

Further Quantum Mechanics

University of Cambridge Part II Natural Sciences Tripos

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Nothing in these lecture notes is original. They are largely based on the notes by Dr. John Morgan, who lectured this course in 2025. Moreover, they are nowhere near accurate representations of what was actually lectured, and in particular, all errors are almost surely mine.

Preface

This course focuses on quantum mechanics, and it is slightly more advanced than what you have learned in Part IB Chemistry A: *Introduction to Quantum Mechanics*. It will mostly focus on perturbation theory, including both the time independent and the time dependent cases, and it also covers topics that are removed from the A4 *Theoretical Techniques* course this year, namely normal modes. This course will avoid the rigorous mathematical formulation of quantum mechanics, and especially, it will not introduce concepts like projective Hilbert space or functional analysis. If you want a more mathematical approach to quantum mechanics, you can find my notes on Mathematical Tripos Part II: *Principles of Quantum Mechanics*.

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1 Foundational Principles

We will start from a revision of the foundational principles of quantum mechanics that should be familiar from part IB Chemistry A.

1.1 Wavefunctions and Operators

In quantum mechanics, all physical information about a system is embodied in its wavefunction, denoted Ψ . The wavefunction is complex-valued, and we will use the *position representation* of the wavefunction, so it is a function of the spatial coordinates. In the Born's interpretation, the probability density of finding a particle at \mathbf{r} is

$$P(\mathbf{r}) \propto |\Psi(\mathbf{r})|^2 . \quad (1.1)$$

Wavefunctions should be single-valued and (at least) twice differentiable. Under such interpretation, we would often choose to normalise the wavefunction such that

$$\int d\tau \Psi^* \Psi = 1 , \quad (1.2)$$

where $d\tau$ is a shorthand notation for integrating over all spatial coordinates. This integral should converge for a proper wavefunction, so that it can be normalised.

A quantum mechanical system is defined by its Hamiltonian, H , the total energy operator. The Hamiltonian usually includes the kinetic and potential energies of the particles. A quantum mechanical system evolves according to the time-dependent Schrödinger equation

$$i\hbar \frac{\partial}{\partial t} \Psi = H\Psi . \quad (1.3)$$

Often, the Hamiltonian operator is independent of time. For such time-independent system, the wavefunction satisfies the time-independent Schrödinger equation (which we often directly refer to as the Schrödinger equation)¹

$$H\psi = E\psi , \quad (1.5)$$

where the constant E is the energy of the system² and $\psi(\mathbf{r})$ is now a wavefunction independent of time. This is a (partial) differential equation, so it is only analytically solvable in a few limited cases, most of which you have seen already. Approximations are generally needed to solve for more complex systems, and one of the most important approximation techniques, the perturbation theory, is exactly the main theme of this course.

In general, the Schrödinger equation will have multiple (usually a countably infinite number of) solutions, which can be indexed by a quantum number n such that

$$H\psi_n = E_n\psi_n . \quad (1.6)$$

The ψ_n are different states available to the system, and the state with the lowest energy E_n is known as the ground state. We usually arrange the states in sequence so that the ground state is labelled ψ_0 (or ψ_1 if you find it more convenient to start numbering from $n = 1$). We say two or more states are degenerate if they have the same energy. Any linear combination of degenerate wavefunctions is also a solution to the Schrödinger equation with the same energy.

¹This is because if H is independent of t , then a special class of solutions of the time-dependent Schrödinger equation exists

$$\Psi(\mathbf{r}, t) = \psi(\mathbf{r})e^{-iEt/\hbar} , \quad (1.4)$$

where $\psi(\mathbf{x})$ is independent of time and satisfies the time-independent Schrödinger equation.

²This is essentially the conservation of energy — if a system has time-translational symmetry, then the energy of the system is conserved. This is an example of the Noether's theorem.

The Schrödinger equation is a specific example of the more general eigenvalue equation. In quantum mechanics, all physical observables A has a corresponding operator \hat{A} , if the wavefunction satisfies

$$\hat{A}\psi = a\psi, \quad (1.7)$$

then the value of A will always be measured to be a . If this equation is not satisfied, then measured values of A will be drawn from a probability distribution. The expectation and the uncertainty of A is

$$\langle A \rangle = \frac{\int d\tau \psi^* \hat{A} \psi}{\int d\tau \psi^* \psi} \quad (1.8)$$

$$\Delta A = \sqrt{\langle A^2 \rangle - \langle A \rangle^2}. \quad (1.9)$$

To avoid writing integrations over and over again, we introduce the Dirac bra-ket notation, in which a bra is $\langle \psi | \equiv \psi^*$ and a ket is $|\psi\rangle \equiv \psi$, and a pair of a bra and a ket forms a bra-ket (or just bracket), which implies integrations³

$$\langle \psi | \psi \rangle := \int d\tau \psi^* \psi. \quad (1.10)$$

An operator can be placed in middle of a bra-ket, so

$$\langle \psi | \hat{A} | \psi \rangle := \int d\tau \psi^* \hat{A} \psi. \quad (1.11)$$

