Advanced **M**olecular **M**odeling **M**ethods

Weds 11am BME 1.112/Zoom

Advances in Modeling Molecular Interactions:

Development of AMOEBA+ Potential – Part I

Chengwen Liu

Department of Biomedical Engineering

The University of Texas at Austin

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AMOEBA: Multipolar and Polarizable Potential

(**A**tomic **M**ultipole **O**ptimized **E**nergetics for **B**iomolecular **A**pplications)

$$E_{valence} = E_{bnd} + E_{ang} + E_{strbnd} + E_{opbend} + E_{torsion} + E_{couplings}$$

$$E_{nonbonded} = \sum \varepsilon_{ij} \left(\frac{1.07}{\rho_{ij} + 0.07} \right)^7 \left(\frac{1.12}{\rho_{ij}^7 + 0.12} - 2 \right) + \sum (\boldsymbol{M_i})^t T_{ij} \boldsymbol{M_j} + \sum \frac{1}{2} (\mu_i^{ind})^T E_i$$

vdW

Electrostatics **Polarization**

$$\boldsymbol{M}_i = \left[q_i, \mu_{ix}, \mu_{iy}, \mu_{iz}, Q_{ixx}, Q_{ixy}, \dots, Q_{izz} \right]^t$$

Ren, ***JPCB***, 2003
Ponder, ***JPCB***, 2010
Jing, ***Ann. Rev. BioPhys.***, 2019

Outlines and Objectives

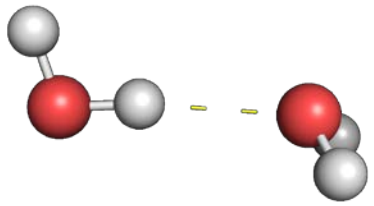
Contents [hide]

- ❑ Theories of SAPT with minimal math
- ❑ Practice on running SAPT with Psi4
- ❑ **How** we explored each energy component
- ❑ Lessons learned from the past
- ❑ General idea of improving a force field

reading material:

https://biomolmd.org/mw/index.php/Ammm:Mm_aplus

Interaction Energy: *Supermolecular* Approach



$$E_{int} = E_{AB} - E_A - E_B$$

- Gold standard
  - CCSD(T)/CBS
- Basis set superposition error

❖ Relies on error cancellation

❖ Lack of nature of interactions

Symmetry Adapted Perturbation Theory

- Schrodinger's equations for monomers *A* and *B*

$$H_X \Phi_X = E_X \Phi_X, \quad X = A \text{ or } B$$

- Hamiltonian of the dimer

$$H = H_A + H_B + V = H_0 + V$$

- Solution of the unperturbed H_0

$$E^{(0)} = E_A + E_B \qquad \Psi^{(0)} = \Phi_A \Phi_B$$

Symmetry Adapted Perturbation Theory

- The interaction energy expressed as a sum of perturbation corrections

$$E_{\text{int}} = E_{\text{RS}}^{(1)} + E_{\text{RS}}^{(2)} + \ldots.$$

- Anti-symmetrizer operation

$$\mathcal{A}\,[a(1)b(2)] = a(1)b(2) - a(2)b(1)$$

- Differences are called exchange energies

$$E_{\text{exch}}^{(i)} = E^{(i)} - E_{\text{RS}}^{(i)}.$$

Symmetry Adapted Perturbation Theory

- Hartree-Fock (HF) Approximation and Correlation
  - Mean-field theory
  - Correlation methods (MBPT, CC)

- SAPT Hamiltonian

$$H = F_A + F_B + W_A + W_B + V$$

F: Fock operator
W: Intramonomer correlation operator
V: Intermonomer interaction operator

Symmetry Adapted Perturbation Theory

- Interaction energy is expressed

$$E_{\text{int}} = \sum_{i=1,\, j=0} E^{(ij)}$$

$i(j)$ is the order in $V(W)$

- SAPT energy component

$$E_{SAPT} = \sum_{m>0} \sum_{n\geq 0} E_{SAPT}^{(mn)} = E_{elst} + E_{exch} + E_{ind} + E_{disp}$$

