rather than just the total exchange-correlation energy which is the default. You can see an example of this directive in the sample input in Section 11.5.

Many alternative exchange and correlation functionals are available to the user as listed in table 11.1. The following sections describe how to use these options.

[2]D.M. Ceperley and B.J. Alder, Phys. Rev. Lett. **45**, 566 (1980).

11.3.1 Exchange-Correlation Functionals

There are several Exchange and Correlation functionals in addition to the default `slater` and `vwn_5` functionals. These are either local or gradient-corrected functionals (GCA); a full list can be found in table 11.1.

The Hartree-Fock exact exchange functional, (which has $O(N^4)$ computation expense), is invoked by specifying

```
XC HFexch
```

Note that the user also has the ability to include only the local or nonlocal contributions of a given functional. In addition the user can specify a multiplicative prefactor (the variable `<prefactor>` in the input) for the local/nonlocal component or total. An example of this might be,

```
XC becke88 nonlocal 0.72
```

The user should be aware that the Becke88 local component is simply the Slater exchange and should be input as such.

Any combination of the supported exchange functional options can be used. For example the popular Gaussian B3 exchange could be specified as:

```
XC slater 0.8 becke88 nonlocal 0.72 HFexch 0.2
```

Any combination of the supported correlation functional options can be used. For example B3LYP could be specified as:

```
XC vwn_1_rpa 0.19 lyp 0.81 HFexch 0.20  slater 0.80 becke88 nonlocal 0.72
```

and X3LYP as:

```
xc vwn_1_rpa 0.129 lyp 0.871 hfexch 0.218 slater 0.782 \
becke88 nonlocal 0.542  xperdew91 nonlocal 0.167
```

11.3.2 Combined Exchange and Correlation Functionals

In addition to the options listed above for the exchange and correlation functionals, the user has the alternative of specifying combined exchange and correlation functionals. A complete list of the available functionals appears in table 11.1.

The available hybrid functionals (where a Hartree-Fock Exchange component is present) consist of the Becke "*half and half*" (see A.D. Becke, J. Chem. Phys. 98, 1372 (1992)), the adiabatic connection method (see A.D. Becke, J. Chem. Phys. 98, 5648 (1993)), B3LYP (popularized by Gaussian9X), Becke 1997 ("Becke V" paper: A.D.Becke, J. Chem. Phys., **107**, 8554 (1997)).

The keyword `beckehandh` specifies that the exchange-correlation energy will be computed as

$$E_{XC} \approx \frac{1}{2}E_X^{\mathrm{HF}} + \frac{1}{2}E_X^{\mathrm{Slater}} + \frac{1}{2}E_C^{\mathrm{PW91LDA}}$$

We know this is NOT the correct Becke prescribed implementation which requires the XC potential in the energy expression. But this is what is currently implemented as an approximation to it.

The keyword `acm` specifies that the exchange-correlation energy is computed as

$$\begin{aligned} E_{XC} &= a_0 E_X^{\mathrm{HF}} + (1-a_0)E_X^{\mathrm{Slater}} + a_X \Delta E_X^{\mathrm{Becke88}} + E_C^{\mathrm{VWN}} + a_C \Delta E_C^{Perdew91} \\ &\quad \text{where} \\ a_0 &= 0.20,\ a_X = 0.72,\ a_C = 0.81 \end{aligned}$$

and Δ stands for a non-local component.

The keyword `b3lyp` specifies that the exchange-correlation energy is computed as

$$\begin{aligned} E_{XC} &= a_0 E_X^{\mathrm{HF}} + (1-a_0)E_X^{\mathrm{Slater}} + a_X \Delta E_X^{\mathrm{Becke88}} + (1-a_C)E_C^{\mathrm{VWN_1_RPA}} + a_C E_C^{LYP} \\ &\quad \text{where} \\ a_0 &= 0.20,\ a_X = 0.72,\ a_C = 0.81 \end{aligned}$$

11.3.3 Meta-GGA Functionals

One way to calculate meta-GGA energies is to use orbitals and densities from fully self-consistent GGA or LDA calculations and run them in one iteration in the meta-GGA functional. It is expected that meta-GGA energies obtained this way will be close to fully self consistent meta-GGA calculations.

It is possible to calculate metaGGA energies both ways in NWChem, that is, self-consistently or with GGA/LDA orbitals and densities. However, since second derivatives are not available for metaGGAs, in order to calculate frequencies, one must use `task dft freq numerical`. A sample file with this is shown below, in 11.5. In this instance, the energy is calculated self-consistently and geometry is optimized using the analytical gradients.

(For more information on metaGGAs, see S. Kurth, J. Perdew, P. Blaha, Int. J. Quant. Chem 75, 889 (1999) for a brief description of meta-GGAs, and citations 14-27 therein for thorough background)

Note: both TPSS and PKZB correlation require the PBE GGA CORRELATION (which is itself dependent on an LDA). The decision has been made to use these functionals with the accompanying local PW91LDA. The user does not have the ability to set the local part of these metaGGA functionals.

11.4 LB94 and CS00 — Asymptotic correction

The keyword `LB94` will correct the asymptotic region of the `XC` definition of exchange-correlation *potential* by the van-Leeuwen–Baerends exchange-correlation *potential* that has the correct $-1/r$ asymptotic behavior. The total energy will be computed by the `XC` definition of exchange-correlation functional. This scheme is known to tend to overcorrect the deficiency of most uncorrected exchange-correlation potentials.

The keyword `CS00`, when supplied with a real value of shift (in atomic units), will perform Casida–Salahub '00 asymptotic correction. This is primarily intended for use in conjunction with TDDFT and the background of this method is given in more detail in Chapter 14. The shift is normally positive (which means that the original uncorrected exchange-correlation potential must be shifted down).

When the keyword `CS00` is specified without the value of shift, the program will automatically supply it according to the semi-empirical formula of Zhan, Nichols, and Dixon (again, see Chapter 14 for more details and references). As the Zhan's formula is calibrated against B3LYP results, it is most meaningful to use this in conjunction with the B3LYP functional, although the program does not prohibit (or even warn) the use of any other functional.

Sample input files of asymptotically corrected TDDFT calculations can be found in Chapter 14.

11.5 Sample input file

A simple example calculates the geometry of water, using the metaGGA functionals `xtpss03` and `ctpss03`. This also highlights some of the print features in the DFT module. Note that you must use the line `task dft freq numerical` because analytic hessians are not available for the metaGGAs:

```
title "WATER 6-311G* meta-GGA XC geometry"
echo
geometry units angstroms
  O       0.0  0.0  0.0
  H       0.0  0.0  1.0
  H       0.0  1.0  0.0
end
basis
  H library 6-311G*
  O library 6-311G*
end
dft
 iterations 50
 print  kinetic_energy
 xc xtpss03 ctpss03
 decomp
end
task dft optimize

task dft freq numerical
```

1. J.C. Slater and K. H. Johnson, Phys. Rev. B **5**, 844 (1972)
2. S.J. Vosko, L. Wilk and M. Nusair, Can. J. Phys. **58**, 1200 (1980)
3. J. P. Perdew and A. Zunger, Phys. Rev. B **23**, 5048 (1981).
4. J.P. Perdew and Y. Wang, Phys. Rev. B **45**, 13244 (1992)
5. A.D. Becke, Phys. Rev. A **88**, 3098 (1988)
6. J.P. Perdew, J.A. Chevary, S.H. Vosko, K.A. Jackson, M.R. Pederson, D.J. Singh and C. Fiolhais, Phys. Rev. B **46**, 6671 (1992)
7. J.P. Perdew, K. Burke and M. Ernzerhof, Phys. Rev. Lett. **77**, 3865 (1996); **78** , 1396 (1997)
8. P.W.Gill , Mol. Phys. **89**, 433 (1996)
9. J. P. Perdew, Phys. Rev. B **33**, 8822 (1986)
10. C. Lee, W. Yang and R. G. Parr, Phys. Rev. B **37**, 785 (1988)
11. F.A.Hamprecht, A.J.Cohen, D.J.Tozer and N.C Handy, J. Chem. Phys. **109**, 6264 (1998)
12. A.D.Boese, N.L.Doltsinis, N.C.Handy and M.Sprik. J. Chem. Phys. **112**, 1670 (2000)
13. A.D. Becke, J. Chem. Phys. **98**, 1372 (1992)
14. A.D. Becke, J. Chem. Phys. **98**, 5648 (1993)
15. A.D.Becke, J. Chem. Phys. **107**, 8554 (1997)
16. H.L.Schmider and A.D. Becke, J. Chem. Phys. **108**, 9624 (1998)
17. C.Adamo and V.Barone, J. Chem. Phys. **110**, 6158 (1998)
18. A.J.Cohen and N.C. Handy, Chem. Phys. Lett. **316**, 160 (2000)
19. A.D.Boese, N.C.Handy, J. Chem. Phys. **114**, 5497 (2001)
20. N.C.Handy, A.J. Cohen, Mol. Phys. **99**, 403 (2001)
21. G. Menconi, P.J. Wilson, D.J. Tozer, J. Chem. Phys **114**, 3958 (2001)
22. P.J. Wilson, T.J. Bradley, D.J. Tozer, J. Chem. Phys **115**, 9233 (2001)
23. C. Adamo and V. Barone, J. Chem. Phys. **108**, 664 (1998); Y. Zhao and D.G. Truhlar, J. Phys. Chem. A **109**, 5656 (2005)
24. M.Filatov and W.Thiel, Mol.Phys. **91**, 847 (1997). M.Filatov and W.Thiel, Int.J.Quantum Chem. **62**, 603 (1997)
25. B.J. Lynch, P.L. Fast, M. Harris and D.G. Truhlar, J. Phys. Chem. A **104**, 4811(2000)
26. J.P. Perdew, S. Kurth, A. Zupan and P. Blaha, Phys. Rev. Lett. **82**, 2544 (1999)
27. A. D. Boese, A. Chandra, J. M. L. Martin and D. Marx, J. Chem. Phys. **119**, 5965 (2003)
28. J. Tao,J.Perdew, V. Staroverov and G. Scuseria, Phys. Rev. Let. **91**, 146401-1 (2003)
29. V. Staroverov, G. Scuseria, J. Tao and J.Perdew, J. Chem.Phys. **119**, 12129 (2003)
30. T.W. Keal, D.J. Tozer, J. Chem. Phys **123**, 121103 (2005)
31. T. Tsuneda, T. Suzumura and K. Hirao, J. Chem Phys. **110**, 10664 (1999)

Keyword	X	C	GGA	Meta	Hybr.	2nd	Ref.
slater	⋆					Y	[1]
vwn_1		⋆				Y	[2]
vwn_2		⋆				Y	[2]
vwn_3		⋆				Y	[2]
vwn_4		⋆				Y	[2]
vwn_5		⋆				Y	[2]
vwn_1_rpa		⋆				Y	[2]
perdew81		⋆				Y	[3]
pw91lda		⋆				Y	[4]
becke88	⋆		⋆			Y	[5]
xperdew91	⋆		⋆			Y	[6]
xpbe96	⋆		⋆			Y	[7]
gill96	⋆		⋆			Y	[8]
optx	⋆		⋆			N	[20]
mpw91	⋆		⋆			Y	[23]
xft97	⋆		⋆			N	[24]
rpbe	⋆		⋆			Y	[33]
revpbe	⋆		⋆			Y	[34]
xpw6b95	⋆		⋆			N	[36]
xpwb6k	⋆		⋆			N	[36]
perdew86		⋆	⋆			Y	[9]
lyp		⋆	⋆			Y	[10]
perdew91		⋆	⋆			Y	[6]
cpbe96		⋆	⋆			Y	[7]
cft97		⋆	⋆			N	[24]
op		⋆	⋆			N	[31]
hcth	⋆	⋆	⋆			N	[11]
hcth120	⋆	⋆	⋆			N	[12]
hcth147	⋆	⋆	⋆			N	[12]
hcth407	⋆	⋆	⋆			N	[19]
becke97gga1	⋆	⋆	⋆			N	[18]
hcthp14	⋆	⋆	⋆			N	[21]
ft97	⋆	⋆	⋆			N	[24]
htch407p	⋆	⋆	⋆			N	[27]
bop	⋆	⋆	⋆			N	[31]
pbeop	⋆	⋆	⋆			N	[32]
xpkzb99	⋆			⋆		N	[26]
cpkzb99		⋆		⋆		N	[26]
xtpss03	⋆			⋆		N	[28]
ctpss03		⋆		⋆		N	[28]
bc95		⋆		⋆		N	[33]
cpw6b95		⋆		⋆		N	[36]
cpwb6k		⋆		⋆		N	[36]
xm05	⋆			⋆		N	[37]
cm05		⋆		⋆		N	[37]
xm05-2x	⋆			⋆		N	[38]
cm05-2x		⋆		⋆		N	[38]
xctpssh				⋆	⋆	N	[28]
bb1k				⋆	⋆	N	[34]
mpw1b95				⋆	⋆	N	[35]
mpwb1k				⋆	⋆	N	[35]
pw6b95				⋆	⋆	N	[36]
pwb6k				⋆	⋆	N	[36]
m05				⋆	⋆	N	[37]
vsxc				⋆	⋆	N	[39]
xvsxc	⋆			⋆		N	[39]
cvsxc		⋆		⋆		N	[39]
m06-L	⋆	⋆		⋆	⋆	N	[40]
xm06-L				⋆		N	[40]
cm06-L		⋆		⋆		N	[40]
m06-hf				⋆	⋆	N	[41]
xm06-hf	⋆			⋆		N	[41]
cm06-hf		⋆		⋆		N	[41]
m06				⋆	⋆	N	[42]
xm06	⋆			⋆		N	[42]
cm06		⋆		⋆		N	[42]
m06-2x				⋆	⋆	N	[42]
xm06-2x	⋆			⋆		N	[42]
cm06-2x		⋆		⋆		N	[42]
beckehandh	⋆	⋆			⋆	Y	[13]
b3lyp	⋆	⋆	⋆		⋆	Y	[14]
acm	⋆	⋆	⋆		⋆	Y	[14]
becke97	⋆	⋆	⋆		⋆	N	[15]
becke97-1	⋆	⋆	⋆		⋆	N	[15]
becke97-2	⋆	⋆	⋆		⋆	N	[22]
becke97-3	⋆	⋆	⋆		⋆	N	[30]
becke98	⋆	⋆	⋆		⋆	N	[16]
pbe0	⋆	⋆	⋆		⋆	Y	[17]
mpw1k	⋆	⋆	⋆		⋆	Y	[25]

Table 11.1: Table of available Exchange (X) and Correlation (C) functionals. GGA is the Generalized Gradient Approximation, and Meta refers to Meta-GGAs. The column *2nd* refers to second derivatives of the energy with respect to nuclear position.

32. T. Tsuneda, T. Suzumura and K. Hirao, J. Chem Phys. **111**, 5656 (1999)
33. B. Hammer, L. B. Hansen and J. Nørskov , Phys. Rev. B **58**, 7413 (1999)
34. Y. Zhang and W. Yang, Phys. Rev. Letters **80**, 890 (1998)
35. A. D. Becke, J. Chem. Phys. **104**, 1040 (1996)
36. Y. Zhao and D. G. Truhlar, J. Phys. Chem. A **108**, 2715 (2004)
37. Y. Zhao and D. G. Truhlar, J. Phys. Chem. A **108**, 6908 (2004)
38. Y. Zhao and D. G. Truhlar, J. Phys. Chem. A **109**, 5656 (2005)
39. Y. Zhao, N. E. Schultz and D. G. Truhlar, J. Chem. Phys. **123**, 161103 (2005)
40. Y. Zhao, N. E. Schultz and D. G. Truhlar, J. Chem. Theory Comput. **2**, 364 (2006)
41. T. Van Voorhis, G. E. Scuseria, J. Chem. Phys. **109**, 400 (1998)
42. Y. Zhao, D. G. Truhlar, J. Chem. Phys. **125**, 194101 (2006)
43. Y. Zhao, D. G. Truhlar, J. Phys. Chem. A. **110**, 13126 (2006)
44. Y. Zhao, D. G. Truhlar, Theor. Chem. Acc. (2006)

11.6 ITERATIONS — Number of SCF iterations

```
ITERATIONS <integer iterations default 30>
```

The default optimization in the DFT module is to iterate on the Kohn-Sham (SCF) equations for a specified number of iterations (default 30). The keyword that controls this optimization is ITERATIONS, and has the following general form,

```
iterations <integer iterations default 30>
```

The optimization procedure will stop when the specified number of iterations is reached or convergence is met. See an example that uses this directive in section 11.5.

11.7 CONVERGENCE — SCF Convergence Control

```
CONVERGENCE [energy <real energy default 1e-6>] \
            [density <real density default 1e-5>] \
            [gradient <real gradient default 5e-4>] \
            [hl_tol <real hl_tol default 0.1>]
            [dampon <real dampon default 0.0>] \
            [dampoff <real dampoff default 0.0>] \
            [ncydp <integer ncydp default 2>] \
            [ncyds <integer ncyds default 30>] \
            [ncysh <integer ncysh default 30>] \
            [damp <integer ndamp default 0>] [nodamping] \
            [diison <real diison default 0.0>] \
            [diisoff <real diisoff default 0.0>] \
            [(diis [nfock <integer nfock default 10>]) || nodiis] \
            [levlon <real levlon default 0.0>] \
            [levloff <real levloff default 0.0>] \
            [(lshift <real lshift default 0.5>) || nolevelshifting] \
            [rabuck [n_rabuck <integer n_rabuck default 25>]]
```

Convergence is satisfied by meeting any or all of three criteria;

- convergence of the total energy; this is defined to be when the total DFT energy at iteration N and at iteration N-1 differ by a value less than some value (the default is 1e-6). This value can be modified using the key word,

  ```
  CONVERGENCE energy <real energy default 1e-6>
  ```

- convergence of the total density; this is defined to be when the total DFT density matrix at iteration N and at iteration N-1 have a RMS difference less than some value (the default is 1e-5). This value can be modified using the key word,

  ```
  CONVERGENCE density <real density default 1e-5>
  ```

- convergence of the orbital gradient; this is defined to be when the DIIS error vector becomes less than some value (the default is 5e-4). This value can be modified using the key word,

```
CONVERGENCE gradient <real gradient default 5e-4>
```

The default optimization strategy is to immediately begin direct inversion of the iterative subspace[3]. Damping is also initiated (using 70% of the previous density) for the first 2 iteration. In addition, if the HOMO - LUMO gap is small and the Fock matrix somewhat diagonally dominant, then level-shifting is automatically initiated. There are a variety of ways to customize this procedure to whatever is desired.