To know what the quantum operator \hat{A} corresponding to a physical observable A is, we write the classical expression of A in terms of position and momentum, and we replace the position and momentum with their quantum operators⁴

$$\hat{x} \longrightarrow x \quad (1.12)$$

$$\hat{p}_x \longrightarrow -i\hbar \frac{\partial}{\partial x}. \quad (1.13)$$

In general, a wavefunction cannot simultaneously be an eigenfunction of two (or more) operators. However, this will happen if and only if the commutator of the two operators, defined as

$$[\hat{A}, \hat{B}] := \hat{A}\hat{B} - \hat{B}\hat{A} \quad (1.14)$$

is zero. If this is the case, then we say the two operators commute. If the condition is not met, then the commutator places a lower bound on the product of the uncertainties

$$\Delta A \Delta B \geq \frac{1}{2} |\langle [A, B] \rangle|. \quad (1.15)$$

1.2 Hermitian Operators

Not all operators can correspond to physical observables. First of all, it has to be linear, so that

$$\hat{A}(a|\phi\rangle + b|\psi\rangle) = a\hat{A}|\phi\rangle + b\hat{A}|\psi\rangle, \quad (1.16)$$

³Actually more formally, $|\psi\rangle$ what truly fundamental, and is the quantum state of a system living in an abstract vector space called a (projective) Hilbert space \mathcal{H} . The wavefunction $\psi(\mathbf{x})$ is just the position-space representation of the vector $|\psi\rangle$. If a quantum state is a vector in the Hilbert space, $|\psi\rangle \in \mathcal{H}$, then an operator is an operator in \mathcal{H} , $\hat{A} : \mathcal{H} \rightarrow \mathcal{H}$, and a bra will be a dual vector living in the dual space of \mathcal{H} , $\langle \psi | \in \mathcal{H}^*$. What allows us to do this is the Riesz representation theorem, which shows for any $|\psi\rangle \in \mathcal{H}$, there is always a corresponding $\langle \psi | \in \mathcal{H}^*$ and *vice versa*.

⁴This is the position-space representations of these operators, which we can act on wavefunctions that are written as a function of spatial coordinates. These operators have different representations in different basis.

where $a, b \in \mathbb{C}$ are constants. Moreover, operators that correspond to physical observable must be Hermitian. For any linear operator \hat{A} , we define its adjoint \hat{A}^\dagger to be the operator such that

$$\langle \phi | \hat{A} | \psi \rangle = \langle \hat{A}^\dagger \phi | \psi \rangle . \quad (1.17)$$

A operator is Hermitian if it is self-adjoint,⁵ meaning $\hat{A} = \hat{A}^\dagger$, so that

$$\langle \phi | \hat{A} | \psi \rangle = \langle \hat{A} \phi | \psi \rangle = \langle \psi | \hat{A} | \phi \rangle^* . \quad (1.18)$$

It is not difficult to show that taking the adjoint has the following properties:

$$(a\hat{A})^\dagger = a^* \hat{A}^\dagger \quad (1.19)$$

$$(\hat{A} + \hat{B})^\dagger = \hat{A}^\dagger + \hat{B}^\dagger \quad (1.20)$$

$$(\hat{A}\hat{B})^\dagger = \hat{B}^\dagger \hat{A}^\dagger \quad (1.21)$$

$$(\hat{A} | \psi \rangle)^\dagger = \langle \psi | \hat{A}^\dagger . \quad (1.22)$$

A Hermitian operator has the following nice properties:

- (i) The eigenvalues are all real.
- (ii) Eigenfunctions with different eigenvalue are orthogonal. Even if some eigenfunctions are degenerate, orthogonal eigenfunctions can always be constructed.
- (iii) The eigenfunction form a complete basis set.

Two functions are orthogonal means that their inner product, defined as $\langle \phi | \psi \rangle$, is zero. Moreover, the completeness of the basis set means that any wavefunction ψ satisfying the boundary conditions can be expressed as a linear combination of the eigenfunctions,

$$\psi = \sum_i c_i \phi_i . \quad (1.23)$$

We can always make this basis set, which we denote as $\{\phi_i\}$, orthonormal by normalising the orthogonal eigenfunctions, so that $\langle \phi_i | \phi_j \rangle = \delta_{ij}$. Then taking the inner product of the above eigenfunction expansion with ϕ_j , we have

