

Time-independent molecular properties

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Time-independent molecular properties

- ▶ When a molecular system is perturbed, its total energy changes

$$\mathcal{E}(\mu) = \mathcal{E}^{(0)} + \mathcal{E}^{(1)}\mu + \frac{1}{2}\mathcal{E}^{(2)}\mu^2 + \dots$$

- ▶ The expansion coefficients are characteristic of the molecule and its quantum state
 - ▶ we refer to these coefficients as **molecular properties**
- ▶ When the perturbation is **static**, the properties may be calculated by differentiation

$$\mathcal{E}^{(1)} = \left. \frac{d\mathcal{E}}{d\mu} \right|_{\mu=0}$$
$$\mathcal{E}^{(2)} = \left. \frac{d^2\mathcal{E}}{d\mu^2} \right|_{\mu=0}$$

- ▶ such properties are said to be **time independent**
- ▶ We do not here consider time-dependent molecular properties

Example I: Geometrical derivatives

- ▶ In the Born–Oppenheimer approximation, the nuclei move on the electronic potential-energy surface $\mathcal{E}(x)$, which is a function of the nuclear geometry:

$$\mathcal{E}(x) = \mathcal{E}_0 + \mathcal{E}^{(1)} \Delta x + \frac{1}{2} \mathcal{E}^{(2)} \Delta x^2 + \dots \leftarrow \text{expansion around the reference geometry}$$

- ▶ The derivatives of this surface are therefore important:

$$\mathcal{E}^{(1)} = \frac{d\mathcal{E}}{dx} \leftarrow \text{molecular gradient}$$

$$\mathcal{E}^{(2)} = \frac{d^2\mathcal{E}}{dx^2} \leftarrow \text{molecular Hessian}$$

- ▶ The geometrical derivatives are
 - ▶ used for locating and characterizing critical points
 - ▶ related to spectroscopic constants, vibrational frequencies, and intensities
- ▶ Usually, only a few terms are needed in the expansions
 - ▶ in some cases low-order expansions are inadequate or useless

Example II: Interaction with an external electric field

- ▶ The energy of interaction in an external electrostatic field is given by

$$\mathcal{E}_{\text{int}} = qV - p\bar{E} - \frac{1}{2}Q\bar{F} - \dots$$

where

V	potential	$q = \frac{d\mathcal{E}}{dV}$	charge
\bar{E}	field	$p = -\frac{d\mathcal{E}}{d\bar{E}}$	dipole moment
\bar{F}	field gradient	$Q = -2\frac{d\mathcal{E}}{d\bar{F}}$	quadrupole moment

- ▶ The permanent and induced moments are given by

$$p(\bar{E}) = \underbrace{p_0}_{\text{permanent moment}} + \underbrace{\alpha\bar{E}}_{\text{induced moment}} + \dots$$

where

$$p_0 = -\left.\frac{d\mathcal{E}}{d\bar{E}}\right|_{\bar{E}=0} \quad \text{permanent dipole moment}$$
$$\alpha = \left.\frac{dp}{d\bar{E}}\right|_{\bar{E}=0} = -\left.\frac{d^2\mathcal{E}}{d\bar{E}^2}\right|_{\bar{E}=0} \quad \text{dipole polarizability}$$

Example III: Magnetic resonance parameters

- ▶ Energy expansion in nuclear magnetic moments m and external magnetic field B :

$$\mathcal{E}(m, B) = \mathcal{E}_0 + \mathcal{E}^{(10)} m + \mathcal{E}^{(01)} B + \frac{1}{2} \mathcal{E}^{(20)} m^2 + \mathcal{E}^{(11)} Bm + \frac{1}{2} \mathcal{E}^{(02)} B^2 + \dots$$

- ▶ In NMR spectroscopy, we measure the coupling between m and B :

$$\mathcal{E}^{(11)} = \frac{d^2 \mathcal{E}}{dm dB}$$

- ▶ in vacuum, the coupling is equal to -1 since $\mathcal{E}_{\text{vac}} = -m \cdot B$
- ▶ in the presence of electrons, it is modified by a few ppm:

$$\mathcal{E}_{\text{mol}}^{(11)} = -1 + \sigma \quad \leftarrow \text{shielding constant}$$

- ▶ We also measure the coupling between magnetic nuclei

$$\mathcal{E}^{(20)} = \frac{d^2 \mathcal{E}}{dm^2} = J \quad \leftarrow \text{nuclear spin-spin coupling}$$

- ▶ in solution, only the indirect coupling (mediated by electrons) survives

Examples of derivatives

- ▶ Responses to geometrical perturbations
 - ▶ forces and force constants
 - ▶ spectroscopic constants
- ▶ Responses to external electromagnetic fields
 - ▶ permanent and induced moments
 - ▶ polarizabilities and magnetizabilities
 - ▶ optical activity
- ▶ Responses to external magnetic fields and nuclear magnetic moments
 - ▶ NMR shielding and indirect spin–spin coupling constants
 - ▶ EPR hyperfine coupling constants and g values
- ▶ Responses to nuclear quadrupole moments
 - ▶ nuclear field gradients, quadrupole coupling constants
- ▶ Responses to molecular rotation
 - ▶ spin–rotation constants and molecular g values

Numerical vs. analytical differentiation

- ▶ Numerical differentiation (finite differences and polynomial fitting)
 - ▶ often simple to implement (at least for real singlet perturbations)
 - ▶ difficulties related to numerical accuracy and computational efficiency
- ▶ Analytical differentiation (derivatives calculated from analytical expressions)
 - ▶ considerable programming effort required
 - ▶ greater speed, precision, and convenience
- ▶ Implementations of analytical techniques
 - ▶ first-order properties (dipole moments and gradients)
 - ▶ second-order properties (polarizabilities and Hessians, NMR parameters)

Overview: Calculation of derivatives

- ▶ Energy functionals:
 - ▶ variational and nonvariational energies
- ▶ Variational wave functions:
 - ▶ gradients and Hessians
 - ▶ response equations
 - ▶ the $2n + 1$ rule
- ▶ Nonvariational wave functions:
 - ▶ Lagrange's method of undetermined multipliers
 - ▶ the $2n + 1$ and $2n + 2$ rules
- ▶ Derivatives in more detail:
 - ▶ Hartree–Fock molecular gradients
- ▶ Hamiltonian derivatives in second quantization:
 - ▶ perturbation-dependent basis sets

The electronic energy function

- ▶ The electronic energy function contains the Hamiltonian and the wave function:

$$E(x, \lambda) = \langle \lambda | H(x) | \lambda \rangle$$

- ▶ It depends on two distinct sets of parameters:

x : external (perturbation) parameters (geometry, external field)

λ : electronic (wave-function) parameters (MOs, cluster amplitudes)

- ▶ The Hamiltonian (here in second quantization)

$$H(x) = \sum_{pq} h_{pq}(x) E_{pq} + \frac{1}{2} \sum_{pqrs} g_{pqrs}(x) e_{pqrs} + h_{\text{nuc}}(x)$$

depends **explicitly** on the external parameters:

$$h_{pq}(x) = \langle \phi_p(x) | h(x) | \phi_q(x) \rangle$$

- ▶ The wave function $|\lambda\rangle$ depends **implicitly** on the external parameters $\lambda(x)$.