An alternative optimization strategy is to specify, by using the change in total energy (from iterations when N and N-1), when to turn damping, level-shifting, and/or DIIS on/off. Start and stop keywords for each of these is available as,

```
CONVERGENCE  [dampon <real dampon default 0.0>] \
             [dampoff <real dampoff default 0.0>] \
             [diison <real diison default 0.0>] \
             [diisoff <real diisoff default 0.0>] \
             [levlon <real levlon default 0.0>] \
             [levloff <real levloff default 0.0>]
```

So, for example, damping, DIIS, and/or level-shifting can be turned on/off as desired.

Another strategy can be to simply specify how many iterations (cycles) you wish each type of procedure to be used. The necessary keywords to control the number of damping cycles (ncydp), the number of DIIS cycles (ncyds), and the number of level-shifting cycles (ncysh) are input as,

```
CONVERGENCE  [ncydp <integer ncydp default 2>] \
             [ncyds <integer ncyds default 30>] \
             [ncysh <integer ncysh default 0>]
```

The amount of damping, level-shifting, time at which level-shifting is automatically imposed, and Fock matrices used in the DIIS extrapolation can be modified by the following keywords

```
CONVERGENCE  [damp <integer ndamp default 0>] \
             [diis [nfock <integer nfock default 10>]] \
             [lshift <real lshift default 0.5>] \
             [hl_tol <real hl_tol default 0.1>]]
```

Damping is defined to be the percentage of the previous iterations density mixed with the current iterations density. So, for example

```
CONVERGENCE damp 70
```

would mix 30% of the current iteration density with 70% of the previous iteration density.

Level-Shifting[4] is defined as the amount of shift applied to the diagonal elements of the unoccupied block of the Fock matrix. The shift is specified by the keyword `lshift`. For example the directive,

```
CONVERGENCE lshift 0.5
```

causes the diagonal elements of the Fock matrix corresponding to the virtual orbitals to be shifted by 0.5 a.u. By default, this level-shifting procedure is switched on whenever the HOMO-LUMO gap is small. Small

[3] P. Pulay, Chem. Phys. Lett. **73**, 393 (1980) and P. Pulay, J. Comp. Chem. **3**, 566 (1982)

[4] M.F. Guest and V.R. Saunders, Mol. Phys. **28**, 819 (1974)

is defined by default to be 0.05 au but can be modified by the directive `hl_tol`. An example of changing the HOMO-LUMO gap tolerance to 0.01 would be,

```
CONVERGENCE hl_tol 0.01
```

Direct inversion of the iterative subspace with extrapolation of up to 10 Fock matrices is a default optimization procedure. For large molecular systems the amount of available memory may preclude the ability to store this number of N**2 arrays in global memory. The user may then specify the number of Fock matrices to be used in the extrapolation (must be greater than three (3) to be effective). To set the number of Fock matrices stored and used in the extrapolation procedure to 3 would take the form,

```
CONVERGENCE diis 3
```

The user has the ability to simply turn off any optimization procedures deemed undesirable with the obvious keywords,

```
CONVERGENCE [nodamping] [nodiis] [nolevelshifting]
```

For systems where the initial guess is very poor, the user can try the method described in [5] that makes use of **fractional occupation** of the orbital levels during the initial cycles of the SCF convergence. The input has the following form

```
CONVERGENCE rabuck [n_rabuck <integer n_rabuck default 25>]]
```

where the optional value `n_rabuck` determines the number of SCF cycles during which the method will be active. For example, to set equal to 30 the number of cycles where the Rabuck method is active, you need to use the following line

```
CONVERGENCE rabuck 30
```

11.8 CDFT — Constrained DFT

This option enables the constrained DFT formalism by Wu and Van Voorhis described in the paper: Q. Wu, T. Van Voorhis, Phys. Rev. A **72**, 024502 (2005).

```
CDFT <integer fatom1 latom1> [<integer fatom2 latom2>] (charge||spin <real constaint_value>) \
     [pop (becke||mulliken||lowdin) default lowdin]
```

Variables fatom1 and latom1 define the first and last atom of the group of atoms to which the constaint will be applied. Therefore the atoms in the same group should be placed continuously in the geometry input. If fatom2 and latom2 are specified, the difference between group 1 and 2 (i.e. 1-2) is constrained.

The constraint can be either on the charge or the spin density (# of alpha - beta electrons) with a user specified constaint_value. Note: No gradients have been implemented for the spin constaints case. Geometry optimizations can only be performed using the charge constaint.

[5] A. D. Rabuck and G. E. Scuseria, J. Chem. Phys **110**,695 (1999)

To calculate the charge or spin density, the Becke, Mulliken, and Lowdin population schemes can be used. The Lowdin scheme is default while the Mulliken scheme is not recommended. If basis sets with many diffuse functions are used, the Becke population scheme is recommended.

Multiple constaints can be defined simultaniously by defining multiple `cdft` lines in the input. The same population scheme will be used for all constaints and only needs to be specified once. If multiple population options are defined, the last one will be used. When there are convergence problems with multiple constaints, the user is advised to do one constraint first and to use the resulting orbitals for the next step of the constained calculations.

It is best to put "convergence nolevelshifting" in the dft directive to avoid issues with gradient calculations and convergence in CDFT. Use orbital swap to get a broken-symmetry solution.

An input example is given below.

```
geometry
symmetry
C  0.0  0.0  0.0
O  1.2  0.0  0.0
C  0.0  0.0  2.0
O  1.2  0.0  2.0
end

basis
* library 6-31G*
end

dft
 xc b3lyp
 convergence nolevelshifting
 odft
 mult 1
 vectors swap beta 14 15
 cdft 1 2 charge 1.0
end
task dft
```

11.9 SMEAR — Fractional Occupation of the Molecular Orbitals

The **SMEAR** keyword is useful in cases with many degenerate states near the HOMO (eg metallic clusters)

```
SMEAR <real smear default 0.001>
```

This option allows fractional occupation of the molecular orbitals. A Gaussian broadening function of exponent `smear` is used as described in the paper: R.W. Warren and B.I. Dunlap, Chem. Phys. Letters **262**, 384 (1996).
The user must be aware that an additional energy term is added to the total energy in order to have energies and gradients consistent.

11.10 GRID — Numerical Integration of the XC Potential

```
GRID [(xcoarse||coarse||medium||fine||xfine) default medium] \
     [(gausleg||lebedev ) default lebedev ] \
     [(becke||erf1||erf2||ssf) default erf1] \
     [(euler||mura||treutler) default mura] \
     [rm <real rm default 2.0>] \
     [nodisk]
```

A numerical integration is necessary for the evaluation of the exchange-correlation contribution to the density functional. The default quadrature used for the numerical integration is an Euler-MacLaurin scheme for the radial components (with a modified Mura-Knowles transformation) and a Lebedev scheme for the angular components. Within this numerical integration procedure various levels of accuracy have been defined and are available to the user. The user can specify the level of accuracy with the keywords; xcoarse, coarse, medium, fine, and xfine. The default is medium.

```
GRID [xcoarse||coarse||medium||fine||xfine]
```

Our intent is to have a numerical integration scheme which would give us approximately the accuracy defined below regardless of molecular composition.

Keyword	Total Energy Target Accuracy
xcoarse	$1x10^{-4}$
coarse	$1x10^{-5}$
medium	$1x10^{-6}$
fine	$1x10^{-7}$
xfine	$1x10^{-8}$

In order to determine the level of radial and angular quadrature needed to give us the target accuracy we computed total DFT energies at the LDA level of theory for many homonuclear atomic, diatomic and triatomic systems in rows 1-4 of the periodic table. In each case all bond lengths were set to twice the Bragg-Slater radius. The total DFT energy of the system was computed using the converged SCF density with atoms having radial shells ranging from 35-235 (at fixed 48/96 angular quadratures) and angular quadratures of 12/24-48/96 (at fixed 235 radial shells). The error of the numerical integration was determined by comparison to a "best" or most accurate calculation in which a grid of 235 radial points 48 theta and 96 phi angular points on each atom was used. This corresponds to approximately 1 million points per atom. The following tables were empirically determined to give the desired target accuracy for DFT total energies. These tables below show the number of radial and angular shells which the DFT module will use for for a given atom depending on the row it is in (in the periodic table) and the desired accuracy. Note, differing atom types in a given molecular system will most likely have differing associated numerical grids. The intent is to generate the desired energy accuracy (with utter disregard for speed).

Table 11.2: Program default number of radial and angular shells empirically determined for Row 1 atoms (Li → F) to reach the desired accuracies.

Keyword	Radial	Angular
xcoarse	21	194
coarse	35	302
medium	49	434
fine	70	590
xfine	100	1202

Table 11.3: Program default number of radial and angular shells empirically determined for Row 2 atoms (Na → Cl) to reach the desired accuracies.

Keyword	Radial	Angular
xcoarse	42	194
coarse	70	302
medium	88	434
fine	123	770
xfine	125	1454

Table 11.4: Program default number of radial and angular shells empirically determined for Row 3 atoms (K → Br) to reach the desired accuracies.

Keyword	Radial	Angular
xcoarse	75	194
coarse	95	302
medium	112	590
fine	130	974
xfine	160	1454

Table 11.5: Program default number of radial and angular shells empirically determined for Row 4 atoms (Rb → I) to reach the desired accuracies.

Keyword	Radial	Angular
xcoarse	84	194
coarse	104	302
medium	123	590
fine	141	974
xfine	205	1454

11.10.1 Angular grids

In addition to the simple keyword specifying the desired accuracy as described above, the user has the option of specifying a custom quadrature of this type in which ALL atoms have the same grid specification. This is accomplished by using the `gausleg` keyword.

Gauss-Legendre angular grid

```
GRID gausleg <integer nradpts default 50> <integer nagrid default 10>
```

In this type of grid, the number of phi points is twice the number of theta points. So, for example, a specification of,

```
GRID gausleg 80 20
```

would be interpreted as 80 radial points, 20 theta points, and 40 phi points per center (or 64000 points per center before pruning).

Lebedev angular grid A second quadrature is the Lebedev scheme for the angular components[6]. Within this numerical integration procedure various levels of accuracy have also been defined and are available to the user. The input for this type of grid takes the form,

```
GRID lebedev <integer radpts > <integer iangquad >
```

In this context the variable iangquad specifies a certain number of angular points as indicated by the table below.[7] Therefore the user can specify any number of radial points along with the level of angular quadrature (1-29).

The user can also specify grid parameters specific for a given atom type: parameters that must be supplied are: atom tag and number of radial points. As an example, here is a grid input line for the water molecule

```
grid lebedev 80 11 H 70 8  O 90 11
```

[6] The subroutine for the Lebedev grid was derived from a routine supplied by M. Causà of the University of Torino and from the grid points supplied by D.N. Laikov from Moscow State University.

[7] V.I. Lebedev and D.N. Laikov, Doklady Mathematics **366**, 741 (1999).

$IANGQUAD$	$N_{angular}$	l
1	38	9
2	50	11
3	74	13
4	86	15
5	110	17
6	146	19
7	170	21
8	194	23
9	230	25
10	266	27
11	302	29
12	350	31
13	434	35
14	590	41
15	770	47
16	974	53
17	1202	59
18	1454	65
19	1730	71
20	2030	77
21	2354	83
22	2702	89
23	3074	95
24	3470	101
25	3890	107
26	4334	113
27	4802	119
28	5294	125
29	5810	131

Table 11.6: List of Lebedev quadratures

11.10.2 Partitioning functions

```
GRID [(becke||erf1||erf2||ssf) default erf1]
```

`becke` A. D. Becke, J. Chem. Phys. **88**, 1053 (1988).

`ssf` R.E.Stratmann, G.Scuseria and M.J.Frisch, Chem. Phys. Lett. **257**, 213 (1996).

`erf1` modified ssf

`erf2` modified ssf

Erf$n$ partioning functions

$$
\begin{aligned}
w_A(r) &= \prod_{B \neq A} \frac{1}{2}[1 - erf(\mu'_{AB})] \\
\mu'_{AB} &= \frac{1}{\alpha} \frac{\mu_{AB}}{(1-\mu_{AB}^2)^n} \\
\mu_{AB} &= \frac{\mathbf{r}_A - \mathbf{r}_B}{|\mathbf{r}_A - \mathbf{r}_B|}
\end{aligned}
$$

11.10.3 Radial grids

```
GRID [[euler||mura||treutler]  default mura]
```

`euler` Euler-McLaurin quadrature wih the transformation devised by C.W. Murray, N.C. Handy, and G.L. Laming, Mol. Phys.**78**, 997 (1993).

`mura` Modification of the Murray-Handy-Laming scheme by M.E.Mura and P.J.Knowles, J Chem Phys **104**, 9848 (1996) (we are not using the scaling factors proposed in this paper).

`treutler` Gauss-Chebyshev using the transformation suggested by O.Treutler and R.Alrhichs, J.Chem.Phys **102**, 346 (1995).

11.10.4 Disk usage for Grid

```
NODISK
```

This keyword turns off storage of grid points and weights on disk.

11.11 TOLERANCES — Screening tolerances

```
TOLERANCES [[tight] [tol_rho <real tol_rho default 1e-10>] \
            [accCoul <integer accCoul default 8>] \
            [radius <real radius default 25.0>]]
```

The user has the option of controlling screening for the tolerances in the integral evaluations for the DFT module. In most applications, the default values will be adequate for the calculation, but different values can be specified in the input for the DFT module using the keywords described below.

The input parameter `accCoul` is used to define the tolerance in Schwarz screening for the Coulomb integrals. Only integrals with estimated values greater than $10^{(-\texttt{accCoul})}$ are evaluated.

```
TOLERANCES accCoul <integer accCoul default 8>
```

Screening away needless computation of the XC functional (on the grid) due to negligible density is also possible with the use of,

```
TOLERANCES tol_rho <real tol_rho default 1e-10>
```

XC functional computation is bypassed if the corresponding density elements are less than `tol_rho`.

A screening parameter, `radius`, used in the screening of the Becke or Delley spatial weights is also available as,

```
TOLERANCES radius <real radius default 25.0>
```

where radius is the cutoff value in bohr.

The tolerances as discussed previously are insured at convergence. More sleazy tolerances are invoked early in the iterative process which can speed things up a bit. This can also be problematic at times because it introduces a discontinuity in the convergence process. To avoid use of initial sleazy tolerances the user can invoke the `tight` option:

```
TOLERANCES tight
```

This option sets all tolerances to their default/user specified values at the very first iteration.

11.12 `DIRECT` and `NOIO` — Hardware Resource Control

```
DIRECT||INCORE
NOIO
```

The inverted charge-density and exchange-correlation matrices for a DFT calculation are normally written to disk storage. The user can prevent this by specifying the keyword `noio` within the input for the DFT directive. The input to exercise this option is as follows,

```
 noio
```

If this keyword is encountered, then the two matrices (inverted charge-density and exchange-correlation) are computed "on-the-fly" whenever needed.

The `INCORE` option is always assumed to be true but can be overridden with the option `DIRECT` in which case all integrals are computed "on-the-fly".

11.13 ODFT and MULT — Open shell systems

```
ODFT
MULT <integer mult default 1>
```

Both *closed-shell* and *open-shell* systems can be studied using the DFT module. Specifying the keyword MULT within the DFT directive allows the user to define the spin multiplicity of the system. The form of the input line is as follows;

```
MULT <integer mult default 1>
```

When the keyword MULT is specified, the user can define the integer variable mult, where mult is equal to the number of alpha electrons minus beta electrons, plus 1.

The keyword ODFT is unnecessary except in the context of forcing a singlet system to be computed as an open shell system (i.e., using a spin-unrestricted wavefunction).

11.14 SIC — Self-Interaction Correction

```
sic [perturbative || oep || oep-loc <default perturbative>]
```

The Perdew and Zunger (see J. P. Perdew and A. Zunger, Phys. Rev. B 23, 5048 (1981)) method to remove the self-interaction contained in many exchange-correlation functionals has been implemented with the Optimized Effective Potential method (see R. T. Sharp and G. K. Horton, Phys. Rev. **90**, 317 (1953), J. D. Talman and W. F. Shadwick, Phys. Rev. A **14**, 36 (1976)) within the Krieger-Li-Iafrate approximation (J. B. Krieger, Y. Li, and G. J. Iafrate, Phys. Rev. A **45**, 101 (1992); **46**, 5453 (1992); 47, 165 (1993)) Three variants of these methods are included in NWChem:

- `sic perturbative` This is the default option for the sic directive. After a self-consistent calculation, the Kohn-Sham orbitals are localized with the Foster-Boys algorithm (see section 10.15) and the self-interaction energy is added to the total energy. All exchange-correlation functionals implemented in the NWChem can be used with this option.