$$\begin{aligned} \langle \phi_j | \psi \rangle &= \left\langle \phi_j \left| \sum_i c_i \phi_i \right. \right\rangle \\ &= \sum_i c_i \langle \phi_j | \phi_i \rangle \\ &= \sum_i c_i \delta_{ij} = c_j , \end{aligned} \quad (1.24)$$

and so

$$\psi = \sum_i \langle \phi_i | \psi \rangle | \phi_i \rangle . \quad (1.25)$$

From now on, we will denote the eigenstates just by its quantum number in the bra-ket notation: $|i\rangle \equiv |\phi_i\rangle$, so that for example, we have

$$|\psi\rangle = \sum_i \langle i | \psi \rangle |i\rangle . \quad (1.26)$$

⁵There is actually some extremely subtle differences between self-adjoint and Hermitian operators in functional analysis, but they would only bother pure mathematicians.

1.3 Unitary Operators

Apart from position space representations, there are many other basis we can represent the wavefunctions, such as the momentum space, or the basis spanned by eigenstates. An important class of linear operators is the *unitary operators* that are used for transformations of basis. To define unitary operators, we first need to define the identity operator. We define the identity operator to be an operator \hat{I} such that

$$\hat{I} |\psi\rangle = |\psi\rangle \quad (1.27)$$

for any $|\psi\rangle$. An useful way of constructing the identity operator is the *resolution of identity*. For any complete orthonormal basis set $\{\phi_i\}$, we have

$$\hat{I} = \sum_i |i\rangle \langle i| . \quad (1.28)$$

This is because if we act this operator on any $|\psi\rangle$, we get its eigenfunction expansion is that basis

$$\hat{I} |\psi\rangle = \sum_i |i\rangle \langle i|\psi\rangle = \sum_i \langle i|\psi\rangle |i\rangle = |\psi\rangle , \quad (1.29)$$

where we moved $\langle i|\psi\rangle$ to the front to make the expression more obvious — we are allowed to do this because $\langle i|\psi\rangle$ is just a number.

Having defined the identity operator, we can define the inverse of an operator \hat{A} , denoted \hat{A}^{-1} , to be the operator such that

$$\hat{A}\hat{A}^{-1} = \hat{A}^{-1}\hat{A} = \hat{I} . \quad (1.30)$$

A unitary operator \hat{U} is one for which the adjoint is equal to the inverse,

$$\hat{U}^{-1} = \hat{U}^\dagger , \quad (1.31)$$

so that

$$\hat{U}\hat{U}^\dagger = \hat{U}^\dagger\hat{U} = \hat{I} . \quad (1.32)$$

As we claimed before, unitary operators are used to define transformations between different representations.⁶ Therefore, if we have an operator \hat{A} , we would like to know what its representation has transformed into after the transformation. Suppose the operator \hat{A} acts on a general wavefunction ψ to get

$$\hat{A}\psi = \phi , \quad (1.33)$$

and after the transformation, we have

$$\tilde{\psi} = \hat{U}\psi , \quad \tilde{\phi} = \hat{U}\phi . \quad (1.34)$$

Then we would like to find \tilde{A} , which is the representation of \hat{A} after the transformation, such that

$$\tilde{A}\tilde{\psi} = \tilde{\phi} . \quad (1.35)$$

We have

$$\tilde{A}\hat{U}\psi = \hat{U}\phi = \hat{U}\hat{A}\psi \implies \tilde{A}\hat{U} = \hat{U}\hat{A} . \quad (1.36)$$

Therefore,

$$\tilde{A} = \hat{U}\hat{A}\hat{U}^\dagger \quad \text{or} \quad \hat{A} = \hat{U}^\dagger\tilde{A}\hat{U} . \quad (1.37)$$

By taking the adjoint of the above equation, we can see that a Hermitian operator after unitary transformation is still an Hermitian operator.

⁶Unitary operators are linked to basis transformations, just like unitary matrices are linked to basis transformations in vector spaces. We will show this later, when we transform a wavefunction from the position basis (wavefunction) to the momentum basis (the momentum representation of the wavefunction), and transform an orbital from the AO basis in to the SO basis.

Moreover, a transformed eigenfunction of an operator is still an eigenfunction of the transformed operator with the same eigenvalue. This means that if

$$\hat{A}\psi_n = a_n\psi_n, \quad (1.38)$$

then since we can insert an identity operator anywhere,

$$\hat{A}\hat{U}^\dagger\hat{U}\psi_n = a_n\hat{U}^\dagger\hat{U}\psi_n, \quad (1.39)$$

and so

$$\hat{U}\hat{A}\hat{U}^\dagger\hat{U}\psi_n = a_n\hat{U}\psi_n, \quad (1.40)$$

which implies

$$\tilde{A}\tilde{\psi}_n = a_n\tilde{\psi}_n. \quad (1.41)$$

We can also show that the expectation values are the same:

$$\begin{aligned} \int d\tau \psi_n^* \hat{A} \psi_n &= \int d\tau \psi_n^* \hat{U}^\dagger \hat{U} \hat{A} \hat{U}^\dagger \hat{U} \psi_n \\ &= \int d\tau (\hat{U} \psi_n)^* \hat{A} \hat{U}^\dagger \hat{U} \psi_n \\ &= \int d\tilde{\tau} \tilde{\psi}_n^* \tilde{A} \tilde{\psi}_n. \end{aligned} \quad (1.42)$$