The electronic energy and its derivatives

- ▶ The electronic energy $\mathcal{E}(x)$ is obtained by **optimizing the energy function** $E(x, \lambda)$ with respect to λ for each value of x :

$$\mathcal{E}(x) = E(x, \lambda^*)$$

- ▶ note: the optimization is not necessarily variational!
- ▶ Our task is to **calculate derivatives** of $\mathcal{E}(x)$ with respect to x :

$$\frac{d\mathcal{E}(x)}{dx} = \underbrace{\frac{\partial E(x, \lambda^*)}{\partial x}}_{\text{explicit dependence}} + \underbrace{\left. \frac{\partial E(x, \lambda)}{\partial \lambda} \right|_{\lambda=\lambda^*} \left. \frac{\partial \lambda}{\partial x} \right|_{\lambda=\lambda^*}}_{\text{implicit dependence}}$$

- ▶ the implicit dependence as well as the explicit dependence must be accounted for
- ▶ The quantity $\partial\lambda/\partial x$ is the **wave-function response**
 - ▶ it tells us how the electronic structure changes when the system is perturbed

Variational wave functions

- ▶ the optimized energy fulfills the **stationary (variational) condition**:

$$\frac{\partial E(x, \lambda)}{\partial \lambda} = 0 \quad (\text{for all } x)$$

- ▶ the Hartree–Fock energy in an unconstrained exponential parameterization

$$|\text{HF}\rangle = \exp(i\kappa)|0\rangle, \quad \kappa^\dagger = \kappa$$

- ▶ the energy of the full CI (FCI) wave function $|\text{FCI}\rangle = \sum_i c_i |i\rangle$ as an expectation value:

$$\frac{\partial E_{\text{FCI}}(x, c)}{\partial c} = 0$$

Nonvariational wave functions

- ▶ wave functions whose energy does not fulfill the stationary condition

$$\frac{\partial E(x, \lambda)}{\partial \lambda} \neq 0$$

- ▶ the Hartree–Fock and Kohn–Sham energies in a constrained parameterization

$$|\text{HF}\rangle = \frac{1}{\sqrt{N!}} \det|\phi_1, \phi_2, \dots, \phi_N|, \quad \phi_p(\mathbf{r}; \mathbf{x}) = \sum_\mu C_{\mu p} \chi_\mu(\mathbf{r}; \mathbf{x})$$

- ▶ the truncated CI energy

$$\frac{\partial E_{\text{CI}}(x, c, \kappa)}{\partial c} = 0, \quad \frac{\partial E_{\text{CC}}(x, c, \kappa)}{\partial \kappa} \neq 0$$

Molecular gradients

- ▶ Applying the **chain rule**, we obtain for the total derivative of the energy:

$$\frac{d\mathcal{E}}{dx} = \frac{\partial E}{\partial x} + \frac{\partial E}{\partial \lambda} \frac{\partial \lambda}{\partial x}$$

- ▶ the first term accounts for the **explicit** dependence on x
 - ▶ the last term accounts for the **implicit** dependence on x
- ▶ We now invoke the **stationary condition**:

$$\frac{\partial E}{\partial \lambda} = 0 \quad (\text{zero electronic gradient})$$

- ▶ The molecular gradient then simplifies to

$$\frac{d\mathcal{E}}{dx} = \frac{\partial E}{\partial x}$$

For variational wave functions, we do not need the response of the wave function $\partial\lambda/\partial x$ to calculate the molecular gradient $d\mathcal{E}/dx$.

- ▶ Examples: HF/KS and MCSCF molecular gradients (exponential parameterization)

The Hellmann–Feynman theorem

- ▶ Assume that the (stationary) energy is an expectation value:

$$E(x, \lambda) = \langle \lambda | H(x) | \lambda \rangle$$

- ▶ The gradient is then given by the **expectation-value expression**:

$$\frac{d\mathcal{E}}{dx} = \frac{\partial E}{\partial x} = \left\langle \lambda^* \left| \frac{\partial H}{\partial x} \right| \lambda^* \right\rangle \quad \leftarrow \text{the Hellmann–Feynman theorem}$$

- ▶ Relationship to **first-order perturbation theory**:

$$E^{(1)} = \langle 0 | H^{(1)} | 0 \rangle$$

- ▶ The Hellmann–Feynman theorem was originally stated for geometrical distortions:

$$\frac{d\mathcal{E}}{d\mathbf{R}_K} = - \left\langle \lambda^* \left| \sum_i \frac{Z_K \mathbf{r}_{iK}}{r_{iK}^3} \right| \lambda^* \right\rangle + \sum_{I \neq K} \frac{Z_I Z_K \mathbf{R}_{IK}}{R_{IK}^3}$$

- ▶ Classical interpretation: integration over the force operator

- ▶ Differentiating the molecular gradient, we obtain:

$$\frac{d^2\mathcal{E}}{dx^2} = \left(\frac{\partial}{\partial x} + \frac{\partial\lambda}{\partial x} \frac{\partial}{\partial\lambda} \right) \frac{\partial E}{\partial x} = \frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial x \partial \lambda} \frac{\partial\lambda}{\partial x}$$

- ▶ Note:

- ▶ we need the **first-order response** $\partial\lambda/\partial x$ to calculate the Hessian
- ▶ but we do **not** need the second-order response $\partial^2\lambda/\partial x^2$ for stationary energies
- ▶ To determine the response, we **differentiate the stationary condition**:

$$\frac{\partial E}{\partial\lambda} = 0 \quad (\text{all } x) \quad \Rightarrow \quad \frac{d}{dx} \frac{\partial E}{\partial\lambda} = \frac{\partial^2 E}{\partial x \partial \lambda} + \frac{\partial^2 E}{\partial \lambda^2} \frac{\partial\lambda}{\partial x} = 0$$

- ▶ These are the first-order (time-independent) **response equations**:

$$\underbrace{\frac{\partial^2 E}{\partial \lambda^2}}_{\text{electronic Hessian}} \frac{\partial\lambda}{\partial x} = - \underbrace{\frac{\partial^2 E}{\partial x \partial \lambda}}_{\text{right-hand side}}$$