- `sic oep` With this option the optimized effective potential is built in each step of the self-consistent process. Because the electrostatic potential generated for each orbital involves a numerical integration, this method can be expensive.

- `sic oep-loc` This option is similar to the oep option with the addition of localization of the Kohn-Sham orbitals in each step of the self-consistent process.

With oep and oep-loc options a **xfine grid** (see section 11.10) must be used in order to avoid numerical noise, furthermore the hybrid functionals can not be used with these options. More details of the implementation of this method can be found in J. Garza, J. A. Nichols and D. A. Dixon, J. Chem. Phys. 112, 7880 (2000). The components of the sic energy can be printed out using:

```
print "SIC information"
```

11.15 MULLIKEN — Mulliken analysis

Mulliken analysis of the charge distribution is invoked by the keyword:

```
MULLIKEN
```

When this keyword is encountered, Mulliken analysis of both the input density as well as the output density will occur. For example, to perform a mulliken analysis and print the explicit population analysis of the basis functions, use the following

```
dft
 mulliken
 print "mulliken ao"
end
task dft
```

11.16 BSSE — Basis Set Superposition Error

Particular care is required to compute BSSE by the counter-poise method for the DFT module. In order to include terms deriving from the numerical grid used in the XC integration, the user must label the ghost atoms not just `bq`, but `bq` followed by the given atomic symbol. For example, the first component needed to compute the BSSE for the water dimer, should be written as follows

```
geometry h2o autosym units au
 O        0.00000000     0.00000000     0.22143139
 H        1.43042868     0.00000000    -0.88572555
 H       -1.43042868     0.00000000    -0.88572555
 bqH      0.71521434     0.00000000    -0.33214708
 bqH     -0.71521434     0.00000000    -0.33214708
 bqO      0.00000000     0.00000000    -0.88572555
end

basis
 H library aug-cc-pvdz
 O library aug-cc-pvdz
 bqH library H aug-cc-pvdz
 bqO library O aug-cc-pvdz
end
```

Please note that the "ghost" oxygen atom has been labeled `bqO`, and not just `bq`.

11.17 Print Control

```
PRINT||NOPRINT
```

The `PRINT||NOPRINT` options control the level of output in the DFT. Please see some examples using this directive in section 11.5, a sample input file. Known controllable print options are:

Name	Print Level	Description
"all vector symmetries"	high	symmetries of all molecular orbitals
"alpha partner info"	high	unpaired alpha orbital analysis
"common"	debug	dump of common blocks
"convergence"	default	convergence of SCF procedure
"coulomb fit"	high	fitting electronic charge density
"dft timings"	high	
"final vectors"	high	
"final vector symmetries"	default	symmetries of final molecular orbitals
"information"	low	general information
"initial vectors"	high	
"intermediate energy info"	high	
"intermediate evals"	high	intermediate orbital energies
"intermediate fock matrix"	high	
"intermediate overlap"	high	overlaps between the alpha and beta sets
"intermediate S2"	high	values of S2
"intermediate vectors"	high	intermediate molecular orbitals
"interm vector symm"	high	symmetries of intermediate orbitals
"io info"	debug	reading from and writing to disk
"kinetic_energy"	high	kinetic energy
"mulliken ao"	high	mulliken atomic orbital population
"multipole"	default	moments of alpha, beta, and nuclear charge densities
"parameters"	default	input parameters
"quadrature"	high	numerical quadrature
"schwarz"	high	integral screening info & stats at completion
"screening parameters"	high	integral accuracies
"semi-direct info"	default	semi direct algorithm

Table 11.7: DFT Print Control Specifications

Chapter 12

Spin-Orbit DFT (SODFT)

The spin-orbit DFT module (SODFT) in the NWChem code allows for the variational treatment of the one-electron spin-orbit operator within the DFT framework. The implementation requires the definition of an effective core potential (ECP) and a matching spin-orbit potential (SO). The current implementation does NOT use symmetry.

The actual SODFT calculation will be performed when the input module encounters the `TASK` directive (Section 5.10).

```
TASK SODFT
```

Input parameters are the same as for the DFT, see section 11 for specifications. Some of the DFT options are not available in the SODFT. These are `max_ovl` and `sic`.

Besides using the standard ECP and basis sets, see Section 8 for details, one also has to specify a spin-orbit (SO) potential. The input specification for the SO potential can be found in section 8.2. At this time we have not included any spin-orbit potentials in the basis set library.

Note: One should use a combination of ECP and SO potentials that were designed for the same size core, i.e. don't use a small core ECP potential with a large core SO potential (it will produce erroneous results).

Also, note that charge fitting basis sets will not work with spin-orbit calculations.

The following is an example of a calculation of UO_2:

```
start uo2_sodft
echo

Memory 32 mw

charge 2

geometry noautoz noautosym units angstrom
 U     0.00000      0.00000     0.00000
 O     0.00000      0.00000     1.68000
 O     0.00000      0.00000    -1.68000
end
```

```
basis "ao basis" cartesian print
U    S
        12.12525300         0.02192100
         7.16154500        -0.22516000
         4.77483600         0.56029900
         2.01169300        -1.07120900
U    S
         0.58685200         1.00000000
U    S
         0.27911500         1.00000000
U    S
         0.06337200         1.00000000
U    S
         0.02561100         1.00000000
U    P
        17.25477000         0.00139800
         7.73535600        -0.03334600
         5.15587800         0.11057800
         2.24167000        -0.31726800
U    P
         0.58185800         1.00000000
U    P
         0.26790800         1.00000000
U    P
         0.08344200         1.00000000
U    P
         0.03213000         1.00000000
U    D
         4.84107000         0.00573100
         2.16016200        -0.05723600
         0.57563000         0.23882800
U    D
         0.27813600         1.00000000
U    D
         0.12487900         1.00000000
U    D
         0.05154800         1.00000000
U    F
         2.43644100         0.35501100
         1.14468200         0.40084600
         0.52969300         0.30467900
U    F
         0.24059600         1.00000000
U    F
         0.10186700         1.00000000
O    S
        47.10551800        -0.01440800
         5.91134600         0.12956800
         0.97648300        -0.56311800
O    S
         0.29607000         1.00000000
```

```
O    P
        16.69221900         0.04485600
         3.90070200         0.22261300
         1.07825300         0.50018800
O    P
         0.28418900         1.00000000
O    P
         0.07020000         1.00000000
END

ECP
U nelec 78
  U s
    2          4.06365300        112.92010300
    2          1.88399500         15.64750000
    2          0.88656700         -3.68997100
  U p
    2          3.98618100        118.75801600
    2          2.00016000         15.07722800
    2          0.96084100          0.55672000
  U d
    2          4.14797200         60.85589200
    2          2.23456300         29.28004700
    2          0.91369500          4.99802900
  U f
    2          3.99893800         49.92403500
    2          1.99884000        -24.67404200
    2          0.99564100          1.38948000
O nelec 2
  O s
    2         10.44567000         50.77106900
  O p
    2         18.04517400         -4.90355100
  O d
    2          8.16479800         -3.31212400
END

SO
  U p
  2    3.986181      1.816350
  2    2.000160     11.543940
  2    0.960841      0.794644
  U d
  2    4.147972      0.353683
  2    2.234563      3.499282
  2    0.913695      0.514635
  U f
  2    3.998938      4.744214
  2    1.998840     -5.211731
  2    0.995641      1.867860
END
```

```
dft
  mult 1
  xc hfexch
  odft
  grid fine
  convergence energy 1.000000E-06
  convergence density 1.000000E-05
  convergence gradient 1E-05
  iterations 100
  mulliken
end

task sodft
```

Chapter 13

COSMO

COSMO is the continuum solvation 'COnductor-like Screening MOdel' of A. Klamt and G. Schüürmann to describe dielectric screening effects in solvents.

1. A. Klamt and G. Schüürmann, J. Chem. Soc. Perkin Trans. 2, 1993 799 (1993).

The NWChem COSMO module implements algorithm for calculation of the energy for the following methods:

1. Restricted Hartree-Fock (RHF),
2. Restricted open-shell Hartree-Fock (ROHF),
3. Restricted Kohn-Sham DFT (DFT),
4. Unrestricted Kohn-Sham DFT (ODFT),

by determining the solvent reaction field self-consistently with the solute charge distribution from the respective methods. Note that COSMO for unrestricted Hartree-Fock (UHF) method can also be performed by invoking the DFT module with appropriate keywords.

Correlation energy of solvent molecules may also be evaluated at

1. MP2,
2. CCSD,
3. CCSD+T(CCSD),
4. CCSD(T),

levels of theory. It is cautioned, however, that these correlated COSMO calculations determine the solvent reaction field using the HF charge distribution of the solute rather than the charge distribution of the correlation theory and are not entirely self consistent in that respect. In other words, these calculations assume that the correlation effect and solvation effect are largely additive, and the combination effect thereof is neglected. COSMO for MCSCF has not been implemented yet.

In the current implementation the code calculates the gas-phase energy of the system followed by the solution-phase energy, and returns the electrostatic contribution to the solvation free energy. At the present

gradients are calculated by finite difference of the energy. Known problems include that the code does not work with spherical basis functions. The code does not calculate the non-electrostatic contributions to the free energy, except for the cavitation/dispersion contribution to the solvation free energy, which is computed and printed. It should be noted that one must in general take into account the standard state correction besides the electrostatic and cavitation/dispersion contribution to the solvation free energy, when a comparison to experimental data is made.

Invoking the COSMO solvation model is done by specifying the input COSMO input block with the input options as:

```
cosmo
   [off]
   [dielec  <real dielec default 78.4>]
   [radius  <real atom1>
            <real atom2>
        . . .
            <real atomN>]
   [rsolv   <real rsolv default 0.00>]
   [iscren  <integer iscren default 0>]
   [minbem  <integer minbem default 2>]
   [maxbem  <integer maxbem default 3>]
   [ificos  <integer ificos default 0>]
   [lineq   <integer lineq default 1>]
end
```

followed by the task directive specifying the wavefunction and type of calculation, e.g., `task scf energy`, `task mp2 energy`, `task dft optimize`, etc.

`off` can be used to turn off COSMO in a compound (multiple task) run. By default, once the COSMO solvation model has been defined it will be used in subsequent calculations. Add the keyword `off` if COSMO is not needed in subsequent calculations.

`Dielec` is the value of the dielectric constant of the medium, with a default value of 78.4 (the dielectric constant for water).

`Radius` is an array that specifies the radius of the spheres associated with each atom and that make up the molecule-shaped cavity. Default values are Van der Waals radii. Values are in units of angstroms. The codes uses the following Van der Waals radii by default:

```
      data vdwr(103) /
     1   0.80,0.49,0.00,0.00,0.00,1.65,1.55,1.50,1.50,0.00,
     2   2.30,1.70,2.05,2.10,1.85,1.80,1.80,0.00,2.80,2.75,
     3   0.00,0.00,1.20,0.00,0.00,0.00,2.70,0.00,0.00,0.00,
     4   0.00,0.00,0.00,1.90,1.90,0.00,0.00,0.00,0.00,1.55,
     5   0.00,1.64,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,
     6   0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,
     7   0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,
     8   0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,
     9   0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,
     1   0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,1.65,
     2   0.00,0.00,0.00/
```

with 0.0 values replaced by 1.80. Other radii can be used as well. See for examples:

1. E. V. Stefanovich and T. N. Truong, Chem. Phys. Lett. 244, 65 (1995).

2. V. Barone, M. Cossi, and J. Tomasi, J. Chem. Phys. 107, 3210 (1997).

`Rsolv` is a parameter used to define the solvent accessible surface. See the original reference of Klamt and Schuurmann for a description. The default value is 0.00 (in angstroms).

`Iscren` is a flag to define the dielectric charge scaling option. "`iscren 1`" implies the original scaling from Klamt and Schüürmann, mainly "$(\epsilon - 1)/(\epsilon + 1/2)$", where ϵ is the dielectric constant. "`iscren 0`" implies the modified scaling suggested by Stefanovich and Truong, mainly "$(\epsilon - 1)/\epsilon$". Default is to use the modified scaling. For high dielectric the difference between the scaling is not significant.

The next three parameters define the tesselation of the unit sphere. The approach follows the original proposal by Klamt and Schüürmann. A very fine tesselation is generated from `maxbem` refining passes starting from either an octahedron or an icosahedron. The boundary elements created with the fine tesselation are condensed down to a coarser tesselation based on `minbem`. The induced point charges from the polarization of the medium are assigned to the centers of the coarser tesselation. Default values are "`minbem 2`" and "`maxbem 3`". The flag `ificos` serves to select the original tesselation, "`ificos 0`" for an octahedron (default) and "`ificos 1`" for an icoshedron. Starting from an icosahedron yields a somewhat finer tesselation that converges somewhat faster. Solvation energies are not really sensitive to this choice for sufficiently fine tesselations.

The `lineq` parameter serves to select the numerical algorithm to solve the linear equations yielding the effective charges that represent the polarization of the medium. "`lineq 0`" selects an iterative method (default), "`lineq 1`" selects a dense matrix linear equation solver. For large molecules where the number of effective charges is large, the codes selects the iterative method.

The following example is for a water molecule in 'water', using the HF/6-31G** level of theory:

```
start
echo
 title "h2o"
geometry
o                  .0000000000         .0000000000        -.0486020332
h                  .7545655371         .0000000000         .5243010666
h                 -.7545655371         .0000000000         .5243010666
end
basis segment cartesian
  o library 6-31g**
  h library 6-31g**
end
cosmo
  dielec 78.0
  radius 1.40
         1.16
         1.16
  rsolv  0.50
  lineq  0
end
task scf energy
```

Chapter 14

CIS, TDHF, and TDDFT

14.1 Overview

NWChem supports a spectrum of single excitation theories for vertical excitation energy calculations, namely, configuration interaction singles (CIS),[1] time-dependent Hartree–Fock (TDHF or also known as random-phase approximation RPA), time-dependent density functional theory (TDDFT),[2] and Tamm–Dancoff approximation to TDDFT.[3] These methods are implemented in a single framework that invokes Davidson's trial vector algorithm (or its modification for a non-Hermitian eigenvalue problem).[4] The capabilities of the module are summarized as follows:

- Vertical excitation energies,
- Spin-restricted singlet and triplet excited states for closed-shell systems,
- Spin-unrestricted doublet, etc., excited states for open-shell systems,
- Tamm–Dancoff and full time-dependent linear response theories,
- Davidson's trial vector algorithm,
- Symmetry (irreducible representation) characterization and specification,
- Spin multiplicity characterization and specification,
- Transition moments and oscillator strengths,
- Geometrical first and second derivatives of vertical excitation energies by numerical differentiation,
- Disk-based and fully incore algorithms,
- Multiple and single trial-vector processing algorithms,
- Frozen core and virtual approximation.

[1] J. B. Foreman, M. Head-Gordon, J. A. Pople, and M. J. Frisch, J. Phys. Chem. **96,** 135 (1992).

[2] C. Jamorski, M. E. Casida, and D. R. Salahub, J. Chem. Phys. **104,** 5134 (1996); R. Bauernschmitt and R. Ahlrichs, Chem. Phys. Lett. **256,** 454 (1996); R. Bauernschmitt, M. Häser, O. Treutler, and R. Ahlrichs, Chem. Phys. Lett. **264,** 573 (1997).

[3] S. Hirata and M. Head-Gordon, Chem. Phys. Lett. **314,** 291 (1999).

[4] E. R. Davidson, J. Comput. Phys. **17,** 87 (1975); J. Olsen, H. J. Aa. Jensen, and P. Jørgensen, J. Comput. Phys. **74,** 265 (1988).

New capability added in the latest version (4.6) is:

- Asymptotically correct exchange-correlation potential by van Leeuwen and Baerends,[5]
- Asymptotic correction by Casida and Salahub,[6]
- Asymptotic correction by Hirata, Zhan, Aprà, Windus, and Dixon.[7]

These are very effective way to rectify the shortcomings of TDDFT when applied to Rydberg excited states (see below).

14.2 Performance of CIS, TDHF, and TDDFT methods

The accuracy of CIS and TDHF for excitation energies of closed-shell systems are comparable to each other, and are normally considered a zeroth-order description of the excitation process. These methods are particularly well balanced in describing Rydberg excited states, in contrast to TDDFT. However, for open-shell systems, the errors in the CIS and TDHF excitation energies are often excessive, primarily due to the multi-determinantal character of the ground and excited state wave functions of open-shell systems in a HF reference.[8] The scaling of the computational cost of a CIS or TDHF calculation per state with respect to the system size is the same as that for a HF calculation for the ground state, since the critical step of the both methods are the Fock build, namely, the contraction of two-electron integrals with density matrices. It is usually necessary to include two sets of diffuse exponents in the basis set to properly account for the diffuse Rydberg excited states of neutral species.

The accuracy of TDDFT may vary depending on the exchange-correlation functional. In general, the exchange-correlation functionals that are widely used today and are implemented in NWChem work well for low-lying valence excited states. However, for high-lying diffuse excited states and Rydberg excited states in particular, TDDFT employing these conventional functionals breaks down and the excitation energies are substantially underestimated. This is because of the fact that the exchange-correlation potentials generated from these functionals decay too rapidly (exponentially) as opposed to the slow $-1/r$ asymptotic decay of the true potential. A rough but useful index is the negative of the highest occupied KS orbital energy; when the calculated excitation energies become close to this threshold, these numbers are most likely underestimated relative to experimental results.[9] It appears that TDDFT provides a better-balanced description of radical excited states.[10] This may be traced to the fact that, in DFT, the ground state wave function is represented well as a single KS determinant, with less multi-determinantal character and less spin contamination, and hence the excitation thereof is described well as a simple one electron transition. The computational cost per state of TDDFT calculations scales as the same as the ground state DFT calculations, although the prefactor of the scaling may be much greater in the former.

