

# Data Review

Yi Xie

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# Intermolecular Energies

► Supermolecular approach

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

- Straightforward, but cannot separate different types of interactions
  - Can adopt to different electronic structure methods
  - DFT-D3 with proper functional can be both cheap and accurate
- Symmetry-Adapted Perturbation Theory
- Can give details about different types of interactions; important in understanding their nature
  - Not as cheap as DFT-D3
  - SAPT0 is somewhat cheap, but does not include intramonomer correlation

# SAPT(DFT)

- ▶ Attempt to include intramonomer correlation in a cheap way
- ▶ Replaces HF orbitals with KS orbitals
- ▶ Needs to consider orbital response for dispersion terms
- ▶ Exchange-dispersion term needs to be estimated from scaling
- ▶ Investigate the accuracy and efficiency of SAPT(DFT)

## Three-Body Interaction

- ▶ Crucial in computing lattice energies
- ▶ DFT-D3 does not perform well for three-body interaction
- ▶ MP2.5 scales as  $O(N^6)$ , MP2 is  $O(N^5)$  but lacks three-body dispersion
- ▶ Three-body dispersion can be implemented with SAPT(DFT) in  $O(N^5)$
- ▶ Combine MP2 with SAPT(DFT) dispersion to model three-body interaction

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## Idea of SAPT(DFT)

- ▶ SAPT energy in orders of interaction and fluctuation potentials;  $n$  denotes order in  $V$  and  $k, l$  for  $W_A, W_B$

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

$$E_{int} = \sum_{n=1}^{\infty} \sum_{k=0}^{\infty} \sum_{l=0}^{\infty} \left( E_{pol}^{(nkl)} + E_{exch}^{(nkl)} \right)$$

- ▶ SAPT0:  $n = 2, k = l = 0$ , no intramonomer correlation,  $O(N^5)$  cost
- ▶ Many-body SAPT:  $k, l \geq 2$ ,  $O(N^7)$  or higher cost
- ▶ SAPT(DFT): Use Kohn-Sham operator  $K_{A,B}$  instead of Fock operator  $F_{A,B}$ ,  $O(N^5)$  cost
- ▶ Primitive SAPT(DFT) works well on 1st-order terms, but not 2nd-order terms (especially dispersion). Needs orbital response for them





## Dispersion Term

- ▶ ALDA kernel good for pure GGA functional, but not for hybrid functional
- ▶ Exact exchange in  $v_{xc} \rightarrow$  increased  $\epsilon_{ij}^{ab} \rightarrow$  decreased  $E_{disp}^{(2)}$

$$E_{disp,u}^{(2)} = -4 \sum_{ia \in A, jb \in B} \frac{|(ia|jb)|^2}{\epsilon_{ij}^{ab}}$$

- ▶ Hybrid ALDA kernel to compensate, or localized HF (LHF) exchange to avoid increase in  $\epsilon_{ij}^{ab}$

$$f_{xc} = \alpha f_{xc}^{HF} + (1 - \alpha) f_{xc}^{ALDA}$$



## Equation for $E_{disp}^{(2)}$

- ▶ Computing coupled FDDS:

$$\chi = \chi'_0 + (\chi'_0 \mathbf{S}^{-1} \mathbf{W} + \mathbf{K}) [\mathbf{S} - (\chi'_0 \mathbf{S}^{-1} \mathbf{W} + \mathbf{K})]^{-1} \chi'_0$$

$$\chi'_0 = \chi_0 - \alpha \mathbf{K}_2 (\lambda)$$

$$\mathbf{K} = [-\alpha \mathbf{K}_1 (\lambda d) - \alpha \mathbf{K}_2 (\lambda d) + \alpha^2 \mathbf{K}_{21} (\lambda)] (\mathbf{R}^t)^{-1} \mathbf{S}$$

- ▶  $O(N^5)$  scaling is limited to forming  $\mathbf{K}_1$ ,  $\mathbf{K}_2$  and  $\mathbf{K}_{21}$
- ▶ Separates nontrivial and trivial parts of the code, also highly reduces need of disk I/O operations
- ▶  $E_{disp}^{(2)}$  from coupled FDDS:

$$E_{disp}^{(2)} = -\frac{1}{2\pi} \int_0^\infty d\omega \int d\mathbf{r}_A d\mathbf{r}'_A d\mathbf{r}_B d\mathbf{r}'_B \frac{1}{|\mathbf{r}_A - \mathbf{r}_B|} \frac{1}{|\mathbf{r}'_A - \mathbf{r}'_B|} \chi^A(\mathbf{r}_A, \mathbf{r}'_A | i\omega) \chi^B(\mathbf{r}_B, \mathbf{r}'_B | i\omega)$$



## Exchange-Dispersion Term

- ▶ Coupled exchange-dispersion requires storing 4-index tensors on disk
- ▶ Estimate from scaling uncoupled exchange-dispersion; Scale with ratio in dispersion term or with pre-fitted (with S22×5) fixed factor

$$\tilde{E}_{\text{exch-disp,r}}^{(2)} = E_{\text{exch-disp,u}}^{(2)} \cdot \frac{E_{\text{disp,r}}^{(2)}}{E_{\text{disp,u}}^{(2)}}$$

$$\tilde{E}_{\text{exch-disp,r}}^{(2)} = \alpha \cdot E_{\text{exch-disp,u}}^{(2)} (\alpha = 0.686361)$$