Response equations

- ▶ The **molecular Hessian** for stationary energies:

$$\frac{d^2\mathcal{E}}{dx^2} = \frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial x \partial \lambda} \frac{\partial \lambda}{\partial x}$$

- ▶ The **response equations**:

$$\text{electronic Hessian} \rightarrow \boxed{\frac{\partial^2 E}{\partial \lambda^2}} \boxed{\frac{\partial \lambda}{\partial x}} = - \boxed{\frac{\partial^2 E}{\partial \lambda \partial x}} \leftarrow \text{perturbed electronic gradient}$$

- ▶ the electronic Hessian is a Hermitian matrix, independent of the perturbation
 - ▶ its dimensions are usually large and it cannot be constructed explicitly
 - ▶ the response equations are usually solved by iterative techniques
 - ▶ key step: multiplication of the Hessian with a trial vector
- ▶ Analogy with **Hooke's law**:

$$\text{force constant} \rightarrow kx = -F \leftarrow \text{force}$$

- ▶ the wave function relaxes by an amount proportional to the perturbation

The $2n + 1$ rule

- ▶ For molecular gradients and Hessians, we have the expressions

$$\frac{d\mathcal{E}}{dx} = \frac{\partial E}{\partial x} \quad \leftarrow \text{zero-order response needed}$$
$$\frac{d^2\mathcal{E}}{dx^2} = \frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial x \partial \lambda} \frac{\partial \lambda}{\partial x} \quad \leftarrow \text{first-order response needed}$$

- ▶ In general, we have the $2n + 1$ rule:

For variational wave functions, the derivatives of the wave function to order n determine the energy derivatives to order $2n + 1$.

- ▶ Examples: wave-function responses needed to fourth order:

energy	$\mathcal{E}^{(0)}$	$\mathcal{E}^{(1)}$	$\mathcal{E}^{(2)}$	$\mathcal{E}^{(3)}$	$\mathcal{E}^{(4)}$
wave function	$\lambda^{(0)}$	$\lambda^{(0)}$	$\lambda^{(0)}, \lambda^{(1)}$	$\lambda^{(0)}, \lambda^{(1)}$	$\lambda^{(0)}, \lambda^{(1)}, \lambda^{(2)}$

Nonvariational wave functions

- ▶ The $2n + 1$ rule simplifies property evaluation for **variational wave functions**
- ▶ What about the **nonvariational wave functions**?
 - ▶ any energy may be made stationary by **Lagrange's method of undetermined multipliers**
 - ▶ the $2n + 1$ rule is therefore of general interest
- ▶ Example: the **CI energy**
 - ▶ the CI energy function is given by:

$$E_{\text{CI}}(x, c, \kappa) \leftarrow \begin{array}{l} \text{CI parameters } c \\ \text{orbital-rotation parameters } \kappa \end{array}$$

- ▶ it is nonstationary with respect to the orbital-rotation parameters:

$$\frac{\partial E_{\text{CI}}(x, c, \kappa)}{\partial c} = 0 \leftarrow \text{stationary}$$

$$\frac{\partial E_{\text{CI}}(x, c, \kappa)}{\partial \kappa} \neq 0 \leftarrow \text{nonstationary}$$

- ▶ We shall now consider its molecular gradient:
 - 1 by straightforward differentiation of the CI energy
 - 2 by differentiation of the CI Lagrangian
- ▶ In CC theory, all parameters are nonvariational

CI molecular gradients the straightforward way

- ▶ Straightforward differentiation of $E_{\text{CI}}(x, c, \kappa)$ gives the expression

$$\begin{aligned}\frac{d\mathcal{E}_{\text{CI}}}{dx} &= \frac{\partial E_{\text{CI}}}{\partial x} + \frac{\partial E_{\text{CI}}}{\partial c} \frac{\partial c}{\partial x} + \frac{\partial E_{\text{CI}}}{\partial \kappa} \frac{\partial \kappa}{\partial x} \\ &= \frac{\partial E_{\text{CI}}}{\partial x} + \frac{\partial E_{\text{CI}}}{\partial \kappa} \frac{\partial \kappa}{\partial x} \quad \leftarrow \kappa \text{ contribution does not vanish}\end{aligned}$$

- ▶ it appears that we need the first-order response of the orbitals
- ▶ The HF orbitals used in CI theory fulfill the following conditions at all geometries:

$$\frac{\partial E_{\text{SCF}}}{\partial \kappa} = 0 \quad \leftarrow \text{SCF stationary conditions}$$

- ▶ we obtain the orbital responses by differentiating this equation wrt x :

$$\frac{\partial^2 E_{\text{SCF}}}{\partial \kappa^2} \frac{\partial \kappa}{\partial x} = - \frac{\partial^2 E_{\text{SCF}}}{\partial x \partial \kappa} \quad \leftarrow \text{1st-order response equations}$$

- ▶ one such set of equations must be solved for **each perturbation**
- ▶ Calculated in this manner, the CI gradient becomes **expensive**

Lagrange's method of undetermined multipliers

- ▶ To calculate the CI energy, we minimize E_{CI} with respect to c and κ :

$$\min_{c, \kappa} E_{\text{CI}}(x, c, \kappa) \quad \text{subject to the constraints} \quad \frac{\partial E_{\text{SCF}}}{\partial \kappa} = 0$$

- ▶ Use **Lagrange's method of undetermined multipliers**:

- ▶ construct the CI Lagrangian by adding constraints to the energy:

$$L_{\text{CI}}(x, c, \kappa, \bar{\kappa}) = E_{\text{CI}}(x, c, \kappa) + \bar{\kappa} \left(\frac{\partial E_{\text{SCF}}(x, \kappa)}{\partial \kappa} - 0 \right)$$

- ▶ adjust the **multipliers** $\bar{\kappa}$ such that the **Lagrangian becomes stationary**:

$$\frac{\partial L_{\text{CI}}}{\partial c} = \frac{\partial E_{\text{CI}}}{\partial c} = 0$$

← CI conditions

$$\frac{\partial L_{\text{CI}}}{\partial \kappa} = \frac{\partial E_{\text{CI}}}{\partial \kappa} + \bar{\kappa} \frac{\partial^2 E_{\text{SCF}}}{\partial \kappa^2} = 0$$

← linear set of equations for $\bar{\kappa}$

$$\frac{\partial L_{\text{CI}}}{\partial \bar{\kappa}} = \frac{\partial E_{\text{SCF}}}{\partial \kappa} = 0$$