If we let $\hat{A} = \hat{I}$, then

$$\int d\tilde{\tau} \tilde{\psi}_n \tilde{\psi}_n = \int d\tau \psi_n^* \psi_n, \quad (1.43)$$

so a normalised state remains normalised after transformation.⁷

1.4 The Momentum Space Representation

Consider the transformation, in one-dimensional space, defined by the unitary operator

$$\phi(p) = \hat{U}\psi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx \psi(x) e^{-ipx}, \quad (1.44)$$

which you may recognise as the *Fourier transform*. This is a unitary transformation because its inverse transform is given by

$$\psi(x) = \hat{U}^\dagger \phi(p) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \phi(p) e^{ipx}, \quad (1.45)$$

which is exactly the adjoint of the forward transformation. This transforms our wavefunction $\phi(x)$ from the position basis to the momentum basis.

Before we proceed, we first introduce a useful result.

Proposition 1.1.

$$\frac{1}{2\pi} \int_{-\infty}^{\infty} dx e^{i(p-p')x} = \delta(p-p'), \quad (1.46)$$

where $\delta(x)$ is the *Dirac delta function*.⁸

⁷We are deliberately not using the bra-ket notation here because technically, ψ_n and $\tilde{\psi}_n$ corresponds to the same $|n\rangle$, just being represented in different basis. For example, if ψ_n is represented in the position (x) basis and $\tilde{\psi}_n$ is represented in the momentum (p) basis, then $\psi_n(x) = \langle x|n\rangle$ and $\tilde{\psi}_n(p) = \langle p|n\rangle$, where $|x\rangle$ and $|p\rangle$ are the position and momentum eigenstates.

⁸Dirac delta function $\delta(x)$ is a weird ‘function’ defined such that $\delta(x) \neq 0 \ \forall x \neq 0$ but for any $\epsilon > 0$, we have

$$\int_{-\epsilon}^{\epsilon} dx \delta(x) = 1. \quad (1.47)$$

You can think of this as a normalised Gaussian in the limit of its variance $\rightarrow 0$.

Dirac delta has a nice property.

$$\int_{-\infty}^{\infty} dx f(x) \delta(x - x') = f(x'). \quad (1.48)$$

Now it's time to investigate the momentum space representation. Specifically, we would like to find out how the position and momentum operators look like in the momentum representation. We do this by rewriting the position-space expectation value of momentum into the momentum space, and we find

$$\begin{aligned} \langle p \rangle &= \int_{-\infty}^{\infty} dx \psi^*(x) \left(-i \frac{\partial}{\partial x} \right) \psi(x) \\ &= \frac{1}{2\pi} \int_{-\infty}^{\infty} dx \left[\int_{-\infty}^{\infty} dp \phi(p)^* e^{-ipx} \right] \left(-i \frac{\partial}{\partial x} \right) \left[\int_{-\infty}^{\infty} dp' \phi(p') e^{-ip'x} \right] \\ &= \frac{1}{2\pi} \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dp \int_{-\infty}^{\infty} dp' p' \phi(p)^* \phi(p') e^{i(p-p')x} \\ &= \int_{-\infty}^{\infty} dp \int_{-\infty}^{\infty} dp' p' \phi(p)^* \phi(p') \delta(p' - p) \\ &= \int_{-\infty}^{\infty} dp \phi(p)^* p \phi(p). \end{aligned} \quad (1.49)$$

This is exactly the momentum-space average of the operator p . We see that in the momentum representation, the momentum operator is unsurprisingly p itself — and in fact that is why we call this representation the momentum representation.

To work out the momentum representation of the position operator, we do the same trick again.

$$\begin{aligned} \langle x \rangle &= \int_{-\infty}^{\infty} dx \psi(x)^* x \psi(x) \\ &= \int_{-\infty}^{\infty} dx \left[\int_{-\infty}^{\infty} dp' \phi(p')^* e^{-ip'x} \right] x \left[\int_{-\infty}^{\infty} dp \phi(p) e^{ipx} \right]. \end{aligned} \quad (1.50)$$

Since

$$-i \frac{\partial}{\partial p} e^{ipx} = x e^{ipx}, \quad (1.51)$$

we can rewrite it as

$$\langle x \rangle = \frac{1}{2\pi} \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dp' \int_{-\infty}^{\infty} dp \phi(p')^* \phi(p) \left(-i \frac{\partial}{\partial p} e^{i(p-p')x} \right). \quad (1.52)$$