- ▶ The value above is fitted from  $E_{\text{exch-disp,u}}^{(2)}$  with LHF orbitals
- ▶ Non-LHF orbitals have greater o-v gaps and smaller  $E_{\text{disp,u}}^{(2)}$ , needs to re-fit with non-LHF results

# LHF vs non-LHF orbitals

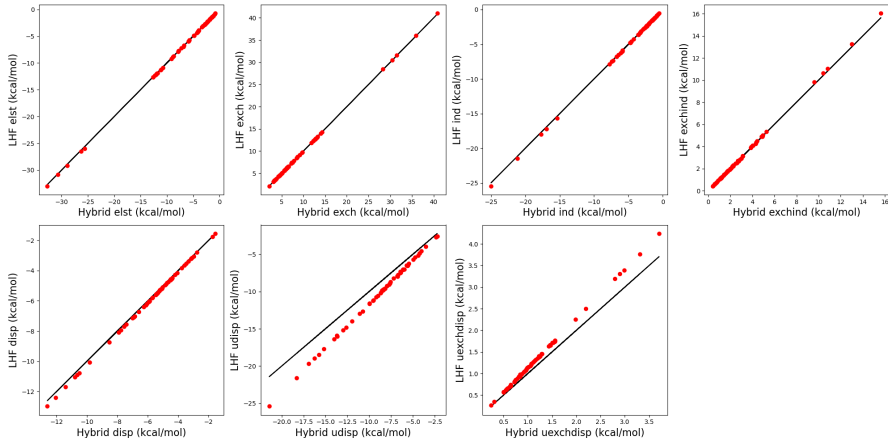


Figure: \*



# GRAC

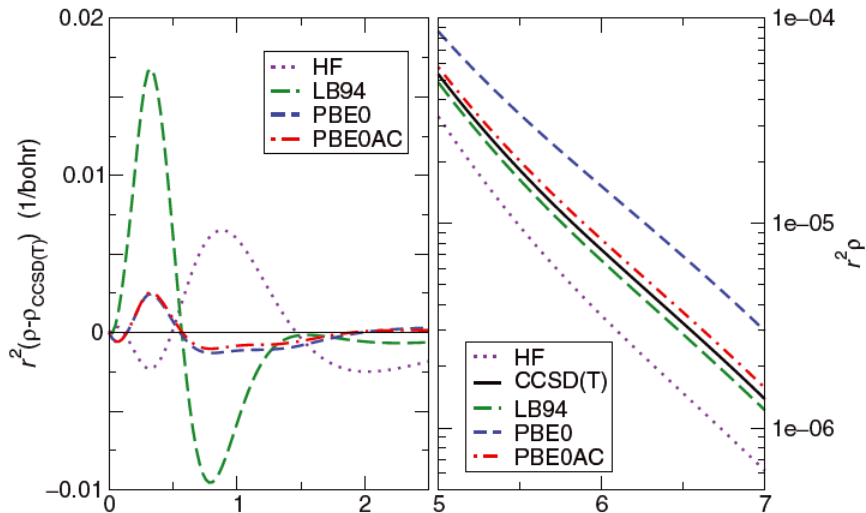
- ▶ (Hybrid-)GGA functionals does not have correct long-range behavior  
 $v_{xc}(r) \rightarrow -1/r + (I_p + \epsilon_{\text{HOMO}})$
- ▶ Underestimates o-v gap as a consequence
- ▶ Functionals like LB94 have correct asymptotic behavior, but poor in bulk region
- ▶ Using gradient-regulated asymptotic correction (GRAC) scheme to connect PBE0 and LB94 with the switching function  $f[g(\mathbf{r})]$ :

$$v_{xc}^{\text{GRAC}} = \{1 - f[g(\mathbf{r})]\} v_{xc}^{\text{PBE0}} + f[g(\mathbf{r})] v_{xc}^{\text{LB94}}$$

$$f[g(\mathbf{r})] = \left(1 + e^{-\alpha[g(\mathbf{r}) - \beta]}\right)^{-1}$$

$$g(\mathbf{r}) = \frac{|\nabla \rho(\mathbf{r})|}{\rho^{4/3}(\mathbf{r})}$$

# GRAC & Long-Range Behavior



# Test 5

Test0	Test1	Test2
Test1	Test2	Test3 $\LaTeX$
Test4	Test5	Test6

# Test 6

## Example block

Test0	Test1	Test2
Test1	Test2	Test3 $\LaTeX$
Test4	Test5	Test6

## Block

Test0	Test1	Test2
Test1	Test2	Test3 $\LaTeX$
Test4	Test5	Test6



# Test 7

## Block A

short Short stuff

long Longer stuff

longest label Longest stuff (insert cat)

- ▶ item1
- ▶ item2
- ▶ item3

## Frame with Columns

Block 1

Text here

Block 2

More text here

# Frame without Columns

Block

Even more text here