← HF conditions

- ▶ note the duality between κ and $\bar{\kappa}$.
- ▶ We now have a **stationary CI energy expression**

CI molecular gradients the easy way

- ▶ The CI Lagrangian is given by

$$L_{\text{CI}} = E_{\text{CI}} + \bar{\kappa} \frac{\partial E_{\text{SCF}}}{\partial \kappa} \quad \leftarrow \text{stationary with respect to all variables}$$

- ▶ Since the Lagrangian is **stationary**, we may invoke the **$2n + 1$** rule:

$$\frac{dE_{\text{CI}}}{dx} = \frac{dL_{\text{CI}}}{dx} = \frac{\partial L_{\text{CI}}}{\partial x} = \frac{\partial E_{\text{CI}}}{\partial x} + \bar{\kappa} \frac{\partial^2 E_{\text{SCF}}}{\partial \kappa \partial x}$$

zero-order response equations $\rightarrow \bar{\kappa} \frac{\partial^2 E_{\text{SCF}}}{\partial \kappa^2} = -\frac{\partial E_{\text{CI}}}{\partial \kappa}$

- ▶ This result should be contrasted with the original expression

$$\frac{dE_{\text{CI}}}{dx} = \frac{\partial E_{\text{CI}}}{\partial x} + \frac{\partial E_{\text{CI}}}{\partial \kappa} \frac{\partial \kappa}{\partial x}$$

first-order response equations $\rightarrow \frac{\partial^2 E_{\text{SCF}}}{\partial \kappa^2} \frac{\partial \kappa}{\partial x} = -\frac{\partial^2 E_{\text{SCF}}}{\partial \kappa \partial x}$

- ▶ We have greatly reduced the number of response equations to be solved

Lagrange's method summarized

- ▶ The **Lagrangian energy function**:

$$\underbrace{L(x, \lambda, \bar{\lambda})}_{\text{Lagrangian}} = \underbrace{E(x, \lambda)}_{\text{energy function}} + \bar{\lambda} \underbrace{(e(x, \lambda) - 0)}_{\text{constraints}}$$

- ▶ The **stationary conditions** for variables and their multipliers:

$$\frac{\partial L}{\partial \bar{\lambda}} = e(x, \lambda) = 0 \quad \leftarrow \text{determines } \lambda$$

$$\frac{\partial L}{\partial \lambda} = \frac{\partial E}{\partial \lambda} + \bar{\lambda} \frac{\partial e}{\partial \lambda} = 0 \quad \leftarrow \text{determines } \bar{\lambda}$$

- ▶ note the **duality** between λ and $\bar{\lambda}$!
- ▶ The Lagrangian approach is generally applicable:
 - ▶ it gives the Hylleraas functional when applied to a perturbation expression
 - ▶ it may be generalized to time-dependent properties

Trivial example

- ▶ Find x such that $f(x) = 1$ when $f(x) = x$.
- ▶ Construct a Lagrangian:

$$L(x, \bar{x}) = f(x) + \bar{x} [f(x) - 1] = x + x\bar{x} - \bar{x}$$

- ▶ Determine the stationary point:

$$\frac{dL}{dx} = 0 \Rightarrow 1 + \bar{x} = 0 \Rightarrow \bar{x} = -1$$

$$\frac{dL}{d\bar{x}} = 0 \Rightarrow x - 1 = 0 \Rightarrow x = 1$$

- ▶ Value of the Lagrangian at the stationary point $\{1, -1\}$:

$$L(1, -1) = 1 = f(1)$$

- ▶ Note: the stationary point is a saddle point.

The $2n + 2$ rule

- ▶ For variational wave functions, we have the $2n + 1$ rule:

$\lambda^{(n)}$ determines the energy to order $2n + 1$.

- ▶ The **Lagrangian technique** extends this rule to nonvariational wave functions
- ▶ For the new variables—the multipliers—the stronger $2n + 2$ rule applies:

$\bar{\lambda}^{(n)}$ determines the energy to order $2n + 2$.

- ▶ Responses required to order 10:

$\mathcal{E}^{(n)}$	0	1	2	3	4	5	6	7	8	9	10
$\lambda^{(k)}$	0	0	1	1	2	2	3	3	4	4	5
$\bar{\lambda}^{(k)}$	0	0	0	1	1	2	2	3	3	4	4

The Hartree–Fock energy

- ▶ The MOs are expanded in atom-fixed AOs

$$\phi_p(\mathbf{r}; \mathbf{x}) = \sum_{\mu} C_{\mu p} \chi_{\mu}(\mathbf{r}; \mathbf{x})$$

- ▶ The HF energy may be written in the general form

$$E_{\text{HF}} = \sum_{pq} D_{pq} h_{pq} + \frac{1}{2} \sum_{pqrs} d_{pqrs} g_{pqrs} + \sum_{K>L} \frac{Z_K Z_L}{R_{KL}}$$

where

$$h_{pq}(\mathbf{x}) = \int \phi_p(\mathbf{r}, \mathbf{x}) \left(-\frac{1}{2} \nabla^2 - \sum_K \frac{Z_K}{r_K} \right) \phi_q(\mathbf{r}, \mathbf{x}) \, d\mathbf{r}$$
$$g_{pqrs}(\mathbf{x}) = \iint \frac{\phi_p(\mathbf{r}_1, \mathbf{x}) \phi_q(\mathbf{r}_1, \mathbf{x}) \phi_s(\mathbf{r}_2, \mathbf{x}) \phi_s(\mathbf{r}_2, \mathbf{x})}{r_{12}} \, d\mathbf{r}_1 d\mathbf{r}_2$$

- ▶ the integrals depend explicitly on the geometry
- ▶ In closed-shell restricted HF (RHF) theory, the energy is given by

$$E_{\text{RHF}} = 2 \sum_i h_{ii} + \sum_{ij} (2g_{ijij} - g_{ijji}) + \sum_{K>L} \frac{Z_K Z_L}{R_{KL}}$$

- ▶ summations over doubly occupied orbitals

The Hartree–Fock equations

- ▶ The HF energy is optimized subject to **orthonormality constraints**

$$S_{ij} = \langle \phi_i | \phi_j \rangle = \delta_{ij}$$

- ▶ We therefore introduce the **HF Lagrangian**:

$$L_{\text{HF}} = E_{\text{HF}} - \sum_{ij} \varepsilon_{ij} (S_{ij} - \delta_{ij})$$