A very simple and effecive way to rectify the TDDFT's failure for Rydberg excited states has been proposed by Tozer and Handy[11] and by Casida and Salahub (see previous reference). They proposed to splice a $-1/r$ asymptotic tail to an exchange-correlation potential that does not have the correct asymptotic behavior. Because the approximate exchange-correlation potentials are too shallow everywhere, a negative constant must be added to them before they can be spliced to the $-1/r$ tail seamlessly in a region that is not sensitive to chemical effects or to the long-range behavior. The negative constant or the shift is usually taken

[5] R. van Leeuwen and E. J. Baerends, Phys. Rev. A **49,** 2421 (1994).
[6] M. E. Casida, C. Jamorski, K. C. Casida, and D. R. Salahub, J. Chem. Phys. **108,** 4439 (1998).
[7] S. Hirata, C.-G. Zhan, E. Aprà, T. L. Windus, and D. A. Dixon, J. Phys. Chem. A **107,** 10154 (2003).
[8] D. Maurice and M. Head-Gordon, J. Phys. Chem. **100,** 6131 (1996).
[9] M. E. Casida, C. Jamorski, K. C. Casida, and D. R. Salahub, J. Chem. Phys. **108,** 4439 (1998).
[10] S. Hirata and M. Head-Gordon, Chem. Phys. Lett. **302,** 375 (1999).
[11] D. J. Tozer and N. C. Handy, J. Chem. Phys. **109,** 10180 (1998).

to be the difference of the HOMO energy from the true ionization potential, which can be obtained either from experiment or from a ΔSCF calculation. Recently, we proposed a new, expedient, and self-contained asymptotic correction that does not require an ionization potential (or shift) as an external parameter from a separate calculation.[12] In this scheme, the shift is computed by a semi-empirical formula proposed by Zhan, Nichols, and Dixon.[13] Both Casida-Salahub scheme and this new asymptotic correction scheme give considerably improved (Koopmans type) ionization potentials and Rydberg excitation energies. The latter, however, supply the shift by itself unlike to former.

14.3 Input syntax

The module is called TDDFT as TDDFT employing a hybrid HF-DFT functional encompasses all of the above-mentioned methods implemented. To use this module, one needs to specify `TDDFT` on the task directive, e.g.,

```
TASK TDDFT ENERGY
```

for a single-point excitation energy calculation, and

```
TASK TDDFT OPTIMIZE
```

for an excited-state geometry optimization (and perhaps an adiabatic excitation energy calculation), and

```
TASK TDDFT FREQUENCIES
```

for an excited-state vibrational frequency calculation. The TDDFT module first invokes DFT module for a ground-state calculation (regardless of whether the calculations uses a HF reference as in CIS or TDHF or a DFT functional), and hence there is no need to perform a separate ground-state DFT calculation prior to calling a TDDFT task. When no second argument of the task directive is given, a single-point excitation energy calculation will be assumed. For geometry optimizations, it is usually necessary to specify the target excited state and its irreducible representation it belongs to. See the subsections `TARGET` and `TARGETSYM` for more detail.

Individual parameters and keywords may be supplied in the TDDFT input block. The syntax is:

```
TDDFT
  [(CIS||RPA) default RPA]
  [NROOTS <integer nroots default 1>]
  [MAXVECS <integer maxvecs default 1000>]
  [(SINGLET||NOSINGLET) default SINGLET]
  [(TRIPLET||NOTRIPLET) default TRIPLET]
  [THRESH <double thresh default 1e-4>]
  [MAXITER <integer maxiter default 100>]
  [TARGET <integer target default 1>]
  [TARGETSYM <character targetsym default 'none'>]
  [SYMMETRY]
  [ALGORITHM <integer algorithm default 0>]
  [FREEZE [[core] (atomic || <integer nfzc default 0>)] \
```

[12] S. Hirata, C.-G. Zhan, E. Aprà, T. L. Windus, and D. A. Dixon, J. Phys. Chem. A **107,** 10154 (2003).
[13] C.-G. Zhan, J. A. Nichols, and D. A. Dixon, J. Phys. Chem. A **107,** 4184 (2003).

```
          [virtual <integer nfzv default 0>]]
  [PRINT (none||low||medium||high||debug)
    <string list_of_names ...>]
END
```

The user can also specify the reference wave function in the DFT input block (even when CIS and TDHF calculations are requested). See the section of Sample input and output for more details.

Since each keyword has a default value, a minimal input file will be

```
GEOMETRY
Be 0.0 0.0 0.0
END

BASIS
Be library 6-31G**
END

TASK TDDFT ENERGY
```

Note that the keyword for the asymptotic correction must be given in the DFT input block, since all the effects of the correction (and also changes in the computer program) occur in the SCF calculation stage. See Chapter 11 (keyword `CS00` and `LB94`) for details.

14.4 Keywords of `TDDFT` input block

14.4.1 `CIS` and `RPA` — the Tamm–Dancoff approximation

These keywords toggle the Tamm–Dancoff approximation. `CIS` means that the Tamm–Dancoff approximation is used and the CIS or Tamm–Dancoff TDDFT calculation is requested. `RPA`, which is the default, requests TDHF (RPA) or TDDFT calculation.

The performance of CIS (Tamm–Dancoff TDDFT) and RPA (TDDFT) are comparable in accuracy. However, the computational cost is slightly greater in the latter due to the fact that the latter involves a non-Hermitian eigenvalue problem and requires left and right eigenvectors while the former needs just one set of eigenvectors of a Hermitian eigenvalue problem. The latter has much greater chance of aborting the calculation due to triplet near instability or other instability problems.

14.4.2 `NROOTS` — the number of excited states

One can specify the number of excited state roots to be determined. The default value is `1`. It is advised that the users request several more roots than actually needed, since owing to the nature of the trial vector algorithm, some low-lying roots can be missed when they do not have sufficient overlap with the initial guess vectors.

14.4.3 `MAXVECS` — the subspace size

This keyword limits the subspace size of Davidson's algorithm; in other words, it is the maximum number of trial vectors that the calculation is allowed to hold. Typically, 10 to 20 trial vectors are needed for each

excited state root to be converged. However, it need not exceed the product of the number of occupied orbitals and the number of virtual orbitals. The default value is 1000.

14.4.4 SINGLET and NOSINGLET — singlet excited states

SINGLET (NOSINGLET) requests (suppresses) the calculation of singlet excited states when the reference wave function is closed shell. The default is SINGLET.

14.4.5 TRIPLET and NOTRIPLET — triplet excited states

TRIPLET (NOTRIPLET) requests (suppresses) the calculation of triplet excited states when the reference wave function is closed shell. The default is TRIPLET.

14.4.6 THRESH — the convergence threshold of Davidson iteration

This keyword specifies the convergence threshold of Davidson's iterative algorithm to solve a matrix eigenvalue problem. The threshold refers to the norm of residual, namely, the difference between the left-hand side and right-hand side of the matrix eigenvalue equation with the current solution vector. With the default value of 1e-4, the excitation energies are usually converged to 1e-5 hartree.

14.4.7 MAXITER — the maximum number of Davidson iteration

It typically takes 10–30 iterations for the Davidson algorithm to get converged results. The default value is 100.

14.4.8 TARGET and TARGETSYM— the target root and its symmetry

At the moment, the first and second geometrical derivatives of excitation energies that are needed in force, geometry, and frequency calculations are obtained by numerical differentiation. These keywords may be used to specify which excited state root is being used for the geometrical derivative calculation. For instance, when TARGET 3 and TARGETSYM a1g are included in the input block, the total energy (ground state energy plus excitation energy) of the third lowest excited state root (excluding the ground state) transforming as the irreducible representation a1g will be passed to the module which performs the derivative calculations. The default values of these keywords are 1 and none, respectively.

The keyword TARGETSYM is essential in excited state geometry optimization, since it is very common that the order of excited states changes due to the geometry changes in the course of optimization. Without specifying the TARGETSYM, the optimizer could (and would likely) be optimizing the geometry of an excited state that is different from the one the user had intended to optimize at the starting geometry. On the other hand, in the frequency calculations, TARGETSYM must be none, since the finite displacements given in the course of frequency calculations will lift the spatial symmetry of the equilibrium geometry. When these finite displacements can alter the order of excited states including the target state, the frequency calculation is not be feasible.

14.4.9 SYMMETRY — restricting the excited state symmetry

By adding this keyword to the input block, the user can request the module to generate the initial guess vectors transforming as the same irreducible representation as `TARGETSYM`. This causes the final excited state roots be (exclusively) dominated by those with the specified irreducible representation. This may be useful, when the user is interested in just the optically allowed transitions, or in the geometry optimization of an excited state root with a particular irreducible representation. By default, this option is not set. `TARGETSYM` must be specified when `SYMMETRY` is invoked.

14.4.10 ALGORITHM — algorithms for tensor contractions

There are four distinct algorithms to choose from, and the default value of `0` (optimal) means that the program makes an optimal choice from the four algorithms on the basis of available memory. In the order of decreasing memory requirement, the four algorithms are:

- `ALGORITHM 1` : Incore, multiple tensor contraction,
- `ALGORITHM 2` : Incore, single tensor contraction,
- `ALGORITHM 3` : Disk-based, multiple tensor contraction,
- `ALGORITHM 4` : Disk-based, single tensor contraction.

The incore algorithm stores all the trial and product vectors in memory across different nodes with the GA, and often decreases the `MAXITER` value to accommodate them. The disk-based algorithm stores the vectors on disks across different nodes with the DRA, and retrieves each vector one at a time when it is needed. The multiple and single tensor contraction refers to whether just one or more than one trial vectors are contracted with integrals. The multiple tensor contraction algorithm is particularly effective (in terms of speed) for CIS and TDHF, since the number of the direct evaluations of two-electron integrals is diminished substantially.

14.4.11 FREEZE — the frozen core/virtual approximation

Some of the lowest-lying core orbitals and/or some of the highest-lying virtual orbitals may be excluded in the CIS, TDHF, and TDDFT calculations by this keyword (this does not affect the ground state HF or DFT calculation). No orbitals are frozen by default. To exclude the atom-like core regions altogether, one may request

```
FREEZE atomic
```

To specify the number of lowest-lying occupied orbitals be excluded, one may use

```
FREEZE 10
```

which causes 10 lowest-lying occupied orbitals excluded. This is equivalent to writing

```
FREEZE core 10
```

To freeze the highest virtual orbitals, use the `virtual` keyword. For instance, to freeze the top 5 virtuals

```
FREEZE virtual 5
```

14.4.12 PRINT — the verbosity

This keyword changes the level of output verbosity. One may also request some particular items in Table 14.1 printed.

Table 14.1: Printable items in the TDDFT modules and their default print levels.

Item	Print Level	Description
"timings"	high	CPU and wall times spent in each step
"trial vectors"	high	Trial CI vectors
"initial guess"	debug	Initial guess CI vectors
"general information"	default	General information
"xc information"	default	HF/DFT information
"memory information"	default	Memory information
"convergence"	debug	Convergence
"subspace"	debug	Subspace representation of CI matrices
"transform"	debug	MO to AO and AO to MO transformation of CI vectors
"diagonalization"	debug	Diagonalization of CI matrices
"iteration"	default	Davidson iteration update
"contract"	debug	Integral transition density contraction
"ground state"	default	Final result for ground state
"excited state"	low	Final result for target excited state

14.5 Sample input

The following is a sample input for a spin-restricted TDDFT calculation of singlet excitation energies for the water molecule at the B3LYP/6-31G*.

```
START h2o

TITLE "B3LYP/6-31G* H2O"

GEOMETRY
O     0.00000000     0.00000000     0.12982363
H     0.75933475     0.00000000    -0.46621158
H    -0.75933475     0.00000000    -0.46621158
END

BASIS
* library 6-31G*
END

DFT
XC B3LYP
END

TDDFT
RPA
```

```
NROOTS 20
END

TASK TDDFT ENERGY
```

To perform a spin-unrestricted TDHF/aug-cc-pVDZ calculation for the CO+ radical,

```
START co

TITLE "TDHF/aug-cc-pVDZ CO+"

CHARGE 1

GEOMETRY
C  0.0  0.0  0.0
O  1.5  0.0  0.0
END

BASIS
* library aug-cc-pVDZ
END

DFT
XC HFexch
MULT 2
END

TDDFT
RPA
NROOTS 5
END

TASK TDDFT ENERGY
```

A geometry optimization followed by a frequency calculation for an excited state is carried out for BF at the CIS/6-31G* level in the following sample input.

```
START bf

TITLE "CIS/6-31G* BF optimization frequencies"

GEOMETRY
B 0.0 0.0 0.0
F 0.0 0.0 1.2
END

BASIS
* library 6-31G*
END

DFT
```

```
XC HFexch
END

TDDFT
CIS
NROOTS 3
NOTRIPLET
TARGET 1
END

TASK TDDFT OPTIMIZE

TASK TDDFT FREQUENCIES
```

TDDFT with an asymptotically corrected SVWN exchange-correlation potential. Casida-Salahub scheme has been used with the shift value of 0.1837 a.u. supplied as an input parameter.

```
START tddft_ac_co

GEOMETRY
O 0.0 0.0  0.0000
C 0.0 0.0  1.1283
END

BASIS SPHERICAL
C library aug-cc-pVDZ
O library aug-cc-pVDZ
END

DFT
XC Slater VWN_5
CS00 0.1837
END

TDDFT
NROOTS 12
END

TASK TDDFT ENERGY
```

TDDFT with an asymptotically corrected B3LYP exchange-correlation potential. Hirata-Zhan-Apra-Windus-Dixon scheme has been used (this is only meaningful with B3LYP functional).

```
START tddft_ac_co

GEOMETRY
O 0.0 0.0  0.0000
C 0.0 0.0  1.1283
END

BASIS SPHERICAL
```

```
C library aug-cc-pVDZ
O library aug-cc-pVDZ
END

DFT
XC B3LYP
CSOO
END

TDDFT
NROOTS 12
END

TASK TDDFT ENERGY
```

Chapter 15

Tensor Contraction Engine Module: CI, MBPT, and CC

15.1 Overview

The Tensor Contraction Engine (TCE) Module of NWChem implements a variety of approximations that converge at the exact solutions of Schrödinger equation. They include configuration interaction theory through singles, doubles, triples, and quadruples substitutions, coupled-cluster theory through connected singles, doubles, triples, and quadruples substitutions, and many-body perturbation theory through fourth order in its tensor formulation. Not only optimized parallel programs of some of these high-end correlation theories are new, but also the way in which they have been developed is unique. The working equations of all of these methods have been derived completely automatically by a symbolic manipulation program called a Tensor Contraction Engine (TCE), and the optimized parallel programs have also been computer-generated by the same program, which were interfaced to NWChem. The development of the TCE program and this portion of the NWChem program has been financially supported by the United States Department of Energy, Office of Science, Office of Basic Energy Science, through the SciDAC program.

The capabilities of the module include:

- Restricted Hartree–Fock, unrestricted Hartree–Fock, and restricted open-shell Hartree–Fock references,
- Restricted KS DFT and unrestricted KS DFT references,
- Unrestricted configuration interaction theory (CISD, CISDT, and CISDTQ),
- Unrestricted coupled-cluster theory (LCCD, CCD, LCCSD, CCSD, QCISD, CCSDT, CCSDTQ),
- Unrestricted iterative many-body perturbation theory [MBPT(2), MBPT(3), MBPT(4)] in its tensor formulation,

New capabilities added in the version 4.6 are:

- Unrestricted coupled-cluster singles and doubles with perturbative connected triples {CCSD(T), CCSD[T]},
- Unrestricted equation-of-motion coupled-cluster theory (EOM-CCSD, EOM-CCSDT, EOM-CCSDTQ) for excitation energies, transition moments and oscillator strengths, and excited-state dipole moments,

- Unrestricted coupled-cluster theory (CCSD, CCSDT, CCSDTQ) for dipole moments.

Version 4.6 and onwards the distributed binary executables do not contain CCSDTQ and its derivative methods, owing to their large volume. The source code includes them, so a user can reinstate them by `setenv CCSDTQ yes` and recompile TCE module. The following optimizations have been used in the module:

- Spin symmetry (spin integration is performed wherever possible within the unrestricted framework, making the present unrestricted program optimal for an open-shell system. The spin adaption was not performed, although in a restricted calculation for a closed-shell system, certain spin blocks of integrals and amplitudes are further omitted by symmetry, and consequently, the present unrestricted CCSD requires only twice as many operations as a spin-adapted restricted CCSD for a closed-shell system),
- Point-group symmetry,
- Index permutation symmetry,
- Runtime orbital range tiling for memory management,
- Dynamic load balancing (local index sort and matrix multiplications) parallelism,
- Multiple parallel I/O schemes including fully incore algorithm using Global Arrays,
- Frozen core and virtual approximation.
- DIIS extrapolation and Jacobi update of excitation amplitudes

This extensible module is designed such that an existing or new model of many-electron theory can be added and further optimization can be incorporated with ease by virtue of the TCE. This module is still being actively enhanced by the TCE and we hope to include more models and optimizations in future releases!