We now use integration by part, and we get

$$\begin{aligned} \langle x \rangle &= \frac{1}{2\pi} \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dp' \int_{-\infty}^{\infty} dp \phi(p')^* e^{i(p-p')x} \left(i \frac{\partial}{\partial p} \phi(p) \right) \\ &= \int_{-\infty}^{\infty} dp' \int_{-\infty}^{\infty} dp \delta(p - p') \phi(p')^* \left(i \frac{\partial}{\partial p} \phi(p) \right) \\ &= \int_{-\infty}^{\infty} dp \phi(p)^* \left(i \frac{\partial}{\partial p} \right) \phi(p). \end{aligned} \quad (1.53)$$

This is the expectation integral of the operator $i\partial/\partial p$.

Proposition 1.2. The momentum representation of the position and momentum operators are

$$\tilde{x} = \hat{U} \hat{x} \hat{U}^\dagger = i \frac{\partial}{\partial p} \quad (1.54)$$

$$\tilde{p} = \hat{U} \hat{p} \hat{U}^\dagger = p. \quad (1.55)$$

1.4.1 The State Vector

You can see that the even though we transformed a wavefunction from the position representation to the momentum representation, it is still fundamentally the same thing — both representations describe the same underlying quantum state. Although we may define various unitary transformations and trying to represent a quantum state in different representations, there must be a invariant underlying object. Just as we may choose different basis to describe a vector, and the vector may have different coordinates in different basis, it is still the same vector. We can do the same thing in quantum mechanics.

The true underlying quantum state is called a *state vector*, denoted $|\psi\rangle$, and it lives in a special vector space called a *Hilbert space*. The position representation of a wavefunction is just writing out the coefficients of a state vector in the position basis $\{|x\rangle\}$, and so $\psi(x) = \langle x|\psi\rangle$. Similarly the momentum representation is $\tilde{\psi}(p) = \langle p|\psi\rangle$.

Let's think again what we are doing when transforming the position wavefunction $\psi(x) = \langle x|\psi\rangle$ to the momentum wavefunction $\tilde{\psi}(x) = \langle p|\psi\rangle$. What we are doing is actually inserting an identity operator⁹

$$\hat{I} = \int dx |x\rangle \langle x| \quad (1.56)$$

into the momentum wavefunction:

$$\tilde{\psi}(x) = \langle p|\psi\rangle = \langle p| \int dx |x\rangle \langle x|\psi\rangle = \int dx \langle p|x\rangle \langle x|\psi\rangle = \int dx \langle p|x\rangle \psi(x). \quad (1.57)$$

All we need to do is to find $\langle p|x\rangle$. We can transform it into a more familiar object, $\langle p|x\rangle = \langle x|p\rangle^*$ — it is the Hermitian conjugate of the position representation of momentum eigenstate wavefunctions. We can find it as the eigenfunction of $-i\hbar d/dx$. You should have done this in Part IB Chemistry A: *Introduction to Quantum Mechanics*, $\langle x|p\rangle = e^{ipx}/\sqrt{2\pi}$. Therefore, we have

$$\tilde{\psi}(x) = \frac{1}{\sqrt{2\pi}} \int dx e^{-ikx} \psi(x). \quad (1.58)$$

We can use any other basis we want to represent a quantum state, but it should better be orthonormal and it should be complete, meaning that the basis should span the whole Hilbert space so that we can represent any quantum state we want in such a basis — the eigenstates of a Hermitian operator seems perfect for this purpose.¹⁰ Then a quantum states is defined by the countably infinite number of coefficients of each basis vector. This leads to the *vectors and matrices representations*.

1.5 Vectors and Matrices Representations

If we have a quantum state $|\psi\rangle$ and a complete, orthogonal basis set $\{|\phi_i\rangle\}$, then we can expand and write

$$|\psi\rangle = \sum_i c_i |\phi_i\rangle, \quad (1.59)$$

where as we claimed before, if the basis functions $|\phi_i\rangle$ are orthonormal, then the coefficients c_i are given by

$$c_i = \langle \phi_i|\psi\rangle. \quad (1.60)$$

This expansion be rewritten in matrix notation as

$$|\psi\rangle = (|\phi_1\rangle \quad |\phi_2\rangle \quad \cdots) \begin{pmatrix} c_1 \\ c_2 \\ \vdots \end{pmatrix} = \boldsymbol{\phi}^T \mathbf{c}, \quad (1.61)$$

⁹We are using an integral instead of a sum since we have a continuum of position eigenstates.