- ▶ The **stationary conditions** on the Lagrangian become:

$$\frac{\partial L_{\text{HF}}}{\partial \varepsilon_{ij}} = S_{ij} - \delta_{ij} = 0$$

$$\frac{\partial L_{\text{HF}}}{\partial C_{\mu i}} = \frac{\partial E_{\text{HF}}}{\partial C_{\mu i}} - \sum_{kl} \varepsilon_{kl} \frac{\partial S_{kl}}{\partial C_{\mu i}} = 0$$

- ▶ the multiplier conditions are the orthonormality constraints
- ▶ the MO stationary conditions are the Roothaan–Hall equations

$$\frac{\partial E_{\text{HF}}}{\partial C_{\mu i}} = \sum_{kl} \varepsilon_{kl} \frac{\partial S_{kl}}{\partial C_{\mu i}} \Rightarrow \mathbf{F}^{\text{AO}} \mathbf{C} = \mathbf{S}^{\text{AO}} \mathbf{C} \boldsymbol{\varepsilon}$$

The Hartree–Fock molecular gradient

- ▶ From the $2n + 1$ rule, we obtain the RHF molecular gradient:

$$\frac{dE_{\text{HF}}}{d\mathbf{x}} = \frac{dL_{\text{HF}}}{d\mathbf{x}} = \frac{\partial L_{\text{HF}}}{\partial \mathbf{x}} = \frac{\partial E_{\text{HF}}}{\partial \mathbf{x}} - \sum_{ij} \varepsilon_{ij} \frac{\partial S_{ij}}{\partial \mathbf{x}}$$

- ▶ In terms of MO integrals and density-matrix elements, we obtain the expression

$$\frac{dE_{\text{HF}}}{d\mathbf{x}} = \sum_{ij} D_{ij} \frac{\partial h_{ij}}{\partial \mathbf{x}} + \frac{1}{2} \sum_{ijkl} d_{ijkl} \frac{\partial g_{ijkl}}{\partial \mathbf{x}} - \sum_{ij} \varepsilon_{ij} \frac{\partial S_{ij}}{\partial \mathbf{x}} + \mathbf{F}_{\text{nuc}}$$

- ▶ We then transform to the AO basis:

$$\frac{dE_{\text{HF}}}{d\mathbf{x}} = \sum_{\mu\nu} D_{\mu\nu}^{\text{AO}} \frac{\partial h_{\mu\nu}^{\text{AO}}}{\partial \mathbf{x}} + \frac{1}{2} \sum_{\mu\nu\rho\sigma} d_{\mu\nu\rho\sigma}^{\text{AO}} \frac{\partial g_{\mu\nu\rho\sigma}^{\text{AO}}}{\partial \mathbf{x}} - \sum_{\mu\nu} \varepsilon_{\mu\nu}^{\text{AO}} \frac{\partial S_{\mu\nu}^{\text{AO}}}{\partial \mathbf{x}} + \mathbf{F}_{\text{nuc}}$$

- ▶ density matrices transformed to AO basis
- ▶ derivative integrals added directly to gradient elements
- ▶ Important points:
 - ▶ the gradient does not involve MO differentiation because of the $2n + 1$ rule
 - ▶ the time-consuming step is integral differentiation

The second-quantization Hamiltonian

- ▶ In **second quantization**, the Hamiltonian operator is given by:

$$H = \sum_{pq} h_{pq} a_p^\dagger a_q + \sum_{pqrs} g_{pqrs} a_p^\dagger a_r^\dagger a_s a_q + h_{\text{nuc}}$$
$$h_{pq} = \langle \phi_p^*(\mathbf{r}) | h(\mathbf{r}) | \phi_q(\mathbf{r}) \rangle$$
$$g_{pqrs} = \langle \phi_p^*(\mathbf{r}_1) \phi_r^*(\mathbf{r}_2) | r_{12}^{-1} | \phi_q(\mathbf{r}_1) \phi_s(\mathbf{r}_2) \rangle$$

- ▶ Its construction assumes an **orthonormal basis of MOs** ϕ_p :

$$[a_p, a_q]_+ = 0, \quad [a_p^\dagger, a_q^\dagger]_+ = 0, \quad [a_p, a_q^\dagger]_+ = \delta_{pq}$$

- ▶ The MOs are expanded in AOs, which often depend explicitly on the perturbation
 - ▶ such basis sets are said to be **perturbation-dependent**:

$$\phi_p(\mathbf{r}) = \sum_{\mu} C_{p\mu} \chi_{\mu}(\mathbf{r}, \mathbf{x})$$

- ▶ we must make sure that the MOs remain orthonormal for all \mathbf{x}
- ▶ this introduces complications as we take derivatives with respect to \mathbf{x}

1. Orthonormal MOs at the reference geometry:

$$\phi(x_0) = \mathbf{C}^{(0)} \chi(x_0)$$

$$\mathbf{S}(x_0) = \langle \phi(x_0) | \phi^\dagger(x_0) \rangle = \mathbf{I}$$

2. Geometrical distortion $x = x_0 + \Delta x$:

$$\phi(x) = \mathbf{C}^{(0)} \chi(x)$$

$$\mathbf{S}(x) = \langle \phi(x) | \phi^\dagger(x) \rangle \neq \mathbf{I}$$

This basis is **nonorthogonal** and not useful for setting up the Hamiltonian.

3. Orthonormalize the basis set:

$$\psi(x) = \mathbf{S}^{-1/2}(x) \phi(x)$$

$$\tilde{\mathbf{S}}(x) = \mathbf{S}^{-1/2}(x) \mathbf{S}(x) \mathbf{S}^{-1/2}(x) = \mathbf{I}$$

- From the **orthonormalized MOs (OMOs)**, the Hamiltonian is constructed as before

Hamiltonian at all geometries

- ▶ The Hamiltonian is now well defined at **all geometries**:

$$H(x) = \sum_{pq} \tilde{h}_{pq}(x) E_{pq}(x) + \frac{1}{2} \sum_{pqrs} \tilde{g}_{pqrs}(x) e_{pqrs}(x) + h_{\text{nuc}}(x)$$

- ▶ The **OMO integrals** are given by

$$\tilde{h}_{pq}(x) = \sum_{mn} h_{mn}(x) [S^{-1/2}]_{mp}(x) [S^{-1/2}]_{nq}(x)$$

in terms of the usual MO integrals

$$h_{mn}(x) = \sum_{\mu\nu} C_{m\mu}^{(0)} C_{n\nu}^{(0)} h_{\mu\nu}^{\text{AO}}(x), \quad S_{mn}(x) = \sum_{\mu\nu} C_{m\mu}^{(0)} C_{n\nu}^{(0)} S_{\mu\nu}^{\text{AO}}(x)$$

and similarly for the two-electron integrals.