In addition to changes made in the 4.7 version the most essential component of the 5.0 release include:

- Several variants of active-space CCSDt and EOMCCSDt methods that employ limited set of triply excited cluster amplitudes defined by active orbitals.
- Ground-state non-iterative CC approaches that account for the effect of triply and/or quadruply excited connected clusters: the perturbative approaches based on the similarity transformed Hamiltonian: CCSD(2), CCSD(2)$_T$, CCSDT(2)$_Q$, the completely and locally renormalized methods: CR-CCSD(T), LR-CCSD(T), LR-CCSD(TQ)-1.
- Excited-state non-iterative corrections due to triples to the EOMCCSD excitation energies: the completely renormalized EOMCCSD(T) method (CR-EOMCCSD(T)).
- Improved DIIS solver.
- New form of the offset tables for files that store cluster amplitudes, recursive intermediates, and one- and two-electron integrals.
- More efficient storage of two-electron integrals for CC calculations based on the RHF or ROHF references.
- Improved scalability of the CCSD and CCSD(T) codes.

15.2 Performance of CI, MBPT, and CC methods

For reviews or tutorials of these highly-accurate correlation methods, the user is referred to:

- A. Szabo and N. S. Ostlund, Modern Quantum Chemistry: Introduction to Advanced Electronic Structure Theory,
- R. J. Bartlett and J. F. Stanton, Applications of Post-Hartree-Fock Methods: A Tutorial, in Reviews in Computational Chemistry, Volume V,
- R. J. Bartlett, Coupled-Cluster Theory: An Overview of Recent Developments, in Modern Electronic Structure Theory, Part II,
- B. O. Roos (editor), Lecture Notes in Quantum Chemistry I and II.

For algorithms and applications of TCE, see:

- S. Hirata, J. Phys. Chem. A **107,** 9887 (2003).
- S. Hirata, T. Yanai, W. A. de Jong, T. Nakajima, and K. Hirao, J. Chem. Phys. **120,** 3297 (2004).
- S. Hirata, J. Chem. Phys. **121**, 51 (2004).
- S. Hirata, Theor. Chem. Acc. **116**, 2 (2006).

For new CC algorithms implemented in 5.0 version, see:

- S. Hirata, P.-D. Fan, A.A. Auer, M. Nooijen, P. Piecuch, J. Chem. Phys. **121**, 12197 (2004).
- K. Kowalski, S. Hirata, M. Włoch, P. Piecuch, T.L. Windus, J. Chem. Phys. **123**, 074319 (2005).
- K. Kowalski, P. Piecuch, J. Chem. Phys. **115**, 643 (2001).
- K. Kowalski, P. Piecuch, Chem. Phys. Lett. **347**, 237 (2001).
- P. Piecuch, S.A. Kucharski, and R.J. Bartlett, J. Chem. Phys. **110**, 6103 (1999).
- P. Piecuch, N. Oliphant, and L. Adamowicz, J. Chem. Phys. **99**, 1875 (1993).
- N. Oliphant and L. Adamowicz, Int. Rev. Phys. Chem. **12**, 339 (1993).
- P. Piecuch, N. Oliphant, and L. Adamowicz, J. Chem. Phys. **99**, 1875 (1993).
- K. Kowalski, P. Piecuch, J. Chem. Phys. **120**, 1715 (2004).
- K. Kowalski, J. Chem. Phys. **123**, 014102 (2005).
- P. Piecuch, K. Kowalski, I.S.O. Pimienta, M.J. McGuire, Int. Rev. Phys. Chem. **21**, 527 (2002).
- K. Kowalski, P. Piecuch, J. Chem. Phys. **122**, 074107 (2005)
- K. Kowalski, W. de Jong, J. Mol. Struct.: THEOCHEM, **768**, 45 (2006).

and references therein.

For new CC algorithms implemented in 5.1 version, see:

- O. Christiansen, H. Koch, P. Jørgensen, Chem. Phys. Lett. **243**, 409 (1995).
- K. Kowalski, J. Chem. Phys. **125**, 124101 (2006)

and references therein.

15.3 Algorithms of CI, MBPT, and CC methods

15.3.1 Spin, spatial, and index permutation symmetry

The TCE thoroughly analyzes the working equation of many-electron theory models and automatically generates a program that takes full advantage of these symmetries at the same time. To do so, the TCE first recognizes the index permutation symmetries among the working equations, and perform strength reduction and factorization by carefully monitoring the index permutation symmetries of intermediate tensors. Accordingly, every input and output tensor (such as integrals, excitation amplitudes, residuals) has just two independent but strictly ordered index strings, and each intermediate tensor has just four independent but strictly ordered index strings. The operation cost and storage size of tensor contraction is minimized by using the index range restriction arising from these index permutation symmetries and also spin and spatial symmetry integration.

15.3.2 Runtime orbital range tiling

To maintain the peak local memory usage at a manageable level, in the beginning of the calculation, the orbitals are rearranged into tiles (blocks) that contains orbitals with the same spin and spatial symmetries. So the tensor contractions in these methods are carried out at the tile level; the spin, spatial, and index permutation symmetry is employed to reduce the operation and storage cost at the tile level also.

15.3.3 Dynamic load balancing parallelism

In a parallel execution, dynamic load balancing of tile-level local tensor index sorting and local tensor contraction (matrix multiplication) will be invoked.

15.3.4 Parallel I/O schemes

Each process is assigned a local tensor index sorting and tensor contraction dynamically. It must first retrieve the tiles of input tensors, and perform these local operations, and accumulate the output tensors to the storage. We have developed a uniform interface for these I/O operations to either (1) a global file on a global file system, (2) a global memory on a global or distributed memory system, and (3) semi-replicated files on a distributed file systems. Some of these operations depend on the ParSoft library.

15.4 Input syntax

The keyword to invoke the many-electron theories in the module is `TCE`. To perform a single-point energy calculation, include

```
TASK TCE ENERGY
```

in the input file, which may be preceeded by the TCE input block that details the calculations:

```
TCE
  [(DFT||HF||SCF) default HF=SCF]
  [FREEZE [[core] (atomic || <integer nfzc default 0>)] \
```

```
          [virtual <integer nfzv default 0>]]
  [(LCCD||CCD||CCSD||CC2||LR-CCSD||LCCSD||CCSDT||CCSDTA||CCSDTQ|| \
    CCSD(T)||CCSD[T]||CCSD(2)_T||CCSD(2)||CCSDT(2)_Q|| \
    CR-CCSD[T]||CR-CCSD(T)|| \
    LR-CCSD(T)||LR-CCSD(TQ)-1||CREOMSD(T)|| \
    QCISD||CISD||CISDT||CISDTQ|| \
    MBPT2||MBPT3||MBPT4||MP2||MP3||MP4) default CCSD]
  [THRESH <double thresh default 1e-6>]
  [MAXITER <integer maxiter default 100>]
  [PRINT (none||low||medium||high||debug)
    <string list_of_names ...>]
  [IO (fortran||eaf||ga||sf||replicated||dra||ga_eaf) default ga]
  [DIIS <integer diis default 5>]
  [LSHIFT <double lshift default is 0.0d0>]
  [NROOTS <integer nroots default 0>]
  [TARGET <integer target default 1>]
  [TARGETSYM <character targetsym default 'none'>]
  [SYMMETRY]
  [2EORB]
  [T3A_LVL]
  [ACTIVE_OA]
  [ACTIVE_OB]
  [ACTIVE_VA]
  [ACTIVE_VB]
  [DIPOLE]
  [TILESIZE <no default (automatically adjusted)>]
  [(NO)FOCK <logical recompf default .true.>]
  [FRAGMENT <default -1 (off)>]
END
```

Also supported are energy gradient calculation, geometry optimization, and vibrational frequency (or hessian) calculation, on the basis of numerical differentiation. To perform these calculations, use

```
TASK TCE GRADIENT
```

or

```
TASK TCE OPTIMIZE
```

or

```
TASK TCE FREQUENCIES
```

Alternatively, more descriptive keywords for each individual method can be used. For instance, to perform a CCSDT energy, gradient, etc. calculation, use

```
TASK UCCSDT ENERGY
```

or

```
TASK UCCSDT GRADIENT
```

or

```
TASK UCCSDT OPTIMIZE
```

or

```
TASK UCCSDT FREQUENCIES
```

with an (optional) input block enclosed either by `UCCSDT` and `END` or by `UCC` and `END`. The keywords for individual methods of TCE module always start with letter `U` which stands for "unrestricted" to avoid confusion with other related methods (such as spin-restricted CCSD and various canonical MP2 implementation) already in place in NWChem.

```
(UCCSDT||UCC)
  [(DFT||HF||SCF) default HF=SCF]
  [FREEZE [[core] (atomic || <integer nfzc default 0>)] \
           [virtual <integer nfzv default 0>]]
  [THRESH <double thresh default 1e-6>]
  [MAXITER <integer maxiter default 100>]
  [PRINT (none||low||medium||high||debug)]
    <string list_of_names ...>]
  [IO (fortran||eaf||ga||sf||replicated||dra||ga_eaf) default ga]
  [DIIS <integer diis default 5>]
  [NROOTS <integer nroots default 0>]
  [TARGET <integer target default 1>]
  [TARGETSYM <character targetsym default 'none'>]
  [SYMMETRY]
  [DIPOLE]
  [TILESIZE <no default (automatically adjusted)>]
  [(NO)FOCK <logical recompf default .true.>]
  [FRAGMENT <default -1 (off)>]
END
```

When a method (CCSDT in this example) is specified in the task directive, a duplicate method specification is not necessary (indeed not allowed) in the corresponding (`UCCSDT` or `UCC` in this case) input block. The keywords of the other methods for task directive are:

```
TASK (UCCD||ULCCD||UCCSD||ULCCSD||UQCISD||UCCSDT||UCCSDTQ) ENERGY
```

or

```
TASK (UCISD||UCISDT||UCISDTQ) ENERGY
```

or

```
TASK (UMP2||UMP3||UMP4||UMBPT2||UMBPT3||UMBPT4) ENERGY
```

etc. The input block can be specified by the same name (`UCISDT` and `END` block for `TASK UCISDT ENERGY`) or `UCC` for the CC family, `UCI` for the CI family, and `UMP` or `UMBPT` for the MP family of methods.

The user may also specify the parameters of reference wave function calculation in a separate block for either HF (SCF) or DFT, depending on the first keyword in the above syntax.

Since each keyword has a default value, a minimal input file will be

```
GEOMETRY
Be 0.0 0.0 0.0
END

BASIS
Be library cc-pVDZ
END

TASK TCE ENERGY
```

which performs a CCSD/cc-pVDZ calculation of the Be atom in its singlet ground state with a spin-restricted HF reference.

15.5 Keywords of TCE input block

15.5.1 HF, SCF, or DFT — the reference wave function

This keyword tells the module which of the HF (SCF) or DFT module is going to be used for the calculation of a reference wave function. The keyword HF and SCF are one and the same keyword internally, and are default. When these are used, the details of the HF (SCF) calculation can be specified in the SCF input block, whereas if DFT is chosen, DFT input block may be provided.

For instance, RHF-RCCSDT calculation (R standing for spin-restricted) can be performed with the following input blocks:

```
SCF
SINGLET
RHF
END

TCE
SCF
CCSDT
END

TASK TCE ENERGY
```

or

```
SCF
SINGLET
RHF
END

UCCSDT
```

```
SCF
END

TASK UCCSDT ENERGY
```

or

```
SCF
SINGLET
RHF
END

UCC
SCF
END

TASK UCCSDT ENERGY
```

This calculation (and any correlation calculation in the TCE module using a RHF or RDFT reference for a closed-shell system) skips the storage and computation of all β spin blocks of integrals and excitation amplitudes. ROHF-UCCSDT (U standing for spin-unrestricted) for an open-shell doublet system can be requested by

```
SCF
DOUBLET
ROHF
END

TCE
SCF
CCSDT
END

TASK TCE ENERGY
```

and likewise, UHF-UCCSDT for an open-shell doublet system can be specified with

```
SCF
DOUBLET
UHF
END

TCE
SCF
CCSDT
END

TASK TCE ENERGY
```

The operation and storage costs of the last two calculations are identical. To use the KS DFT reference wave function for a UCCSD calculation of an open-shell doublet system,

```
DFT
ODFT
MULT 2
END

TCE
DFT
CCSD
END

TASK TCE ENERGY
```

Note that the default model of the DFT module is LDA.

15.5.2 CCSD,CCSDT,CCSDTQ,CISD,CISDT,CISDTQ, MBPT2,MBPT3,MBPT4, etc. — the correlation models

These keywords stand for the following models:

- LCCD: linearized coupled-cluster doubles,
- CCD: coupled-cluster doubles,
- LCCSD: linearized coupled-cluster singles & doubles,
- CCSD: coupled-cluster singles & doubles (also EOM-CCSD),
- LR-CCSD: locally renormalized EOMCCSD method,
- CC2: second-order approximate coupled cluster with singles and doubles model
- CCSDT: coupled-cluster singles, doubles, & triples (also EOM-CCSDT),
- CCSDTA: coupled-cluster singles, doubles, & active triples (also EOM-CCSDT). Three variants of the active-space CCSDt and EOMCCSDt approaches can be selected based on various definitions of triply excited clusters: (1) version I (keyword `T3A_LVL 1`) uses the largest set of triply excited amplitudes defined by at least one occupied and one unoccupied active spinorbital labels. (2) Version II (keyword `T3A_LVL 2`) uses triply excited amplitudes that carry at least two occupied and unoccupied active spinorbital labels. (3) Version III (keyword `T3A_LVL 3`) uses triply excited amplitudes that are defined by active indices only. Each version requires defining relevant set of occupied active α and β spinorbitals (`ACTIVE_OA` and `ACTIVE_OB`) as well as active unoccupied α and β spinorbitals (`ACTIVE_VA` and `ACTIVE_VB`).
- CCSDTQ: coupled-cluster singles, doubles, triples, & quadruples (also EOM-CCSDTQ),
- CCSD(T): CCSD and perturbative connected triples,
- CCSD[T]: CCSD and perturbative connected triples,
- CR-CCSD[T]: completely renormalized CCSD[T] method,
- CR-CCSD(T): completely renormalized CCSD(T) method,
- CCSD(2)_T: CCSD and perturbative CCSD(T)$_T$ correction,

- CCSD(2)_TQ: CCSD and perturbative CCSD(2) correction,
- CCSDT(2)_Q: CCSDT and perturbative CCSDT(2)$_Q$ correction.
- LR-CCSD(T): CCSD and perturbative locally renormalized CCSD(T) correction,
- LR-CCSD(TQ)-1: CCSD and perturbative locally renormalized CCSD(TQ) (LR-CCSD(TQ)-1) correction,
- CREOMSD(T): EOMCCSD energies and completely renormalized EOMCCSD(T)(IA) correction. In this option NWCHEM prints two components: (1) total energy of the K-th state $E_K = E_K^{\rm EOMCCSD} + \delta_K^{\rm CR-EOMCCSD(T),IA}(T)$ and (2) the so-called δ-corrected EOMCCSD excitation energy $\omega_K^{\rm CR-EOMCCSD(T),IA} = \omega_K^{\rm EOMCCSD} + \delta_K^{\rm CR-EOMCCSD(T),IA}(T)$.
- QCISD: quadratic configuration interaction singles & doubles,
- CISD: configuration interaction singles & doubles,
- CISDT: configuration interaction singles, doubles, & triples,
- CISDTQ: configuration interaction singles, doubles, triples, & quadruples,
- MBPT2=MP2: iterative tensor second-order many-body or Møller–Plesset perturbation theory,
- MBPT3=MP3: iterative tensor third-order many-body or Møller–Plesset perturbation theory,
- MBPT4=MP4: iterative tensor fourth-order many-body or Møller–Plesset perturbation theory,

All of these models are based on spin-orbital expressions of the amplitude and energy equations, and designed primarily for spin-unrestricted reference wave functions. However, for a restricted reference wave function of a closed-shell system, some further reduction of operation and storage cost will be made. Within the unrestricted framework, all these methods take full advantage of spin, spatial, and index permutation symmetries to save operation and storage costs at every stage of the calculation. Consequently, these computer-generated programs will perform significantly faster than, for instance, a hand-written spin-adapted CCSD program in NWChem, although the nominal operation cost for a spin-adapted CCSD is just one half of that for spin-unrestricted CCSD (in spin-unrestricted CCSD there are three independent sets of excitation amplitudes, whereas in spin-adapted CCSD there is only one set, so the nominal operation cost for the latter is one third of that of the former. For a restricted reference wave function of a closed-shell system, all β spin block of the excitation amplitudes and integrals can be trivially mapped to the all α spin block, reducing the ratio to one half).

While the MBPT (MP) models implemented in the TCE module give identical correlation energies as conventional implementation for a canonical HF reference of a closed-shell system, the former are intrinsically more general and theoretically robust for other less standard reference wave functions and open-shell systems. This is because the zeroth order of Hamiltonian is chosen to be the full Fock operatior (not just the diagonal part), and no further approximation was invoked. So unlike the conventional implementation where the Fock matrix is assumed to be diagonal and a correlation energy is evaluated in a single analytical formula that involves orbital energies (or diagonal Fock matrix elements), the present tensor MBPT requires the iterative solution of amplitude equations and subsequent energy evaluation and is generally more expensive than the former. For example, the operation cost of many conventional implementation of MBPT(2) scales as the fourth power of the system size, but the cost of the present tensor MBPT(2) scales as the fifth power of the system size, as the latter permits non-canonical HF reference and the former does not (to reinstate the non-canonical HF reference in the former makes it also scale as the fifth power of the system size).

15.5.3 THRESH — the convergence threshold of iterative solutions of amplitude equations

This keyword specifies the convergence threshold of iterative solutions of amplitude equations, and applies to all of the CI, CC, and MBPT models. The threshold refers to the norm of residual, namely, the deviation from the amplitude equations. The default value is `1e-6`.

15.5.4 MAXITER — the maximum number of iterations

It sets the maximum allowed number iterations for the iterative solutions of amplitude equations. The default value is `100`.