¹⁰In fact the position and the momentum representations are one of the worst representations. They are examples of continuum bases, and their eigenstates like $\langle x|x'\rangle = \delta(x-x')$ are not normalisable.

where ϕ is the column vector of the basis set and \mathbf{c} is the column vector of coefficients.

Now, let's do a basis transformation. We define a new basis set $|\theta_j\rangle = \sum_i |\phi_i\rangle U_{ij}$ for some set of coefficients $U_{ij} = \langle \phi_i | \theta_j \rangle$, which can be written in the matrix form as

$$(|\theta_1\rangle \quad |\theta_2\rangle \quad \dots) = (|\phi_1\rangle \quad |\phi_2\rangle \quad \dots) \begin{pmatrix} U_{11} & U_{12} & \dots \\ U_{21} & U_{22} & \dots \\ \vdots & \vdots & \ddots \end{pmatrix}, \quad (1.62)$$

or

$$\boldsymbol{\theta}^T = \boldsymbol{\phi}^T \mathbf{U}. \quad (1.63)$$

If we want to keep the new basis orthonormal, then we must have

$$\begin{aligned} \delta_{ij} &= \langle \theta_i | \theta_j \rangle \\ &= \sum_{k,l} U_{ki}^* U_{lj} \langle \phi_k | \phi_l \rangle \\ &= \sum_k U_{ki}^* U_{kj}, \end{aligned} \quad (1.64)$$

which implies

$$\mathbf{U}^\dagger \mathbf{U} = \mathbf{I}, \quad (1.65)$$

and so \mathbf{U} is a unitary matrix. The transformation between orthonormal bases is given by a unitary matrix.

We hope to represent the same $|\psi\rangle$ in this new transformed basis $\{|\theta_i\rangle\}$

$$|\psi\rangle = \boldsymbol{\theta}^T \mathbf{d}. \quad (1.66)$$

Then clearly, we should have

$$|\psi\rangle = \boldsymbol{\theta}^T \mathbf{d} = \boldsymbol{\phi}^T \mathbf{U} \mathbf{d} = \boldsymbol{\phi}^T \mathbf{c}, \quad (1.67)$$

so

$$\mathbf{c} = \mathbf{U} \mathbf{d} \quad \text{or} \quad \mathbf{d} = \mathbf{U}^\dagger \mathbf{c}. \quad (1.68)$$

The components transform in the opposite way as the basis.

Just as for the position and momentum transformation, by inserting the resolution of identity we can write

$$c_i = \langle \phi_i | \psi \rangle = \langle \phi_i | \sum_j |\theta_j\rangle \langle \theta_j | \psi \rangle = \sum_j \langle \phi_i | \theta_j \rangle d_j, \quad (1.69)$$

and so

$$U_{ij} = \langle \phi_i | \theta_j \rangle. \quad (1.70)$$

The same thing goes for operators. If a Hermitian operator \hat{A} is represented in the $|\phi_i\rangle$ basis with matrix elements $A_{ij} = \langle \phi_i | \hat{A} | \phi_j \rangle$, then in the new basis $|\theta_i\rangle$, the matrix element A' will be given by

$$\begin{aligned} A'_{ij} &= \langle \theta_i | \hat{A} | \theta_j \rangle \\ &= \sum_{k,l} U_{ki}^* U_{lj} \langle \phi_k | \hat{A} | \phi_l \rangle \\ &= \sum_{k,l} U_{ki}^* A_{kl} U_{lj}, \end{aligned} \quad (1.71)$$

and so

$$\mathbf{A}' = \mathbf{U}^\dagger \mathbf{A} \mathbf{U}. \quad (1.72)$$

1.5.1 Symmetry Orbitals

The above transformation is exactly what we are doing when we transform from the atomic orbital basis (denoted $|\phi_i\rangle$) to symmetry orbitals (denoted θ_i) in Hückel theory. If we have figured out the symmetry orbitals to be $|\theta_j\rangle = \sum_i |\phi_i\rangle U_{ij}$ and the Hamiltonian in the atomic orbital basis to be $H_{ij} = \langle \phi_i | \hat{H} | \phi_j \rangle$, then the Hamiltonian in the symmetry orbital basis set is

$$H' = U^\dagger H U. \quad (1.73)$$

In practise we don't usually do this by matrix multiplication because we already know that a lot of the matrix elements will be zero, so we would rather work out H'_{ij} element by element. The goal of Hückel theory is usually to work out the Hückel molecular orbitals as well as their energies, which are the eigenvectors and eigenvalues of H . By doing a unitary basis transformation, the eigenvalues of H' should be the same as H , and the eigenvectors should be the same ones but represented in the symmetry orbital basis. The point is that the block diagonal form of H' makes them easier to find.

1.6 Uncertainty Principle

We have asserted that the uncertainties of two observables are related to the expectation value of their commutator. It is time to see where the uncertainty principle comes from.