- ▶ What about the geometry dependence of the **excitation operators**?
 - ▶ this may be neglected when calculating derivatives since, for all geometries,

$$\left[a_p(x), a_q^\dagger(x) \right]_+ = \tilde{S}_{pq}(x) = \delta_{pq}$$

HF molecular gradients in second quantization

- ▶ The molecular gradient now follows from the **Hellmann–Feynman theorem**:

$$E^{(1)} = \langle 0 | H^{(1)} | 0 \rangle = \sum_{pq} D_{pq} \tilde{h}_{pq}^{(1)} + \frac{1}{2} \sum_{pqrs} d_{pqrs} \tilde{g}_{pqrs}^{(1)} + h_{\text{nuc}}^{(1)}$$

- ▶ We need the derivatives of the OMO integrals:

$$\tilde{h}_{pq}^{(1)} = \sum_{mn} [h_{mn} (S^{-1/2})_{mp} (S^{-1/2})_{nq}]^{(1)} = h_{pq}^{(1)} - \frac{1}{2} \sum_m S_{pm}^{(1)} h_{mq}^{(0)} - \frac{1}{2} \sum_m h_{pm}^{(0)} S_{mq}^{(1)}$$

- ▶ The gradient may therefore be written in the form

$$E^{(1)} = \sum_{pq} D_{pq} h_{pq}^{(1)} + \frac{1}{2} \sum_{pqrs} d_{pqrs} g_{pqrs}^{(1)} - \sum_{pq} F_{pq} S_{pq}^{(1)} + h_{\text{nuc}}^{(1)},$$

where the **generalized Fock matrix** is given by:

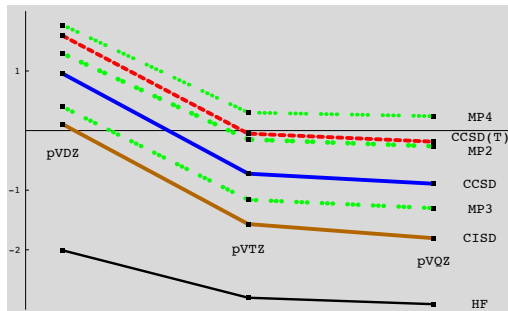
$$F_{pq} = \sum_n D_{pn} h_{qn} + \sum_{nrs} d_{pnrs} g_{qnrs}$$

- ▶ For RHF theory, this result is equivalent to that derived in first quantization

Uses of geometrical derivatives

- ▶ To explore molecular potential-energy surfaces ($3N - 6$ dimensions)
 - ▶ localization and characterization of stationary points
 - ▶ localization of avoided crossings and conical intersections
 - ▶ calculation of reaction paths and reaction-path Hamiltonians
 - ▶ application to direct dynamics
- ▶ To calculate spectroscopic constants
 - ▶ molecular structure
 - ▶ quadratic force constants and harmonic frequencies
 - ▶ cubic and quartic force constants; fundamental frequencies
 - ▶ partition functions
 - ▶ dipole gradients and vibrational infrared intensities
 - ▶ polarizability gradients and Raman intensities

- ▶ Mean and mean abs. errors for 28 distances at the all-el. cc-pVXZ level (pm):

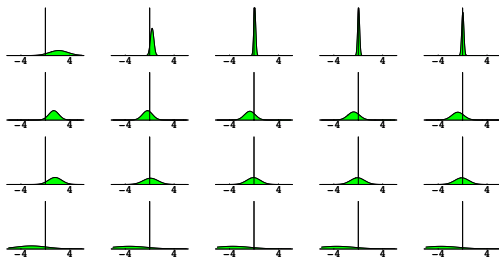


$ \bar{\Delta} $	DZ	TZ	QZ
CCSD	1.2	0.6	0.8
CCSD(T)	1.7	0.2	0.2

- ▶ Bonds shorten with increasing basis:
 - ▶ HF: DZ \rightarrow TZ 0.8 pm; TZ \rightarrow QZ 0.1 pm
 - ▶ corr.: DZ \rightarrow TZ 1.6 pm; TZ \rightarrow QZ 0.1–0.2 pm
- ▶ Bonds lengthen with improvements in the N -electron model:
 - ▶ singles < doubles < triples < ...
- ▶ There is considerable scope for error cancellation: CISD/DZ, MP3/DZ

Bond distances II

- ▶ Normal distributions of errors (pm) relative to experiment for HF, MP2, CCSD, and CCSD(T) at the valence-electron cc-pVXZ level of theory:



- ▶ CCSD(T) bond distances compared with exp. (pm):

	DZ	TZ	QZ
$\overline{\Delta}$	1.68	0.01	-0.12
$ \overline{\Delta} $	1.68	0.20	0.16

- ▶ However, the high accuracy arises in part because of error cancellation.
 - ▶ basis-set extension QZ \rightarrow 6Z: ≈ -0.10 pm
 - ▶ triples relaxation CCSD(T) \rightarrow CCSDT: ≈ -0.02 pm
- ▶ Intrinsic error of the CCSDT model: ≈ -0.2 pm

Bond distances III (pm)

		HF	MP2	CCSD	CCSD(T)	emp.	exp.
H ₂	R_{HH}	73.4	73.6	74.2	74.2	74.1	74.1
HF	R_{FH}	89.7	91.7	91.3	91.6	91.7	91.7
H ₂ O	R_{OH}	94.0	95.7	95.4	95.7	95.8	95.7
HOF	R_{OH}	94.5	96.6	96.2	96.6	96.9	96.6
HNC	R_{NH}	98.2	99.5	99.3	99.5	99.5	99.4
NH ₃	R_{NH}	99.8	100.8	100.9	101.1	101.1	101.1
N ₂ H ₂	R_{NH}	101.1	102.6	102.5	102.8	102.9	102.9
C ₂ H ₂	R_{CH}	105.4	106.0	106.0	106.2	106.2	106.2
HCN	R_{CH}	105.7	106.3	106.3	106.6	106.5	106.5
C ₂ H ₄	R_{CH}	107.4	107.8	107.9	108.1	108.1	108.1
CH ₄	R_{CH}	108.2	108.3	108.5	108.6	108.6	108.6
N ₂	R_{NN}	106.6	110.8	109.1	109.8	109.8	109.8
CH ₂ O	R_{CH}	109.3	109.8	109.9	110.1	110.1	110.1
CH ₂	R_{CH}	109.5	110.1	110.5	110.7	110.6	110.7
CO	R_{CO}	110.2	113.2	112.2	112.9	112.8	112.8
HCN	R_{CN}	112.3	116.0	114.6	115.4	115.3	115.3
CO ₂	R_{CO}	113.4	116.4	115.3	116.0	116.0	116.0
HNC	R_{CN}	114.4	117.0	116.2	116.9	116.9	116.9
C ₂ H ₂	R_{CC}	117.9	120.5	119.7	120.4	120.4	120.3
CH ₂ O	R_{CO}	117.6	120.6	119.7	120.4	120.5	120.3
N ₂ H ₂	R_{NN}	120.8	124.9	123.6	124.7	124.6	124.7
C ₂ H ₄	R_{CC}	131.3	132.6	132.5	133.1	133.1	133.1
F ₂	R_{FF}	132.7	139.5	138.8	141.1	141.3	141.2
HOF	R_{OF}	136.2	142.0	141.2	143.3	143.4	143.4