15.5.5 IO — parallel I/O scheme

There are five parallel I/O schemes implemented for all the models, which need to be wisely chosen for a particular problem and computer architecture.

- `fortran` : Fortran77 direct access,
- `eaf` : Exclusive Access File library,
- `ga` : Fully incore, Global Array virtual file,
- `sf` : Shared File library,
- `replicated` : Semi-replicated file on distributed file system with EAF library.
- `dra` : Distributed file on distributed file system with DRA library.
- `ga_eaf` : Semi-replicated file on distributed file system with EAF library. GA is used to speedup the file reconciliation.

The GA algorithm, which is default, stores all input (integrals and excitation amplitudes), output (residuals), and intermediate tensors in the shared memory area across all nodes by virtue of GA library. This fully incore algorithm replaces disk I/O by inter-process communications. This is a recommended algorithm whenever feasible. Note that the memory management through runtime orbital range tiling described above applies to local (unshared) memory of each node, which may be separately allocated from the shared memory space for GA. So when there is not enough shared memory space (either physically or due to software limitations, in particular, shmmax setting), the GA algorithm can crash due to an out-of-memory error. The replicated scheme is the currently the only disk-based algorithm for a genuinely distributed file system. This means that each node keeps an identical copy of input tensors and it holds non-identical overlapping segments of intermediate and output tensors in its local disk. Whenever data coherency is required, a file reconcilation process will take place to make the intermediate and output data identical throughout the nodes. This algorithm, while requiring redundant data space on local disk, performs reasonably efficiently in parallel. For sequential execution, this reduces to the EAF scheme. For a global file system, the SF scheme is recommended. This together with the Fortran77 direct access scheme does not usually exhibit scalability unless shared files on the global file system also share the same I/O buffer. For sequential executions, the SF, EAF, and replicated schemes are interchangeable, while the Fortran77 scheme is appreciably slower.

Two new I/O algorithms `dra` and `ga_eaf` combines GA and DRA or EAF based replicated algorithm. In the former, arrays that are not active (e.g., prior T amplitudes used in DIIS or EOM-CC trial vectors) in GA algorithm will be moved to DRA. In the latter, the intermediates that are formed by tensor contractions are

initially stored in GA, thereby avoiding the need to accumulate the fragments of the intermediate scattered in EAFs in the original EAF algorithm. Once the intermediate is formed completely, then it will be replicated as EAFs.

15.5.6 DIIS — the convergence acceleration

It sets the number iterations in which a DIIS extrapolation is performed to accelerate the convergence of excitation amplitudes. The default value is 5, which means in every five iteration, one DIIS extrapolation is performed (and in the rest of the iterations, Jacobi rotation is used). When zero or negative value is specified, the DIIS is turned off. It is not recommended to perform DIIS every iteration, whereas setting a large value for this parameter necessitates a large memory (disk) space to keep the excitation amplitudes of previous iterations. In 5.0 version we significantly improved the DIIS solver by re-organizing the itrative process and by introducing the level shift option (`lshift`) that enable to increase small orbital energy differences used in calculating the up-dates for cluster amplitudes. Typical values for `lshift` oscillates between 0.3 and 0.5 for CC calculations for ground states of multi-configurational character. Otherwise, the value of `lshift` is by default set equal to 0.

15.5.7 FREEZE — the frozen core/virtual approximation

Some of the lowest-lying core orbitals and/or some of the highest-lying virtual orbitals may be excluded in the calculations by this keyword (this does not affect the ground state HF or DFT calculation). No orbitals are frozen by default. To exclude the atom-like core regions altogether, one may request

```
FREEZE atomic
```

To specify the number of lowest-lying occupied orbitals be excluded, one may use

```
FREEZE 10
```

which causes 10 lowest-lying occupied orbitals excluded. This is equivalent to writing

```
FREEZE core 10
```

To freeze the highest virtual orbitals, use the `virtual` keyword. For instance, to freeze the top 5 virtuals

```
FREEZE virtual 5
```

15.5.8 NROOTS — the number of excited states

One can specify the number of excited state roots to be determined. The default value is `1`. It is advised that the users request several more roots than actually needed, since owing to the nature of the trial vector algorithm, some low-lying roots can be missed when they do not have sufficient overlap with the initial guess vectors.

15.5.9 TARGET and TARGETSYM — the target root and its symmetry

At the moment, the first and second geometrical derivatives of excitation energies that are needed in force, geometry, and frequency calculations are obtained by numerical differentiation. These keywords may be used

to specify which excited state root is being used for the geometrical derivative calculation. For instance, when TARGET 3 and TARGETSYM a1g are included in the input block, the total energy (ground state energy plus excitation energy) of the third lowest excited state root (excluding the ground state) transforming as the irreducible representation a1g will be passed to the module which performs the derivative calculations. The default values of these keywords are 1 and none, respectively.

The keyword TARGETSYM is essential in excited state geometry optimization, since it is very common that the order of excited states changes due to the geometry changes in the course of optimization. Without specifying the TARGETSYM, the optimizer could (and would likely) be optimizing the geometry of an excited state that is different from the one the user had intended to optimize at the starting geometry. On the other hand, in the frequency calculations, TARGETSYM must be none, since the finite displacements given in the course of frequency calculations will lift the spatial symmetry of the equilibrium geometry. When these finite displacements can alter the order of excited states including the target state, the frequency calculation is not be feasible.

15.5.10 SYMMETRY — restricting the excited state symmetry

By adding this keyword to the input block, the user can request the module to seek just the roots of the specified irreducible representation as TARGETSYM. By default, this option is not set. TARGETSYM must be specified when SYMMETRY is invoked.

15.5.11 2EORB — alternative storage of two-electron integrals

In the 5.0 version a new option has been added in order to provide more economical way of storing two-electron integrals used in CC calculations based on the RHF and ROHF references. The 2EORB keyword can be used in the context of all (except for the active-space approaches) CC approaches. All two-electron integrals are transfromed and subsequently stored in a way which is compatible with assumed tiling scheme. The transformation from orbital to spinorbital form of the two-electron integrals is performed on-the-fly during execution of the CC module. This option, although slower, allows to significantly reduce the memory requirements needed by the first half of 4-index transformation and final file with fully transformed two-electron integrals . Savings in the memory requirements on the order of magnitude (and more) have been observed for large-scale open-shell calculations.

In addition to the algorithm implemented in the 5.0 version, several new computation-intensive algorithms has been added to the 5.1 version with the purpose of improving scalability and overcoming local memory bottleneck of the 5.0 2EORB 4-index transformation. All new variants of 4-index transormation should be executed on multiprocessor machines. In order to give the user a full control over this part of the TCE code several keywords were designed to define the most vital parameters that determine the perfromance of 4-index transformation. All new keywords must be used with the 2EORB keyword. The 2emet keyword (default value 1 or "2emet 1", refers to the old 5.0 version of the 4-index transformation), defines the algorithm to be used. By putting "2emet 2" the TCE code will execute the algoritm based on the two step procedure with two intermediate files. In many instances this algorithm is characterized by better timings compared to algorithms 3 and 4, although it is more memory demanding. In contrast to algorithms nr 1,3, and 4 this approach can make use of a disk to store intermediate files. For this purpose one should use the keyword idiskx ("idiskx 0" causes that all intermediate files are stored on globall arrays, while "idiskx 1" tells the code to use a disk to store intermediates; default value of idiskx is equal 0). Algorithm nr 3 ("2emet 3") uses only one intermediate file whereas algorithm nr 4 ("2emet 4") is a version of algorithm 3 with inbuild option of reducing the memory requirements. For example, by using new keyword "split 4" we will reduce the size of only intermediate file by factor of 4 (the split keyword can be only used in the context of algorithm nr 4). All new algorithms (i.e., 2,3,4) use the attilesize to define the size of atomic

tile. By default `attilesize` is set equal 30. For larger systems the use of larger values of `attilesize` is recommended (typically between 40-60).

In the later part of this manual several examples illustrate the use of the newly introduced keywords.

15.5.12 DIPOLE — the ground- and excited-state dipole moments

When this is set, the ground-state CC calculation will enter another round of iterative step for the so-called Λ equation to obtain the one-particle density matrix and dipole moments. Likewise, for excited-states (EOM-CC), the transition moments and dipole moments will be computed when (and only when) this option is set. In the latter case, EOM-CC left hand side solutions will be sought incurring approximately three times the computational cost of excitation energies alone (note that the EOM-CC effective Hamiltonian is not Hermitian and has distinct left and right eigenvectors).

15.5.13 (NO)FOCK — (not) recompute Fock matrix

The default is `FOCK` meaning that the Fock matrix will be reconstructed (as opposed to using the orbital energies as the diagonal part of Fock). This is essential in getting correct correlation energies with ROHF or DFT reference wave functions. However, currently, this module cannot reconstruct the Fock matrix when one-component relativistic effects are operative. So when a user wishes to run TCE's correlation methods with DK or other relativistic reference, `NOFOCK` must be set and orbital energies must be used for the Fock matrix.

15.5.14 PRINT — the verbosity

This keyword changes the level of output verbosity. One may also request some particular items in Table 15.1 printed.

15.6 Sample input

The following is a sample input for a ROHF-UCCSD energy calculation of a water radical cation.

```
START h2o

TITLE "ROHF-UCCSD/cc-pVTZ H2O"

CHARGE 1

GEOMETRY
O     0.00000000     0.00000000     0.12982363
H     0.75933475     0.00000000    -0.46621158
H    -0.75933475     0.00000000    -0.46621158
END

BASIS
* library cc-pVTZ
END
```

Table 15.1: Printable items in the TCE modules and their default print levels.

Item	Print Level	Description
"time"	vary	CPU and wall times
"tile"	vary	Orbital range tiling information
"t1"	debug	T_1 excitation amplitude dumping
"t2"	debug	T_2 excitation amplitude dumping
"t3"	debug	T_3 excitation amplitude dumping
"t4"	debug	T_4 excitation amplitude dumping
"general information"	default	General information
"correlation information"	default	TCE information
"mbpt2"	debug	Caonical HF MBPT2 test
"get_block"	debug	I/O information
"put_block"	debug	I/O information
"add_block"	debug	I/O information
"files"	debug	File information
"offset"	debug	File offset information
"ao1e"	debug	AO one-electron integral evaluation
"ao2e"	debug	AO two-electron integral evaluation
"mo1e"	debug	One-electron integral transformation
"mo2e"	debug	Two-electron integral transformation

```
SCF
ROHF
DOUBLET
THRESH 1.0e-10
TOL2E  1.0e-10
END

TCE
CCSD
END

TASK TCE ENERGY
```

The same result can be obtained by the following input:

```
START h2o

TITLE "ROHF-UCCSD/cc-pVTZ H2O"

CHARGE 1

GEOMETRY
O     0.00000000     0.00000000     0.12982363
H     0.75933475     0.00000000    -0.46621158
H    -0.75933475     0.00000000    -0.46621158
END
```

```
BASIS
* library cc-pVTZ
END

SCF
ROHF
DOUBLET
THRESH 1.0e-10
TOL2E  1.0e-10
END

TASK UCCSD ENERGY
```

EOM-CCSDT calculation for excitation energies, excited-state dipole, and transition moments.

```
START tce_h2o_eomcc

GEOMETRY UNITS BOHR
H    1.474611052297904   0.000000000000000   0.863401706825835
O    0.000000000000000   0.000000000000000  -0.215850436155089
H   -1.474611052297904   0.000000000000000   0.863401706825835
END

BASIS
* library sto-3g
END

SCF
SINGLET
RHF
END

TCE
CCSDT
DIPOLE
FREEZE CORE ATOMIC
NROOTS 1
END

TASK TCE ENERGY
```

Active-space CCSDt/EOMCCSDt calculations (version I) of several excited states of the Be_3 molecule. Three highest-lying occupied α and β orbitals (`active_oa` and `active_ob`) and nine lowest-lying unoccupied α and β orbitals (`active_va` and `active_vb`) define the active space.

```
START TCE_ACTIVE_CCSDT

ECHO

GEOMETRY UNITS ANGSTROM
```

```
SYMMETRY C2V
BE  0.00  0.00   0.00
BE  0.00  1.137090 -1.96949
end

BASIS spherical
# --- DEFINE YOUR BASIS SET ---
END

SCF
THRESH 1.0e-10
TOL2E 1.0e-10
SINGLET
RHF
END

TCE
FREEZE ATOMIC
CCSDTA
TILESIZE 15
THRESH 1.0d-5
ACTIVE_OA 3
ACTIVE_OB 3
ACTIVE_VA 9
ACTIVE_VB 9
T3A_LVL 1
NROOTS  2
END

TASK TCE ENERGY
```

Completely renormalized EOMCCSD(T) (CR-EOMCCSD(T)) calculations for the ozone molecule as described by the POL1 basis set. The `CREOMSD(T)` directive automatically initialize three-step procedure: (1) CCSD calculations; (2) EOMCCSD calculations; (3) non-iterative CR-EOMCCSD(T) corrections.

```
START TCE_CR_EOM_T_OZONE

ECHO

GEOMETRY UNITS BOHR
SYMMETRY C2V
O   0.0000000000        0.0000000000        0.0000000000
O   0.0000000000       -2.0473224350       -1.2595211660
O   0.0000000000        2.0473224350       -1.2595211660
END

BASIS SPHERICAL
O    S
     10662.285000000      0.00079900
```

```
      1599.709700000      0.00615300
       364.725260000      0.03115700
       103.651790000      0.11559600
        33.905805000      0.30155200
O    S
        12.287469000      0.44487000
         4.756805000      0.24317200
O    S
         1.004271000      1.00000000
O    S
         0.300686000      1.00000000
O    S
         0.090030000      1.00000000
O    P
        34.856463000      0.01564800
         7.843131000      0.09819700
         2.306249000      0.30776800
         0.723164000      0.49247000
O    P
         0.214882000      1.00000000
O    P
         0.063850000      1.00000000
O    D
         2.306200000      0.20270000
         0.723200000      0.57910000
O    D
         0.214900000      0.78545000
         0.063900000      0.53387000
END

SCF
THRESH 1.0e-10
TOL2E 1.0e-10
SINGLET
RHF
END

TCE
FREEZE ATOMIC
CREOMSD(T)
TILESIZE 20
THRESH 1.0d-6
NROOTS 2
END

TASK TCE ENERGY
```

The LR-CCSD(T) calculations for the glycine molecule in the aug-cc-pVTZ basis set. Option `2EORB` is used in order to minimize memory requirements associated with the storage of two-electron integrals.

```
START TCE_LR_CCSD_T

ECHO

GEOMETRY UNITS BOHR
O      -2.8770919486        1.5073755650        0.3989960497
C      -0.9993929716        0.2223265108       -0.0939400216
C       1.6330980507        1.1263991128       -0.7236778647
O      -1.3167079358       -2.3304840070       -0.1955378962
N       3.5887721300       -0.1900460352        0.6355723246
H       1.7384347574        3.1922914768       -0.2011420479
H       1.8051078216        0.9725472539       -2.8503867814
H       3.3674278149       -2.0653924379        0.5211399625
H       5.2887327108        0.3011058554       -0.0285088728
H      -3.0501350657       -2.7557071585        0.2342441831
END

BASIS
* library aug-cc-pVTZ
END

SCF
THRESH 1.0e-10
TOL2E 1.0e-10
SINGLET
RHF
END

TCE
FREEZE ATOMIC
2EORB
TILESIZE 15
LR-CCSD(T)
THRESH 1.0d-7
END

TASK TCE ENERGY
```

The CCSD calculations for the triplet state of the C_{20} molecule. New algorithms for 4-index tranformation are used.

```
title "c20_cage"
echo
start c20_cage
memory stack 2320 mb heap 180 mb global 2000 mb noverify

geometry print xyz units bohr
   symmetry c2
   C      -0.761732  -1.112760   3.451966
   C       0.761732   1.112760   3.451966
```

```
   C       0.543308  -3.054565   2.168328
   C      -0.543308   3.054565   2.168328
   C       3.190553   0.632819   2.242986
   C      -3.190553  -0.632819   2.242986
   C       2.896910  -1.982251   1.260270
   C      -2.896910   1.982251   1.260270
   C      -0.951060  -3.770169   0.026589
   C       0.951060   3.770169   0.026589
   C       3.113776   2.128908   0.076756
   C      -3.113776  -2.128908   0.076756
   C       3.012003  -2.087494  -1.347695
   C      -3.012003   2.087494  -1.347695
   C       0.535910  -2.990532  -2.103427
   C      -0.535910   2.990532  -2.103427
   C       3.334106   0.574125  -2.322563
   C      -3.334106  -0.574125  -2.322563
   C      -0.764522  -1.081362  -3.453211
   C       0.764522   1.081362  -3.453211
end

basis spherical
 * library cc-pvtz
end

scf
   triplet
   rohf
   thresh 1.e-8
   maxiter 200
end

tce
   ccsd
   maxiter 60
   diis 5
   thresh 1.e-6
   2eorb
   2emet 3
   attilesize 40
   tilesize 30
   freeze atomic
end

task tce energy
```

15.7 TCE Response Properties

15.7.1 Introduction

Response properties can be calculated within the TCE. The current functionality is limited to ground-state dipole polarizabilities for the CCSD and CCSDT levels of theory. Like the rest of the TCE, properties can be calculated with RHF, UHF, ROHF and DFT reference wavefunctions.

Specific details about the CCSD-LR implementation can be found in the following papers:

- J. R. Hammond, M. Valiev, W. A. deJong and K. Kowalski, *J. Phys. Chem. A*, **111**, 5492 (2007).
- J. R. Hammond, K. Kowalski and W. A. de Jong, *J. Chem. Phys.*, **127**, 144105 (2007).

An appropriate background on coupled-cluster linear response (CC-LR) can be found in the references of those papers.