In statistics, the variance of a random variable A is given by

$$\sigma_A^2 = \langle A^2 \rangle - \langle A \rangle^2 = \langle (A - \langle A \rangle)^2 \rangle. \quad (1.74)$$

This can be translated into the quantum mechanical expression of the uncertainty of a physical observable

$$\Delta A^2 = \left\langle \psi \left| \left(\hat{A} - \langle \hat{A} \rangle \right)^2 \right| \psi \right\rangle. \quad (1.75)$$

If \hat{A} is a Hermitian operator, then we can write this as

$$\Delta A^2 = \left\langle \left(\hat{A} - \langle \hat{A} \rangle \right) \psi \left| \left(\hat{A} - \langle \hat{A} \rangle \right) \psi \right\rangle. \quad (1.76)$$

If we denote $\psi_A = \left(\hat{A} - \langle \hat{A} \rangle \right) \psi$, then ΔA^2 is exactly the norm of ψ_A :

$$\Delta A^2 = \langle \psi_A | \psi_A \rangle. \quad (1.77)$$

Suppose we have another observable with operator \hat{B} , then if $\psi_B = \left(\hat{B} - \langle \hat{B} \rangle \right) \psi$, we have

$$\Delta B^2 = \langle \psi_B | \psi_B \rangle \quad (1.78)$$

by exactly the same argument. The product of the two variances is

$$\Delta A^2 \Delta B^2 = \langle \psi_A | \psi_A \rangle \langle \psi_B | \psi_B \rangle. \quad (1.79)$$

Next, we will use Cauchy–Schwarz inequality.

Lemma 1.3 (Cauchy–Schwarz inequality). Let V be a vector space with an inner product \cdot , then for all $\mathbf{u}, \mathbf{v} \in V$,

$$|\mathbf{u} \cdot \mathbf{v}|^2 \leq (\mathbf{u} \cdot \mathbf{u})(\mathbf{v} \cdot \mathbf{v}). \quad (1.80)$$

Therefore, we have

$$\Delta A^2 \Delta B^2 \geq |\langle \psi_A | \psi_B \rangle|^2. \quad (1.81)$$

For any complex number $z \in \mathbb{C}$, we have

$$|z|^2 = \text{Re}(z)^2 + \text{Im}(z)^2 = \left(\frac{z + z^*}{2} \right)^2 + \left(\frac{z - z^*}{2i} \right)^2, \quad (1.82)$$

and since $\langle \psi_A | \psi_B \rangle = \langle \psi_B | \psi_A \rangle^*$, we have

$$\Delta A^2 \Delta B^2 \geq \left(\frac{\langle \psi_A | \psi_B \rangle + \langle \psi_B | \psi_A \rangle}{2} \right)^2 + \left(\frac{\langle \psi_A | \psi_B \rangle - \langle \psi_B | \psi_A \rangle}{2i} \right)^2. \quad (1.83)$$

To simplify things up, we need to work out $\langle \psi_A | \psi_B \rangle$ and $\langle \psi_B | \psi_A \rangle$.

$$\begin{aligned} \langle \psi_A | \psi_B \rangle &= \left\langle \left(\hat{A} - \langle \hat{A} \rangle \right) \psi \middle| \left(\hat{B} - \langle \hat{B} \rangle \right) \psi \right\rangle \\ &= \left\langle \psi \middle| \left(\hat{A} - \langle \hat{A} \rangle \right) \left(\hat{B} - \langle \hat{B} \rangle \right) \middle| \psi \right\rangle \\ &= \left\langle \psi \middle| \hat{A} \hat{B} - \hat{A} \langle \hat{B} \rangle - \hat{B} \langle \hat{A} \rangle + \langle \hat{A} \rangle \langle \hat{B} \rangle \middle| \psi \right\rangle \\ &= \langle \hat{A} \hat{B} \rangle - \langle \hat{A} \rangle \langle \hat{B} \rangle. \end{aligned} \quad (1.84)$$

Similarly

$$\langle \psi_B | \psi_A \rangle = \langle \hat{B} \hat{A} \rangle - \langle \hat{A} \rangle \langle \hat{B} \rangle. \quad (1.85)$$

Defining the *anti-commutator*

$$\{\hat{A}, \hat{B}\} := \hat{A} \hat{B} + \hat{B} \hat{A}, \quad (1.86)$$

we have

$$\langle \psi_A | \psi_B \rangle + \langle \psi_B | \psi_A \rangle = \langle \{\hat{A}, \hat{B}\} \rangle - 2 \langle \hat{A} \rangle \langle \hat{B} \rangle, \quad (1.87)$$

$$\langle \psi_A | \psi_B \rangle - \langle \psi_B | \psi_A \rangle = \langle [\hat{A}, \hat{B}] \rangle. \quad (1.88)$$

This gives what is known as the Robertson–Schrödinger uncertainty principle.