Contributions to equilibrium bond distances (pm)

	RHF	SD	T	Q	5	rel.	adia.	theory	exp.	err.
HF	89.70	1.67	0.29	0.02	0.00	0.01	0.0	91.69	91.69	0.00
N ₂	106.54	2.40	0.67	0.14	0.03	0.00	0.0	109.78	109.77	0.01
F ₂	132.64	6.04	2.02	0.44	0.03	0.05	0.0	141.22	141.27	-0.05
CO	110.18	1.87	0.75	0.04	0.00	0.00	0.0	112.84	112.84	0.00

- ▶ We have agreement with experiment to within 0.01 pm except for F₂
- ▶ Hartree–Fock theory underestimates bond distances by up to 8.6 pm (for F₂)
- ▶ All correlation contributions are positive
 - ▶ approximate linear convergence, slowest for F₂
 - ▶ triples contribute up to 2.0, quadruples up to 0.4, and quintuples 0.03 pm
 - ▶ sextuples are needed for convergence to within 0.01 pm
- ▶ Relativistic corrections are small except for F₂ (0.05 pm)
 - ▶ of the same magnitude and direction as the quintuples

Calculation of harmonic frequencies

- ▶ Generate parabolic potential by calculating the molecular Hessian at equilibrium:

$$V(\mathbf{x}) = \frac{1}{2} \mathbf{x}^T \mathbf{G} \mathbf{x}$$

- ▶ Calculate mass-weighted Hessian:

$$H_{ij} = \frac{G_{ij}}{\sqrt{m_i m_j}}$$

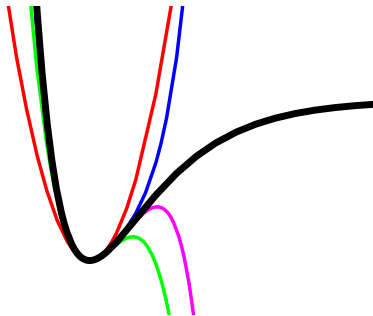
- ▶ Diagonalize the Hessian \mathbf{H} to obtain **normal coordinates** and **harmonic frequencies**:

$$\mathbf{H} \mathbf{q} = \lambda \mathbf{q}, \quad \omega_i = 2\pi \nu_i = \sqrt{\lambda_i}$$

- ▶ Harmonic frequencies are too high (by a few percent) but often qualitatively useful

Anharmonic potentials

- ▶ Anharmonic potentials may be generated by:
 - ▶ higher-order Taylor expansions
 - ▶ numerical fitting
 - ▶ analytical functions (e.g., Morse potential)
- ▶ Taylor expansion of Morse potential up to fifth order:



- ▶ odd-order expansions are unbounded from below.

- ▶ Vibrational energy levels of an **asymmetric top**:

$$E(\mathbf{n}) = V_0 + \sum_k \hbar\omega_k(n_k + \frac{1}{2}) + \sum_{k \leq l} x_{kl}(n_k + \frac{1}{2})(n_l + \frac{1}{2}).$$

- ▶ The **anharmonic constants** x_{kl} may be obtained from:
 - ▶ the harmonic constants ω_k ;
 - ▶ the cubic and quartic force constants with respect to the normal coordinates Q_k :

$$f_{klm} = \frac{d^3 V}{dQ_k dQ_l dQ_m}, \quad f_{klmn} = \frac{d^4 V}{dQ_k dQ_l dQ_m dQ_n},$$

- ▶ the rotational constants B_α and the Coriolis-coupling constants ζ_{kl}^α .
- ▶ The **fundamentals** are then given by:

$$\nu_k = \omega_k + \frac{2}{\hbar} x_{kk} + \frac{1}{2\hbar} \sum_{l \neq k} x_{kl}.$$

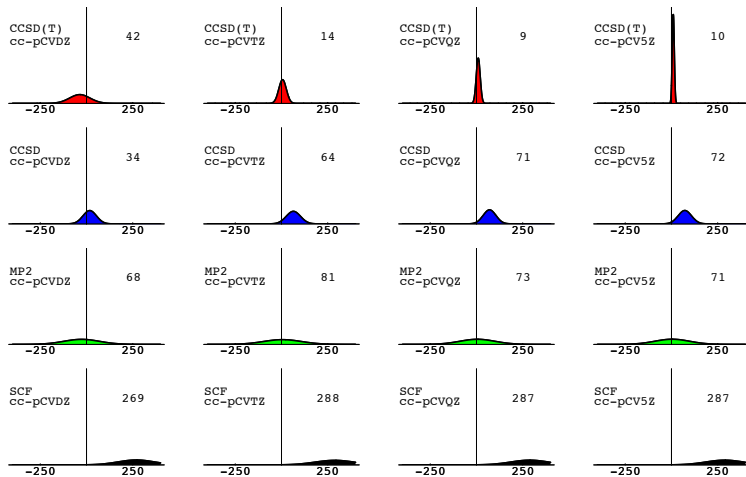
- ▶ Diagonal anharmonic constants (asymmetric top):

$$x_{kk} = \frac{\hbar^2}{16\omega_k^2} \left[f_{kkkk} - \sum_l \frac{f_{kkl}^2 (8\omega_k^2 - 3\omega_l^2)}{\omega_l^2 (4\omega_k^2 - \omega_l^2)} \right]$$