15.7.2 Performance

The coupled-cluster response codes were generated in the same manner as the rest of the TCE, thus all previous comments on performance apply here as well. The improved offsets available in the CCSD and EOM-CCSD codes is now also available in the CCSD-Λ and CCSD-LR codes. The bottleneck for CCSD-LR is the same as EOM-CCSD, likewise for CCSDT-LR and EOM-CCSDT. The CCSD-LR code has been tested on as many as 720 processors for systems with more than 1000 spin-orbitals, while the CCSDT-LR code has been tested on as many as 128 processors.

15.7.3 Input

The input commands for TCE response properties exclusively use set directives (see Section 5.7) instead of TCE input block keywords. There are currently only three commands available:

```
set tce:lineresp <logical lineresp default: F>
set tce:afreq <double precision afreq(9) default: 0.0>
set tce:respaxis <logical respaxis(3) default: T T T>
```

The boolean variable `lineresp` invokes the linear response equations for the corresponding coupled-cluster method (only CCSD and CCSDT possess this feature) and evaluates the dipole polarizability. When `lineresp` is true, the Λ-equations will also be solved, so the dipole moment is also calculated. If no other options are set, the complete dipole polarizability tensor will be calculated at zero frequency (static). Up to nine real frequencies can be set; adding more should not crash the code but it will calculate meaningless quanities. If one desires to calculate more frequencies at one time, merely change the line `double precision afreq(9)` in `$(NWCHEM_TOP)/src/tce/include/tce.fh` appropriately and recompile.

The user can choose to calculate response amplitudes only for certain axis, either because of redundancy due to symmetry or because of memory limitations. The boolean vector of length three `respaxis` is used to determine whether or not a given set of response amplitudes are allocated, solved for, and used in the polarizability tensor evaluation. The logical variables represent the X, Y, Z axes, respectively. If respaxis is set to `T F T`, for example, the responses with respect to the X and Z dipoles will be calculated, and the four (three unique) tensor components will be evaluated. This feature is also useful for conserving memory. By

calculating only one axis at a time, memory requirements can be reduced by 25% or more, depending on the number of DIIS vectors used. Reducing the number of DIIS vectors also reduces the memory requirements.

It is strongly advised that when calculating polarizabilities at high-frequencies, that user set the frequencies in increasing order, preferably starting with zero or other small value. This approach is computationally efficient (the initial guess for subsequent responses is the previously converged value) and mitigates starting from a zero vector for the response amplitudes.

15.7.4 Examples

This example runs in-core on a large workstation.

```
geometry units angstrom
 symmetry d2h
 C               0.000    1.390    0.000
 H               0.000    2.470    0.000
 C               1.204    0.695    0.000
 H               2.139    1.235    0.000
 C               0.000   -1.390    0.000
 H               0.000   -2.470    0.000
 C              -1.204   -0.695    0.000
 H              -2.139   -1.235    0.000
 C               1.204   -0.695    0.000
 H               2.139   -1.235    0.000
 C              -1.204    0.695    0.000
 H              -2.139    1.235    0.000
end

basis spherical
  * library aug-cc-pvdz
end

tce
  freeze atomic
  ccsd
  io ga
  2eorb
  tilesize 16
end

set tce:lineresp T
set tce:afreq 0.000 0.072
set tce:respaxis T T T

task tce energy
```

This is a relatively simple example for CCSDT-LR.

```
geometry units au
  symmetry c2v
```

```
  H 0       0        0
  F 0       0        1.7328795
end

basis spherical
  * library aug-cc-pvdz
end

tce
  ccsdt
  io ga
  2eorb
end

set tce:lineresp T
set tce:afreq 0.0 0.1 0.2 0.3 0.4
set tce:respaxis T F T

task tce energy
```

Chapter 16

MP2

There are (at least) three algorithms within NWChem that compute the Møller-Plesset (or many-body) perturbation theory second-order correction to the Hartree-Fock energy (MP2). They vary in capability, the size of system that can be treated and use of other approximations

- Semi-direct — this is recommended for most large applications (up to about 2800 basis functions), especially on the IBM SP and other machines with significant disk I/O capability. Partially transformed integrals are stored on disk, multi-passing as necessary. RHF and UHF references may be treated including computation of analytic derivatives. This is selected by specifying `mp2` on the task directive, e.g.

```
TASK MP2
```

- Fully-direct — this is of utility if only limited I/O resources are available (up to about 2800 functions). Only RHF references and energies are available. This is selected by specifying `direct_mp2` on the task directive, e.g.

```
TASK DIRECT_MP2
```

- Resolution of the identity (RI) approximation MP2 (RI-MP2) — this uses the RI approximation and is therefore only exact in the limit of a complete fitting basis. However, with some care, high accuracy may be obtained with relatively modest fitting basis sets. An RI-MP2 calculation can cost over 40 times less than the corresponding exact MP2 calculation. RHF and UHF references with only energies are available. This is selected by specifying `rimp2` on the task directive, e.g.,

```
TASK RIMP2
```

All three MP2 tasks share the same input block.

```
MP2
  [FREEZE [[core] (atomic || <integer nfzc default 0>)] \
          [virtual <integer nfzv default 0>]]
  [TIGHT]
  [PRINT]
  [NOPRINT]
  [VECTORS <string filename default scf-output-vectors> \
```

```
    [swap [(alpha||beta)] <integer pair-list>] ]
  [RIAPPROX <string riapprox default V>]
  [FILE3C <string filename default $file_prefix$.mo3cint">]
  [SCRATCHDISK <integer>]
END
```

16.1 FREEZE — Freezing orbitals

All MP2 modules support frozen core orbitals, however, only the direct MP2 and RI-MP2 modules support frozen virtual orbitals.

By default, no orbitals are frozen. The `atomic` keyword causes orbitals to be frozen according to the rules in Table 16.1. Note that *no* orbitals are frozen on atoms on which the nuclear charge has been modified either by the user or due to the presence of an ECP. The actual input would be

```
freeze atomic
```

For example, in a calculation on $Si(OH)_2$, by default the lowest seven orbitals would be frozen (the oxygen $1s$, and the silicon $1s$, $2s$ and $2p$).

Period	Elements	Core Orbitals	Number of Core
0	H – He	—	0
1	Li – Ne	$1s$	1
2	Na – Ar	$1s2s2p$	5
3	K – Kr	$1s2s2p3s3p$	9
4	Rb – Xe	$1s2s2p3s3p4s3d4p$	18
5	Cs – Rn	$1s2s2p3s3p4s3d4p5s4d5p$	27
6	Fr – Lr	$1s2s2p3s3p4s3d4p5s4d5p6s4f5d6p$	43

Table 16.1: Number of orbitals considered "core" in the "freeze by atoms" algorithm.

Caution: The rule for freezing orbitals "by atoms" are rather unsophisticated: the number of orbitals to be frozen is computed from the Table 16.1 by summing the number of core orbitals in each atom present. The corresponding number of lowest-energy orbitals are frozen — if for some reason the actual core orbitals are not the lowest lying, then correct results will not be obtained. From limited experience, it seems that special attention should be paid to systems including third- and higher- period atoms.

The user may also specify the number of orbitals to be frozen by atom. Following the $Si(OH)_2$ example, the user could specify

```
freeze atomic O 1 Si 3
```

In this case only the lowest four orbitals would be frozen. If the user does not specify the orbitals by atom, the rules default to Table 16.1.

Caution: The system does not check for a valid number of orbitals per atom. If the user specifies to freeze more orbitals then are available for the atom, the system will not catch the error. The user must specify a logical number of orbitals to be frozen for the atom.

The `FREEZE` directive may also be used to specify the number of core orbitals to freeze. For instance, to freeze the first 10 orbitals

```
freeze 10
```

or equivalently, using the optional keyword `core`

```
freeze core 10
```

Again, note that if the 10 orbitals to be frozen do not correspond to the first 10 orbitals, then the `swap` keyword of the `VECTORS` directive must be used to order the input orbitals correctly (Section 16.5).

To freeze the highest virtual orbitals, use the `virtual` keyword. For instance, to freeze the top 5 virtuals

```
freeze virtual 5
```

Again, note that this only works for the direct-MP2 and RI-MP2 energy codes.

16.2 TIGHT — Increased precision

The `TIGHT` directive can be used to increase the precision in the MP2 energy and gradients.

By default the MP2 gradient package should compute energies accurate to better than a micro-Hartree, and gradients accurate to about five decimal places (atomic units). However, if there is significant linear dependence in the basis set the precision might not be this good. Also, for computing very accurate geometries or numerical frequencies, greater precision may be desirable.

This option increases the precision to which both the SCF (from 10^{-6} to 10^{-8}) and CPHF (from 10^{-4} to 10^{-6}) are solved, and also tightens thresholds for computation of the AO and MO integrals (from 10^{-9} to 10^{-11}) within the MP2 code.

16.3 SCRATCHDISK — Limiting I/O usage

This directive – used only in the semi-direct algorithm – allows to limit the per process disk usage. Mandatory argument for this keyword is the maximum number of MBytes. For example, the following input line

```
scratchdisk 512
```

puts an upper limit of 512 MBytes to the semi-direct MP2 usage of disk (again, on a per process base).

16.4 PRINT and NOPRINT

The standard print control options are recognized. The list of recognized names are given in Table 16.2.

16.5 VECTORS — MO vectors

All of the (supported) MP2 modules require use of converged canonical SCF (RHF or UHF) orbitals for correct results. The vectors are by default obtained from the preceding SCF calculation, but it is possible to specify a different source using the `VECTORS` directive. For instance, to obtain vectors from the file `/tmp/h2o.movecs`, use the directive

Table 16.2: Printable items in the MP2 modules and their default print levels.

Item	Print Level	Description
RI-MP2		
"2/3 ints"	debug	Partial 3-center integrals
"3c ints"	debug	MO 3-center integrals
"4c ints b"	debug	"B" matrix with approx. 4c integrals
"4c ints"	debug	Approximate 4-center integrals
"amplitudes"	debug	"B" matrix with denominators
"basis"	high	
"fit xf"	debug	Transformation for fitting basis
"geombas"	debug	Detailed basis map info
"geometry"	high	
"information"	low	General information about calc.
"integral i/o"	high	File size information
"mo ints"	debug	
"pair energies"	debug	(working only in direct_mp2)
"partial pair energies"	debug	Pair energy matrix each time it is updated
"progress reports"	default	Report completion of time-consuming steps
"reference"	high	Details about reference wavefunction
"warnings"	low	Non-fatal warnings

```
vectors /tmp/h2o.movecs
```

As noted above (Section 16.1) if the SCF orbitals are not in the correct order, it is necessary to permute the input orbitals using the `swap` keyword of the `VECTORS` directive. For instance, if it is desired to freeze a total six orbitals corresponding to the SCF orbitals 1–5, and 7, it is necessary to swap orbital 7 into the 6th position. This is accomplished by

```
vectors swap 6 7
```

The swap capability is examined in more detail in Section 10.5.

16.6 RI-MP2 fitting basis

The RI-MP2 method requires a fitting basis, which must be specified with the name `"ri-mp2 basis"` (see Section 7). For instance,

```
basis "ri-mp2 basis"
  O s; 10000.0 1
  O s;  1000.0 1
  O s;   100.0 1
  ...
end
```

Alternatively, using a standard capability of basis sets (Section 7) another named basis may be associated with the fitting basis. For instance, the following input specifies a basis with the name

"small fitting basis" and then defines this to be the "ri-mp2 basis".

```
basis "small fitting basis"
  H s; 10    1
  H s;  3    1
  H s;  1    1
  H s;  0.1  1
  H s;  0.01 1
end

set "ri-mp2 basis" "small fitting basis"
```

16.7 FILE3C — RI-MP2 3-center integral filename

The default name for the file used to store the transformed 3-center integrals is "$file_prefix$.mo3cint" in the scratch directory. This may be overridden using the FILE3C directive. For instance, to specify the file /scratch/h2o.3c, use this directive

```
file3c /scratch/h2o.3c
```

16.8 RIAPPROX — RI-MP2 Approximation

The type of RI approximation used in the RI-MP2 calculation is controlled by means of the RIAPPROX directive. The two possible values are V and SVS (case sensitive), which correspond to the approximations with the same names described in O. Vahtras, J Almlöf, and M. W. Feyereisen, *Chem. Phys. Lett.* **213**, 514–518 (1993). The default is V.

16.9 Advanced options for RI-MP2

These options, which functioned at the time of writing, are not currently supported.

16.9.1 Control of linear dependence

Construction of the RI fit requires the inversion of a matrix of fitting basis integrals which is carried out via diagonalization. If the fitting basis includes near linear dependencies, there will be small eigenvalues which can ultimately lead to non-physical RI-MP2 correlation energies. Eigenvectors of the fitting matrix are discarded if the corresponding eigenvalue is less than $mineval$ which defaults to 10^{-8}. This parameter may be changed by setting the a parameter in the database. For instance, to set it to 10^{-10}

```
set "mp2:fit min eval" 1e-10
```

16.9.2 Reference Spin Mapping for RI-MP2 Calculations

The user has the option of specifying that the RI-MP2 calculations are to be done with variations of the SCF reference wavefunction. This is accomplished with a SET directive of the form,

```
set "mp2:reference spin mapping" <integer array default 0>
```

Each element specified for `array` is the SCF spin case to be used for the corresponding spin case of the correlated calculation. The number of elements set determines the overall type of correlated calculation to be performed. The default is to use the unadulterated SCF reference wavefunction.

For example, to perform a spin-unrestricted calculation (two elements) using the alpha spin orbitals (spin case 1) from the reference for both of the correlated reference spin cases, the `SET` directive would be as follows,

```
set "mp2:reference spin mapping" 1 1
```

The SCF calculation to produce the reference wavefunction could be either RHF or UHF in this case.

The `SET` directive for a similar case, but this time using the beta-spin SCF orbitals for both correlated spin cases, is as follows,

```
set "mp2:reference spin mapping" 2 2
```

The SCF reference calculation must be UHF in this case.

The `SET` directive for a spin-restricted calculation (one element) from the beta-spin SCF orbitals using this option is as follows,

```
set "mp2:reference spin mapping" 2
```

The `SET` directive for a spin-unrestricted calculation with the spins flipped from the original SCF reference wavefunction is as follows,

```
set "mp2:reference spin mapping" 2 1
```

16.9.3 Batch Sizes for the RI-MP2 Calculation

The user can control the size of each batch in the transformation and energy evaluation in the MP2 calculation, and consequently the memory requirements and number of passes required. This is done using two `SET` directives of the following form,

```
set "mp2:transformation batch size" <integer size default -1>
set "mp2:energy batch size" <integer isize jsize default -1 -1>
```

The default is for the code to determine the batch size based on the available memory. Should there be problems with the program-determined batch sizes, these variables allow the user to override them. The program will always use the smaller of the user's value of these entries and the internally computed batch size.

The transformation batch size computed in the code is the number of occupied orbitals in the $(occ\, vir|fit)$ three-center integrals to be produced at a time. If this entry is less than the number of occupied orbitals in the system, the transformation will require multiple passes through the two-electron integrals. The memory requirements of this stage are *two* global arrays of dimension $< batchsize > \times vir \times fit$ with the "fit" dimension distributed across all processors (on shell-block boundaries). The compromise here is memory space versus multiple integral evaluations.

The energy evaluation batch sizes are computed in the code from the number of occupied orbitals in the two sets of three-center integrals to be multiplied together to produce a matrix of approximate four-center integrals. Two blocks of integrals of dimension ($< batchisize > \times vir$) and ($< batchjsize > \times vir$) by fit are read in from disk and multiplied together to produce $< batchisize >< batchjsize > vir^2$ approximate integrals. The compromise here is performance of the distributed matrix multiplication (which requires large matrices) versus memory space.

16.9.4 Energy Memory Allocation Mode: RI-MP2 Calculation

The user must choose a strategy for the memory allocation in the energy evaluation phase of the RI-MP2 calculation, either by minimizing the amount of I/O, or minimizing the amount of computation. This can be accomplished using a `SET` directive of the form,

```
set "mp2:energy mem minimize" <string mem_opt default I>
```

A value of `I` entered for the string `mem_opt` means that a strategy to minimize I/O will be employed. A value of `C` tells the code to use a strategy that minimizes computation.

When the option to minimize I/O is selected, the block sizes are made as large as possible so that the total number of passes through the integral files is as small as possible. When the option to minimize computation is selected, the blocks are chosen as close to square as possible so that permutational symmetry in the energy evaluation can be used most effectively.

16.9.5 Local Memory Usage in Three-Center Transformation

For most applications, the code will be able to size the blocks without help from the user. Therefore, it is unlikely that users will have any reason to specify values for these entries except when doing very particular performance measurements.

The size of `xf3ci:AO 1 batch size` is the most important of the three, in terms of the effect on performance.

Local memory usage in the first two steps of the transformation is controlled in the RI-MP2 calculation using the following `SET` directives,

```
set "xf3ci:AO 1 batch size" <integer max>
set "xf3ci:AO 2 batch size" <integer max>
set "xf3ci:fit batch size" <integer max>
```

The size of the local arrays determines the sizes of the two matrix multiplications. These entries set limits on the size of blocks to be used in each index. The listing above is in order of importance of the parameters to performance, with `xf3ci:AO 1 batch size` being most important.

Note that these entries are only upper bounds and that the program will size the blocks according to what it determines as the best usage of the available local memory. The absolute maximum for a block size is the number of functions in the AO basis, or the number of fitting basis functions on a node. The absolute minimum value for block size is the size of the largest shell in the appropriate basis. Batch size entries specified for `max` that are larger than these limits are automatically reset to an appropriate value.