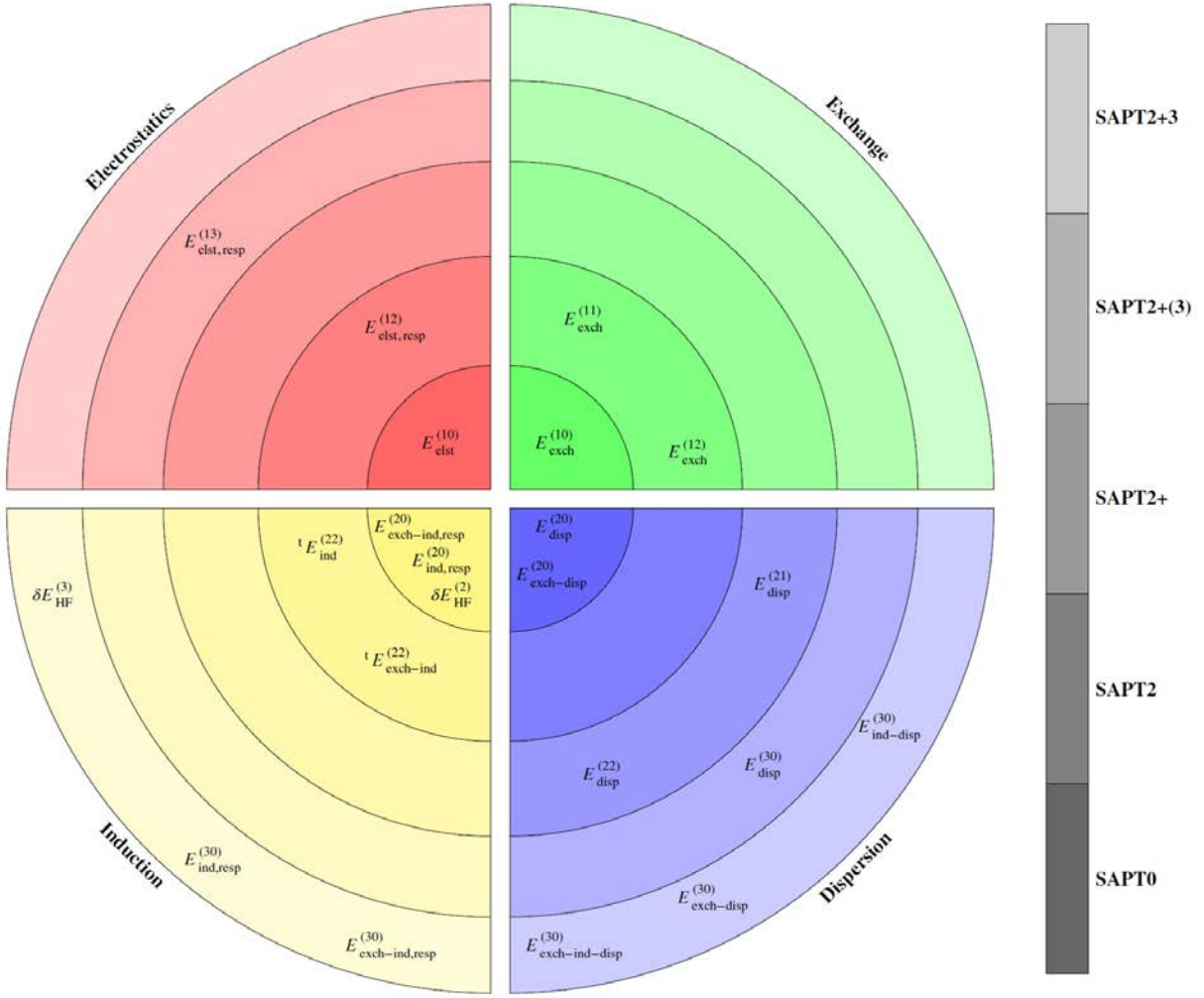
Symmetry Adapted Perturbation Theory

- Levels of SAPT

$$
\begin{aligned}
E_{SAPT0} &= E_{elst}^{(10)} + E_{exch}^{(10)} + E_{ind,resp}^{(20)} + E_{exch-ind,resp}^{(20)} + \delta E_{HF}^{(2)} + E_{disp}^{(20)} + E_{exch-disp}^{(20)} \\
E_{SAPT2} &+= E_{elst,resp}^{(12)} + E_{exch}^{(11)} + E_{exch}^{(12)} + {}^{t}E_{ind}^{(22)} + {}^{t}E_{exch-ind}^{(22)} \\
E_{SAPT2+} &+= E_{disp}^{(21)} + E_{disp}^{(22)} \\
E_{SAPT2+(3)} &+= E_{elst,resp}^{(13)} + E_{disp}^{(30)} \\
E_{SAPT2+3} &+= E_{exch-disp}^{(30)} + E_{ind-disp}^{(30)} + E_{exch-ind-disp}^{(30)}
\end{aligned}
$$

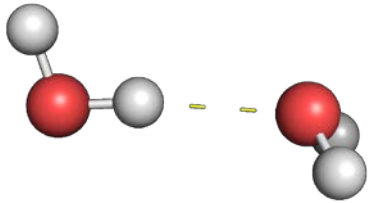
Symmetry Adapted Perturbation Theory

- Levels of SAPT
  - Electrostatics
  - Induction
  - Exchange
  - Dispersion



SAPT and CCSD(T)/CBS Calculations

- **Input files**



  - /home/liuchw/public_html/AMM_aplus
  - https://biomol.bme.utexas.edu/~liuchw/AMM_aplus