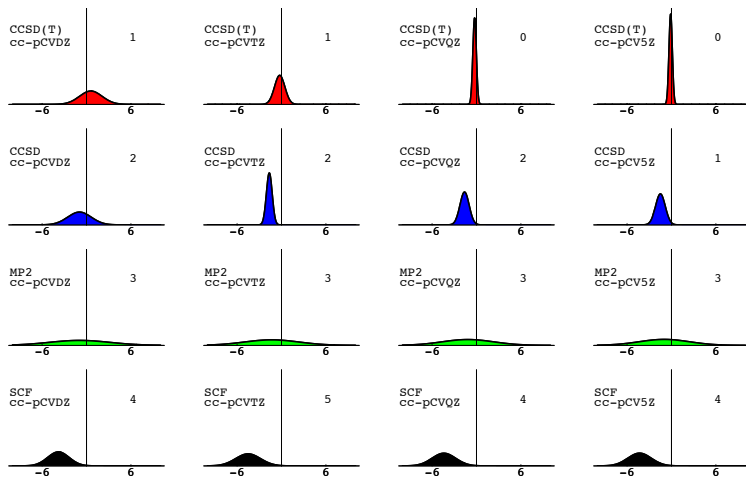
- ▶ Off-diagonal anharmonic constants (asymmetric top):

$$\begin{aligned} x_{kl} = \frac{\hbar^2}{4\omega_k\omega_l} & \left[f_{kkll} - \sum_m \frac{f_{kkm}f_{llm}}{\omega_m^2} \right. \\ & + \sum_m \frac{2f_{klm}^2(\omega_k^2 + \omega_l^2 - \omega_m^2)}{[(\omega_k + \omega_l)^2 - \omega_m^2][(\omega_k - \omega_l)^2 - \omega_m^2]} \\ & \left. + \left(\frac{\omega_k}{\omega_l} + \frac{\omega_l}{\omega_k} \right) \sum_{\alpha} B_{\alpha} (\zeta_{kl}^{\alpha})^2 \right] \end{aligned}$$

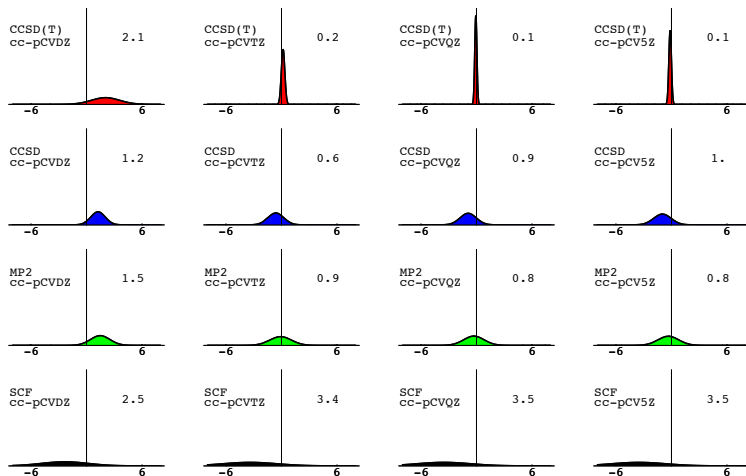
Harmonic constants ω_e of BH, CO, N₂, HF, and F₂ (cm⁻¹)



Anharmonic constants $\omega_e x_e$ of BH, CO, N₂, HF, and F₂ (cm⁻¹)



Bond distances R_e of BH, CO, N₂, HF, and F₂ (cm⁻¹)



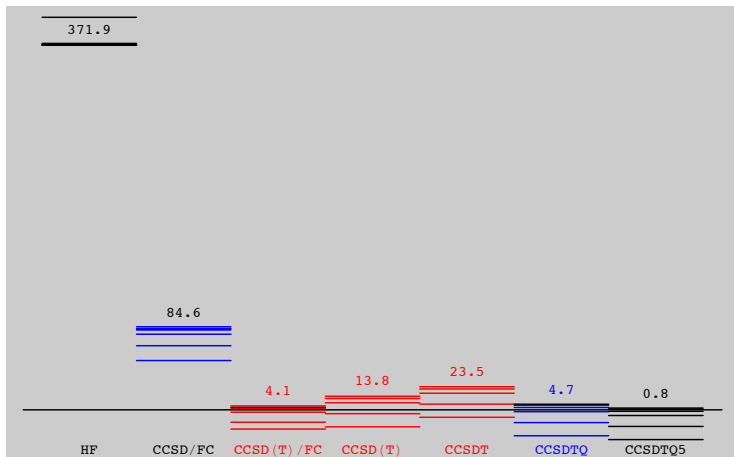
Contributions to harmonic frequencies ω_e (cm^{-1})

	RHF	SD	T	Q	5	rel.	adia.	theory	exp.	err.
HF	4473.8	-277.4	-50.2	-4.1	-0.1	-3.5	0.4	4138.9	4138.3	0.1
N ₂	2730.3	-275.8	-72.4	-18.8	-3.9	-1.4	0.0	2358.0	2358.6	-0.6
F ₂	1266.9	-236.1	-95.3	-15.3	-0.8	-0.5	0.0	918.9	916.6	2.3
CO	2426.7	-177.4	-71.7	-7.2	0.0	-1.3	0.0	2169.1	2169.8	0.7

- ▶ We have agreement with experiment to within 1 cm^{-1} except for F₂
- ▶ Hartree–Fock theory overestimates harmonic frequencies by up to 38% (in F₂).
- ▶ All correlation contributions are large and negative
 - ▶ triples contribute up to 95 cm^{-1} , quadruples 20 cm^{-1} , and quintuples 4 cm^{-1}
 - ▶ sextuples are sometimes needed for convergence to within 1 cm^{-1}
- ▶ The relativistic corrections are of the order of 1 cm^{-1}
 - ▶ of the same magnitude and direction as the quadruples or quintuples

Higher-order connected contributions to ω_e in N_2

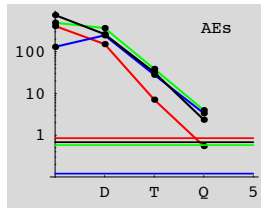
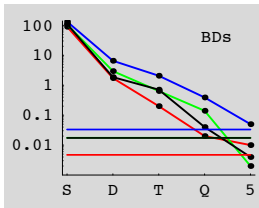
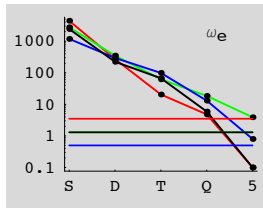
- ▶ There are substantial higher-order corrections:



- ▶ connected triples relaxation contributes 9.7 cm^{-1} (total triples -70.5 cm^{-1})
- ▶ connected quadruples contribute -18.8 cm^{-1}
- ▶ connected quintuples contribute -3.9 cm^{-1}

Excitation-level convergence

- ▶ Contributions to harmonic frequencies, bond lengths, and atomization energies:



- ▶ color code: HF (red), N_2 (green), F_2 (blue), and CO (black)
- ▶ straight lines indicate first-order relativistic corrections
- ▶ Excitation-level convergence is approximately exponential
- ▶ Relativity becomes important beyond connected quadruples
- ▶ Basis-set convergence is much slower: X^{-3}