16.10 One-electron properties and natural orbitals

If an MP2 energy gradient is computed, all contributions are available to form the MP2 linear-response density. This is the density that when contracted with any spin-free, one-electron operator yields the associated property defined as the derivative of the energy. Thus, the reported MP2 dipole moment is the derivative of the energy w.r.t. an external magnetic field and is *not* the expectation value of the operator over the wavefunction. Only dipole moments are printed by the MP2 gradient code, but natural orbitals are produced and stored in the permanent directory with a file extension of `".mp2nos"`. These may be fed into the property package (see Section 28) to compute more general properties. Note that the MP2 linear response density matrix is not necessarily positive definite so it is not unusual to see a few small negative natural orbital occupation numbers.

Chapter 17

Multiconfiguration SCF

The NWChem multiconfiguration SCF (MCSCF) module can currently perform complete active space SCF (CASSCF) calculations with at most 20 active orbitals and about 500 basis functions. It is planned to extend it to handle 1000+ basis functions.

```
MCSCF
  STATE <string state>
  ACTIVE <integer nactive>
  ACTELEC <integer nactelec>
  MULTIPLICITY <integer multiplicity>
  [SYMMETRY <integer symmetry default 1>]
  [VECTORS [[input] <string input_file default $file_prefix$.movecs>]
         [swap <integer vec1 vec2> ...] \
         [output <string output_file default input_file>] \
         [lock]
  [HESSIAN (exact||onel)]
  [MAXITER <integer maxiter default 20>]
  [THRESH  <real thresh default 1.0e-4>]
  [TOL2E <real tol2e default 1.0e-9>]
  [LEVEL <real shift default 0.1d0>]
END
```

Note that the `ACTIVE`, `ACTELEC`, and `MULTIPLICITY` directives are *required*. The symmetry and multiplicity may alternatively be entered using the `STATE` directive.

17.1 `ACTIVE` — Number of active orbitals

The number of orbitals in the CASSCF active space must be specified using the `ACTIVE` directive.

E.g.,

```
active 10
```

The input molecular orbitals (see the vectors directive, Sections 17.6 and 10.5) must be arranged in order

1. doubly occupied orbitals,
2. active orbitals, and
3. unoccupied orbitals.

17.2 ACTELEC — Number of active electrons

The number of electrons in the CASSCF active space must be specified using the the `ACTELEC` directive. An error is reported if the number of active electrons and the multiplicity are inconsistent.

The number of closed shells is determined by subtracting the number of active electrons from the total number of electrons (which in turn is derived from the sum of the nuclear charges minus the total system charge).

17.3 MULTIPLICITY

The spin multiplicity must be specified and is enforced by projection of the determinant wavefunction.

E.g., to obtain a triplet state

```
multiplicity 3
```

17.4 SYMMETRY — Spatial symmetry of the wavefunction

This species the irreducible representation of the wavefunction as an integer in the range 1—8 using the same numbering of representations as output by the SCF program. Note that only Abelian point groups are supported.

E.g., to specify a B_1 state when using the C_{2v} group

```
symmetry 3
```

17.5 STATE — Symmetry and multiplicity

The electronic state (spatial symmetry and multiplicity) may alternatively be specified using the conventional notation for an electronic state, such as $^3B_2$ for a triplet state of B_2 symmetry. This would be accomplished with the input

```
state 3b2
```

which is equivalent to

```
symmetry 4
multiplicity 3
```

17.6 VECTORS — Input/output of MO vectors

Calculations are best started from RHF/ROHF molecular orbitals (see Section 10), and by default vectors are taken from the previous MCSCF or SCF calculation. To specify another input file use the VECTORS directive. Vectors are by default output to the input file, and may be redirected using the output keyword. The swap keyword of the VECTORS directive may be used to reorder orbitals to obtain the correct active space. See Section 10.5 for an example.

The LOCK keyword allows the user to specify that the ordering of orbitals will be locked to that of the initial vectors, insofar as possible. The default is to order by ascending orbital energies within each orbital space. One application where locking might be desirable is a calculation where it is necessary to preserve the ordering of a previous geometry, despite flipping of the orbital energies. For such a case, the LOCK directive can be used to prevent the SCF calculation from changing the ordering, even if the orbital energies change.

Output orbitals of a converged MCSCF calculation are canonicalized as follows:

- Doubly occupied and unoccupied orbitals diagonalize the corresponding blocks of an effective Fock operator. Note that in the case of degenerate orbital energies this does not fully determine the orbtials.
- Active-space orbitals are chosen as natural orbitals by diagonalization of the active space 1-particle density matrix. Note that in the case of degenerate occupations that this does not fully determine the orbitals.

17.7 HESSIAN — Select preconditioner

The MCSCF will use a one-electron approximation to the orbital-orbital Hessian until some degree of convergence is obtained, whereupon it will attempt to use the exact orbital-orbital Hessian which makes the micro iterations more expensive but potentially reduces the total number of macro iterations. Either choice may be forced throughout the calculation by specifying the appropriate keyword on the HESSIAN directive.

E.g., to specify the one-electron approximation throughout

```
hessian onel
```

17.8 LEVEL — Level shift for convergence

The Hessian (Section 17.7) used in the MCSCF optimization is by default level shifted by 0.1 until the orbital gradient norm falls below 0.01, at which point the level shift is reduced to zero. The initial value of 0.1 may be changed using the LEVEL directive. Increasing the level shift may make convergence more stable in some instances.

E.g., to set the initial level shift to 0.5

```
level 0.5
```

17.9 PRINT and NOPRINT

Specific output items can be selectively enabled or disabled using the print control mechanism (5.6) with the available print options listed in table(17.9).

Option	Class	Synopsis
`ci energy`	default	CI energy eigenvalue
`fock energy`	default	Energy derived from Fock matrices
`gradient norm`	default	Gradient norm
`movecs`	default	Converged occupied MO vectors
`trace energy`	high	Trace Energy
`converge info`	high	Convergence data and monitoring
`precondition`	high	Orbital preconditioner iterations
`microci`	high	CI iterations in line search
`canonical`	high	Canonicalization information
`new movecs`	debug	MO vectors at each macro-iteration
`ci guess`	debug	Initial guess CI vector
`density matrix`	debug	One- and Two-particle density matrices

Table 17.1: MCSCF Print Options

Chapter 18

Selected CI

The selected CI module is integrated into NWChem but as yet no input module has been written. The input thus consists of setting the appropriate variables in the database.

It is assumed that an initial SCF/MCSCF calculation has completed, and that MO vectors are available. These will be used to perform a four-index transformation, if this has not already been performed.

18.1 Background

This is a general spin-adapted, configuration-driven CI program which can perform arbitrary CI calculations, the only restriction being that all spin functions are present for each orbital occupation. CI wavefunctions may be specified using a simple configuration generation program, but the prime usage is intended to be in combination with perturbation correction and selection of new configurations. The second-order correction (Epstein-Nesbet) to the CI energy may be computed, and at the same time configurations that interact greater than a certain threshold with the current CI wavefunction may be chosen for inclusion in subsequent calculations. By repeating this process (typically twice is adequate) with the same threshold until no new configurations are added, the CI expansion may be made consistent with the selection threshold, enabling tentative extrapolation to the full-CI limit.

A typical sequence of calculations is as follows:

1. Pick as an initial CI reference the previously executed SCF/MCSCF.
2. Define an initial selection threshold.
3. Determine the roots of interest in the current reference space.
4. Compute the perturbation correction and select additional configurations that interact greater than the current threshold.
5. Repeat steps 3 and 4.
6. Lower the threshold (a factor of 10 is common) and repeat steps 3, 4, and 5. The *first* pass through step 4 will yield the approximately self-consistent CI and CI+PT energies from the *previous* selection threshold.

To illustrate this, below is some abbreviated output from a calculation on water in an augmented cc-PVDZ basis set with one frozen core orbital. The SCF was converged to high precision in C_{2v} symmetry with the following input

```
start h2o
geometry; symmetry c2v
  O 0 0 0; H 0 1.43042809 -1.10715266
end
basis
  H library aug-cc-pvdz; O library aug-cc-pvdz
end
task scf
scf; thresh 1d-8; end
```

The following input restarts from the SCF to perform a sequence of selected CI calculations with the specified tolerances, starting with the SCF reference.

```
restart h2o
set fourindex:occ_frozen 1
set selci:mode select
set "selci:selection thresholds" \
    0.001 0.001 0.0001 0.0001 0.00001 0.00001 0.000001
task selci
```

Table 18.1 summarizes the output from each of the major computational steps that were performed.

Step	Description	CI dimension	Energy
1	Four-index, one frozen-core		
2	Config. generator, SCF default	1	
3+4	CI diagonalization	1	$E_{CI} = -76.041983$
5	PT selection T=0.001	1	$E_{CI+PT} = -76.304797$
6+7	CI diagonalization	75	$E_{CI} = -76.110894$
8	PT selection T=0.001	75	$E_{CI+PT} = -76.277912$
9+10	CI diagonalization	75	$E_{CI}(T = 0.001) = -76.110894$
11	PT selection T=0.0001	75	$E_{CI+PT}(T = 0.001) = -76.277912$
12+13	CI diagonalization	823	$E_{CI} = -76.228419$
14	PT selection T=0.0001	823	$E_{CI+PT} = -76.273751$
15+16	CI diagonalization	841	$E_{CI}(T = 0.0001) = -76.2300544$
17	PT selection T=0.00001	841	$E_{CI+PT}(T = 0.0001) = -76.274073$
18+19	CI diagonalization	2180	$E_{CI} = -76.259285$
20	PT selection T=0.00001	2180	$E_{CI+PT} = -76.276418$
21+22	CI diagonalization	2235	$E_{CI}(T = 0.00001) = -76.259818$
23	PT selection T=0.000001	2235	$E_{CI+PT}(T = 0.00001) = -76.276478$
24	CI diagonalization	11489	

Table 18.1: Summary of steps performed in a selected CI calculation on water.

18.2 Files

Currently, no direct control is provided over filenames. All files are prefixed with the standard file-prefix, and any files generated by all nodes are also postfixed with the processor number. Thus, for example the molecular integrals file, used only by process zero, might be called `h2o.moints` whereas the off-diagonal Hamiltonian matrix element file used by process number eight would be called `h2o.hamil.8`.

`ciconf` — the CI configuration file, which holds information about the current CI expansion, indexing vectors, etc. This is the most important file and is required for all restarts. Note that the CI configuration generator is only run if this file does not exist. Referenced only by process zero.

`moints` — the molecular integrals, generated by the four-index transformation. As noted above these must currently be manually deleted, or the database entry `selci:moints:force` set, to force regeneration. Referenced only by process zero.

`civecs` — the CI vectors. Referenced only by process zero.

`wmatrx` — temporary file used to hold coupling coefficients. Deleted at calculation end. Referenced only by process zero.

`rtname, roname` — restart information for the PT selection. Should be automatically deleted if no restart is necessary. Referenced only by process zero.

`hamdg` — diagonal elements of the Hamiltonian. Deleted at calculation end. Referenced only by process zero.

`hamil` — off-diagonal Hamiltonian matrix elements. All processes generate a file containing a subset of these elements. These files can become very large. Deleted at calculation end.

18.3 Configuration Generation

If no configuration is explicitly specified then the previous SCF/MCSCF wavefunction is used, adjusting for any orbitals frozen in the four-index transformation. The four-index transformation must have completed successfully before this can execute. Orbital configurations for use as reference functions may also be explicitly specified.

Once the default/user-input reference configurations have been determined additional reference functions may be generated by applying multiple sets of creation-annihilation operators, permitting for instance, the ready specification of complete or restricted active spaces.

Finally, a uniform level of excitation from the current set of configurations into all orbitals may be applied, enabling, for instance, the simple creation of single or single+double excitation spaces from an MCSCF reference.

18.3.1 Specifying the reference occupation

A single orbital configuration or occupation is specified by

```
ns  (socc(i),i=1,ns)  (docc(i),i=1,nd)
```

where `ns` specifies the number of singly occupied orbitals, `socc()` is the list of singly occupied orbitals, and `docc()` is the list of doubly occupied orbitals (the number of doubly occupied orbitals, `nd`, is inferred from `ns` and the total number of electrons). All occupations may be strung together and inserted into the database as a single integer array with name `"selci:conf"`. For example, the input

```
set "selci:conf" \
  0               1  2  3  4 \
  0               1  2  3 27 \
  0               1  3  4 19 \
  2   11 19       1  3  4 \
  2    8 27       1  2  3 \
  0               1  2  4 25 \
  4   3  4 25 27   1  2 \
  4   2  3 19 20   1 4 \
  4   2  4 20 23   1 3
```

specifies the following nine orbital configurations

```
1(2)  2(2)  3(2)  4(2)
1(2)  2(2)  3(2) 27(2)
1(2)  3(2)  4(2) 19(2)
1(2)  3(2)  4(2) 11(1) 19(1)
1(2)  2(2)  3(2)  8(1) 27(1)
1(2)  2(2)  4(2) 25(2)
1(2)  2(2)  3(1)  4(1) 25(1) 27(1)
1(2)  2(1)  3(1)  4(2) 19(1) 20(1)
1(2)  2(1)  3(2)  4(1) 20(1) 23(1)
```

The optional formatting of the input is just to make this arcane notation easier to read. Relatively few configurations can be currently specified in this fashion because of the input line limit of 1024 characters.

18.3.2 Applying creation-annihilation operators

Up to 10 sets of creation-annihilation operator pairs may be specified, each set containing up to 255 pairs. This suffices to specify complete active spaces with up to ten electrons.

The number of sets is specified as follows,

```
set selci:ngen 4
```

which indicates that there will be four sets. Each set is then specified as a separate integer array

```
set "selci:refgen  1" 5 4    6 4   5 3   6 3
set "selci:refgen  2" 5 4    6 4   5 3   6 3
set "selci:refgen  3" 5 4    6 4   5 3   6 3
set "selci:refgen  4" 5 4    6 4   5 3   6 3
```

In the absence of friendly, input note that the names `"selci:refgen n"` must be formatted with n in `I2` format. Each set specifies a list of creation-annihilation operator pairs (in that order). So for instance, in the above example each set is the same and causes the excitations

```
4->5   4->6   3->5   3->6
```

If orbitals 3 and 4 were initially doubly occupied, and orbitals 5 and 6 initially unoccupied, then the application of this set of operators four times in succession is sufficient to generate the four electron in four orbital complete active space.

The precise sequence in which operators are applied is

1. loop through sets of operators
2. loop through reference configurations
3. loop through operators in the set
4. apply the operator to the configuration, if the result is new add it to the new list
5. end the loop over operators
6. end the loop over reference configurations
7. augment the configuration list with the new list
8. end the loop over sets of operators

18.3.3 Uniform excitation level

By default no excitation is applied to the reference configurations. If, for instance, you wanted to generate a single excitation CI space from the current configuration list, specify

```
set selci:exci 1
```

Any excitation level may be applied, but since the list of configurations is explicitly generated, as is the CI Hamiltonian matrix, you will run out of disk space if you attempt to use more than a few tens of thousands of configurations.

18.4 Number of roots

By default, only one root is generated in the CI diagonalization or perturbation selection. The following requests that 2 roots be generated

```
set selci:nroot 2
```

There is no imposed upper limit. If many roots are required, then, to minimize root skipping problems, it helps to perform an initial approximate diagonalization with several more roots than required, and then resetting this parameter once satisfied that the desired states are obtained.

18.5 Accuracy of diagonalization

By default, the CI wavefunctions are converged to a residual norm of 10^{-6} which provides similar accuracy in the perturbation corrections to the energy, and much higher accuracy in the CI eigenvalues. This may be adjusted with

```
set "selci:diag tol" 1d-3
```

the example setting much lower precision, appropriate for the approximate diagonalization discussed in the preceding section.

18.6 Selection thresholds

When running in the selected-CI mode the program will loop through a list of selection thresholds (T), performing the CI diagonalization, computing the perturbation correction, and augmenting the CI expansion with configurations that make an energy lowering to any root greater than T. The list of selection thresholds is specified as follows

```
set "selci:selection thresholds" \
    0.001 0.001 0.0001 0.0001 0.00001 0.00001 0.000001
```

There is no default for this parameter.

18.7 Mode

By default the program runs in `"ci+davids"` mode and just determines the CI eigenvectors/values in the current configuration space. To perform a selected-CI with perturbation correction use the following

```
set selci:mode select
```

and remember to define the selection thresholds.

18.8 Memory requirements

No global arrays are used inside the selected-CI, though the four-index transformation can be automatically invoked and it does use GAs. The selected CI replicates inside each process

- all unique two-electron integrals in the MO basis that are non-zero by symmetry, and
- all CI information, including the CI vectors.

These large data structures are allocated on the local stack. A fatal error will result if insufficient memory is available.

18.9 Forcing regeneration of the MO integrals

When scanning a potential energy surface or optimizing a geometry the MO integrals need to be regenerated each time. Specify

```
set selci:moints:force logical .true.
```

to accomplish this.

18.10 Disabling update of the configuration list

When computing CI+PT energy the reference configuration list is normally updated to reflect all configurations that interact more than the specified threshold. This is usually desirable. But when scanning a potential energy surface or optimizing a geometry the reference list must be kept fixed to keep the potential energy surface continuous and well defined. To do this specify

```
set selci:update logical .false.
```

18.11 Orbital locking in CI geometry optimization

The selected CI wavefunction is not invariant to orbital rotations or to swapping two or more orbitals. Orbitals could be swapped or rotated when the geometry is changed in a geometry optimization step. The keyword `lock` has to be set in the SCF/MCSCF (vectors) input block to keep the orbitals in the same order throughout the geometry optimization.