- **Compare the results**

SAPT and CCSD(T)/CBS Calculations

SAPT

```
  SAPT Results
-------------------------------------------------------------------------------------------
  Electrostatics              -12.88305289 [mEh]      -8.08423774 [kcal/mol]     -33.82445069 [kJ/mol]
    Elst10,r                  -13.28732680 [mEh]      -8.33792345 [kcal/mol]     -34.88587172 [kJ/mol]
    Elst12,r                    0.16858266 [mEh]       0.10578721 [kcal/mol]       0.44261370 [kJ/mol]
    Elst13,r                    0.23569126 [mEh]       0.14789850 [kcal/mol]       0.61880732 [kJ/mol]

  Exchange                     12.88899409 [mEh]       8.08796590 [kcal/mol]      33.84004933 [kJ/mol]
    Exch10                     11.14311571 [mEh]       6.99241068 [kcal/mol]      29.25624627 [kJ/mol]
    Exch10(S^2)                11.06411493 [mEh]       6.94283694 [kcal/mol]      29.04882975 [kJ/mol]
    Exch11(S^2)                 0.14286433 [mEh]       0.08964872 [kcal/mol]       0.37509025 [kJ/mol]
    Exch12(S^2)                 1.60301405 [mEh]       1.00590650 [kcal/mol]       4.20871280 [kJ/mol]

  Induction                    -4.02156434 [mEh]      -2.52356972 [kcal/mol]     -10.55861572 [kJ/mol]
    Ind20,r                    -4.77703438 [mEh]      -2.99763433 [kcal/mol]     -12.54210203 [kJ/mol]
    Ind22                      -0.70315409 [mEh]      -0.44123585 [kcal/mol]      -1.84613081 [kJ/mol]
    Exch-Ind20,r                2.61902451 [mEh]       1.64346270 [kcal/mol]       6.87624792 [kJ/mol]
    Exch-Ind22                  0.38550650 [mEh]       0.24190898 [kcal/mol]       1.01214718 [kJ/mol]
    delta HF,r (2)             -1.46694123 [mEh]      -0.92051952 [kcal/mol]      -3.85145368 [kJ/mol]
    delta MP2,r (2)            -0.07896565 [mEh]      -0.04955169 [kcal/mol]      -0.20732429 [kJ/mol]

  Dispersion                   -3.85052017 [mEh]      -2.41623789 [kcal/mol]     -10.10953932 [kJ/mol]
    Disp20                     -4.05563051 [mEh]      -2.54494657 [kcal/mol]     -10.64805645 [kJ/mol]
    Disp30                      0.14638417 [mEh]       0.09185745 [kcal/mol]       0.38433159 [kJ/mol]
    Disp21                      0.07191071 [mEh]       0.04512465 [kcal/mol]       0.18880155 [kJ/mol]
    Disp22 (SDQ)               -0.06804450 [mEh]      -0.04269857 [kcal/mol]      -0.17865081 [kJ/mol]
    Disp22 (T)                 -0.57474478 [mEh]      -0.36065779 [kcal/mol]      -1.50899220 [kJ/mol]
    Est. Disp22 (T)            -0.68081841 [mEh]      -0.42722000 [kcal/mol]      -1.78748849 [kJ/mol]
    Exch-Disp20                 0.73567837 [mEh]       0.46164515 [kcal/mol]       1.93152329 [kJ/mol]

Total HF                       -5.76916219 [mEh]      -3.62020393 [kcal/mol]     -15.14693324 [kJ/mol]
Total SAPT0                    -9.08911433 [mEh]      -5.70350535 [kcal/mol]     -23.86346639 [kJ/mol]
Total SAPT2                    -7.49230089 [mEh]      -4.70148979 [kcal/mol]     -19.67103327 [kJ/mol]
Total SAPT2+                   -8.16925309 [mEh]      -5.12628371 [kcal/mol]     -21.44837102 [kJ/mol]
Total SAPT2+(3)                -7.78717766 [mEh]      -4.88652775 [kcal/mol]     -20.44523212 [kJ/mol]
Total SAPT2+dMP2               -8.24821874 [mEh]      -5.17583540 [kcal/mol]     -21.65569531 [kJ/mol]
Total SAPT2+(3)dMP2            -7.86614331 [mEh]      -4.93607945 [kcal/mol]     -20.65255641 [kJ/mol]

Special recipe for scaled SAPT0 (see Manual):
  Electrostatics sSAPT0        -13.28732680 [mEh]      -8.33792345 [kcal/mol]     -34.88587172 [kJ/mol]
  Exchange sSAPT0               11.14311571 [mEh]       6.99241068 [kcal/mol]      29.25624627 [kJ/mol]
  Induction sSAPT0              -3.56844793 [mEh]      -2.23923488 [kcal/mol]      -9.36895874 [kJ/mol]
  Dispersion sSAPT0             -3.30408052 [mEh]      -2.07334183 [kcal/mol]      -8.67486222 [kJ/mol]
Total sSAPT0                    -9.01673954 [mEh]      -5.65808949 [kcal/mol]     -23.67344641 [kJ/mol]
-------------------------------------------------------------------------------------------
```

CCSD(T)

```
==> N-Body: Counterpoise Corrected (CP) energies <==

n-Body      Total Energy [Eh]          I.E. [kcal/mol]          Delta [kcal/mol]
     1                    N/A          0.000000000000          0.000000000000
     2                    N/A         -5.112334965607         -5.112334965607
```

