

Computational Methods Summary

Types of Energy Models (QM or MM)

1. Molecular mechanics (MM)

- Useful for initial calculations on small organics, can do **any size up through proteins**.
- Uses classical ball-and-spring laws where each force constant, ideal bond length, angle and dihedral angle are empirical parameters. Through-space electrostatic and VDW interactions are also added.
- *Empirical parameters* mean that method is only useful if you have parameters (a **force field**) closely matching every type of linkage in your system.
- Programs available here: MacroModel, AMBER, NAMD, Desmond, Gromacs, more.....

2. Hartree-Fock (QM)

- Mainly used as a starting point for high-level *ab initio* calculations or mixed with DFT (see 3).
- *Approximate solution of the Schrödinger equation* neglecting instantaneous electron-electron interactions (correlation) unless corrections are applied.
- Energy and orbital coefficients solved for by an iterative **self consistent field (SCF) method**.
- High-level calculations (configuration interaction, coupled cluster, G3, etc.) can correct for correlation and achieve chemical accuracy but only possible for small numbers of atoms, very time consuming.
- Programs available here: Gaussian, Jaguar, QChem, Gamess, NWChem, more

3. Density functional theory (QM)

- Appropriate for systems **up to ca. 100 atoms** (sometimes larger), best choice for most organometallics
- Based on an equation analogous to the Schrödinger equation where *energy is a functional of electron density*, not the true wavefunction. Iterative SCF procedure is similar to that of HF.
- Implicitly includes electron correlation, so much **more accurate than HF**, but behavior is sometimes **unpredictable** because the electronic density functional cannot be derived *ab initio*.
- Myriad functionals designed (parameterized) based on certain principles. The most *popular* one is **B3-LYP** which includes some HF exchange (**hybrid DFT**). **B3LYP** has very good performance for organic molecules, but may not be suitable for metal complexes and structures with non-covalent interactions. Some recently developed functionals are **ω B97X-D**, **M06**, **HSE06**, **BMK**, **TPSSH**, etc...
- Programs available here: Gaussian, Jaguar, QChem, Gamess, NWChem, more.....

Basis Sets (for QM calculations only)

- The set of atomic orbitals whose coefficients are optimized in SCF.
- Each orbital usually represented by a *linear combination of Gaussian functions*.
- The number of Slater-type orbital (STO) determines the size of a basis set. The bigger the basis set, the better the results, but for DFT not much gain beyond triple-zeta level (three STO).
- **6-31G** is a *popular* double-zeta level split-valence basis set. It uses 6 Gaussian functions to describe inner shell orbitals, while 3 and 1 Gaussian functions for the 1st and the 2nd valence STO, respectively.
- **Polarization functions** (** or (d,p) after G) add d functions to p shells (carbon, phosphorus, etc.) and p functions to hydrogen. *Must use at least d functions on p shells (one *) for acceptable results!*
- **Diffuse functions** (++) before G) add next-principal-quantum-number shell. In DFT, normally only useful for anions, excited states or sometimes late transition metals.
- **Effective core potentials (ECP)** replace core electrons with a potential felt by valence electrons, simplifies calculation of heavy atoms. The relativistic effect of core electrons can be included in the ECP. Normally needed for atoms heavier than 1st-row transition metals.
- If you have **metals/heavy atoms**, start with **LANL2DZ** but then see our page for suggestions about better basis sets: http://glab.cchem.berkeley.edu/gl原因/faq/gauss_custombasis.html

QM Output:

- Can include orbital energies/pictures, excitation energies, partial charges, dipole and multipole moments, polarizabilities, NMR shielding and coupling constants, etc.

Common Types of Geometry Algorithms

1. Molecular energy (calculates energy of input geometry – no geometry change)

- Can be used on a previously optimized geometry
 - MM:** Energy is relative to a hypothetical unstrained system.
 - QM:** SCF energy, relative to a separated collection of electrons and nuclei.
- Add up energies of species on each side of a **balanced** chemical equation and calculate reaction energy (*Make sure the total number of basis functions are the same in the whole reaction*).

2. Geometry optimization (also called minimization)

- Finds **local minimum**: the bottom of whichever potential energy well in which a molecule is drawn.
- **Iterative** process, with the molecular energy calculated between *each* optimization cycle.
- Can optimize all coordinates or constrain one or more coordinates.
- Default **convergence criteria** are arbitrarily set, you might allow looser or need tighter criteria.

3. Coordinate Scan

- Can be used to manually adjust a distance, angle or torsion systematically. Commonly used for searching torsions (dihedral drive) or as a manual method to locate transition states (TS).

4. Conformational searching

- Best methods **randomly sample potential energy surface** to find **global minimum**-energy structure.
- Nearly always confined to **MM** methods due to number of structures generated/minimized.
- For flexible organic species, *perform conformational search before QM geometry optimization*.

5. Transition state searching

- Needed to model chemical **kinetics**, locates an energy *maximum* along a reaction coordinate while *minimizing* energy w.r.t. all other coordinates for a reaction mechanism study.
- Normally used with **QM** methods, locating correct TS in the reaction pathway is much more difficult to be successfully achieved than optimization for intermediates.
- A converged TS must have exactly one imaginary vibrational frequency.
- Perform intrinsic reaction coordinate (IRC) calculation for a TS and confirm reactant and product.

6. Vibrational frequencies

- Normally used with **QM** methods, calculates the molecular vibrational frequencies and sometimes IR and/or Raman intensities.
- Also calculates **zero-point energies** (ZPE), thermal enthalpies and thermal Gibbs free energies which should be added to SCF energies when studying reaction kinetics or thermodynamics.
- A true minimum has all real-valued frequencies, a transition state has exactly one imaginary frequency.

7. Molecular dynamics

- Applicable to **MM** (up to macromolecules) and sometimes **QM** methods (very small systems).
- Models molecular **motion over time**, response to forces acting on molecule.
- Will eventually sample *all* accessible conformations at a given temperature, if the simulation is run long enough (this can be very long and in some cases impractical).
- For large systems (proteins, DNA, etc.) more useful than conformational searching.
- Takes into account that reaction trajectories do not always follow the exact minimum-energy path.