$E_{HF} = -3.62\ kcal/mol$

$E_{SAPT0} = -5.70\ kcal/mol$

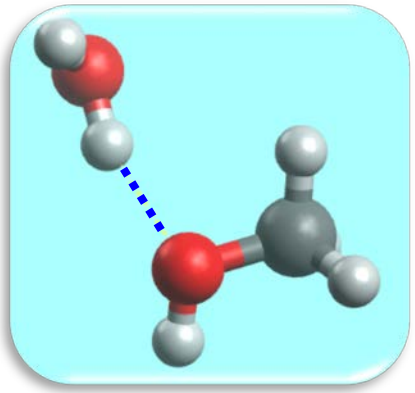
$E_{SAPT2+} = -5.13\ kcal/mol$

$E_{SAPT2+dMP2} = -5.18\ kcal/mol$

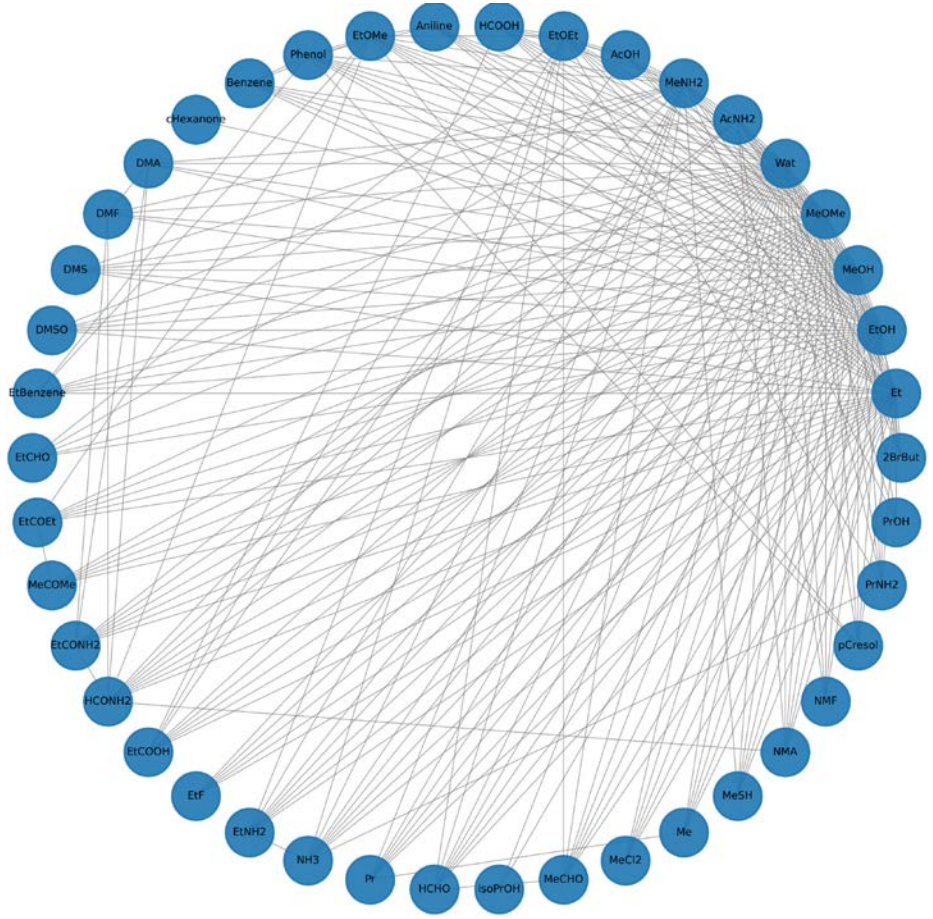
$E_{SAPT2+(3)dMP2} = -4.94\ kcal/mol$

$E_{CCSD(T)/CBS} = -5.11\ kcal/mol$

Dimer Interaction Networks for Organics



(Wat-MeOH)



- **Dimer set**
  - Homodimer
  - Heterodimer
  - 42 molecules
  - 280 pairs
  - 10 separations
- **Interaction energy**
  - SAPT2+(3)dMP2/aTZ
  - MP2/CBS
  - CCSD(T)/CBS (some)

- Element coverage: C, H, O, N, S, F, Cl, Br