Theorem 1.4 (Robertson–Schrödinger uncertainty principle). For two observables A and B ,

$$\Delta A \Delta B \geq \sqrt{\left(\frac{1}{2} \langle \{\hat{A}, \hat{B}\} \rangle - \langle \hat{A} \rangle \langle \hat{B} \rangle \right)^2 + \left(\frac{1}{2i} \langle [\hat{A}, \hat{B}] \rangle \right)^2}. \quad (1.89)$$

This version of the uncertainty principle is very general, but it simplifies in the special case of uncorrelated operators. The first parenthesised quantity in (1.89) is

$$\text{cov}(\hat{A}, \hat{B}) := \frac{1}{2} \langle \hat{A} \hat{B} - \hat{B} \hat{A} \rangle - \langle \hat{A} \rangle \langle \hat{B} \rangle, \quad (1.90)$$

which is known as the *covariance* of the operators. The corresponding quantity in statistics is

$$\text{cov}(X, Y) := \langle XY \rangle - \langle X \rangle \langle Y \rangle, \quad (1.91)$$

but in quantum mechanics we have to be a little bit more careful because in general $\langle \hat{A} \hat{B} \rangle \neq \langle \hat{B} \hat{A} \rangle$. The covariance is a measure of the correlation between operators, and is 0 if the operators are uncorrelated. If this is the case, then (1.89) reduces to the more familiar Robertson uncertainty principle.

Theorem 1.5 (Robertson Uncertainty Principle). If A and B are two uncorrelated physical observables, then

$$\Delta A \Delta B \geq \frac{1}{2} \left| \langle [\hat{A}, \hat{B}] \rangle \right|. \quad (1.92)$$

Note that if the two operators are correlated, then the Robertson–Schrödinger lower bound is larger than the Robertson lower bound, in other words the Robertson–Schrödinger provides a stronger condition.

2 Normal Modes

In Part IB Chemistry A, we discussed the use of symmetry and group theory to make qualitative conclusions about normal modes.

Example. For example, consider the C – H stretching modes in benzene, with point group D_{6h} .

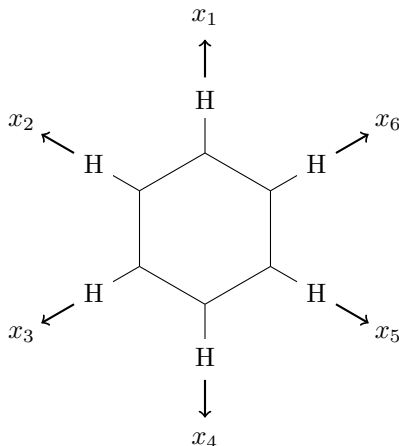


Figure 1: The basis set for representing the C – H stretches in benzene.

Reducing the representation formed by these basis vectors, we get

$$\Gamma^{C-H} = A_{1g} \oplus E_{2g} \oplus B_{1u} \oplus E_{1u}. \quad (2.1)$$

Since there is only one combination for each irreducible representation, it should be easy to determine the symmetry adapted linear combinations of displacements along the C – H bonds that transform according to the symmetries. Based on the Cartesian functions listed in the character table, intuition, or the projection operators, we can determine the normal modes to be

$$Q_{A_{1g}} = \frac{1}{\sqrt{6}}(x_1 + x_2 + x_3 + x_4 + x_5 + x_6) \quad (2.2)$$

$$Q_{E_{2g},1} = \frac{1}{2}(x_2 - x_3 + x_5 - x_6) \quad (2.3)$$

$$Q_{E_{2g},2} = \frac{1}{\sqrt{12}}(2x_1 - x_2 - x_3 + 2x_4 - x_5 - x_6) \quad (2.4)$$

$$Q_{E_{1u},1} = \frac{1}{\sqrt{12}}(2x_1 - x_2 - x_3 - 2x_4 + x_5 + x_6) \quad (2.5)$$

$$Q_{E_{1u},2} = \frac{1}{2}(x_2 + x_3 - x_5 - x_6) \quad (2.6)$$

$$Q_{B_{1u}} = \frac{1}{\sqrt{6}}(x_1 - x_2 + x_3 - x_4 + x_5 - x_6). \quad (2.7)$$

This method is nice and easy, especially for simple cases like this with restricted basis sets. But it does leave unanswered questions. What if we have more than one symmetry adapted combination transforming as a particular IR? These symmetry adapted combinations of displacement vectors are like symmetry orbitals, and some process analogous to combining symmetry orbitals to form molecular orbitals should be indicated. Most of the combinations we have here are only approximations (albeit useful ones) to normal modes, as we can see a lot of them would move the centre of mass. Also, it is impossible that only H atoms are moving during the vibrations — we also need the motion of C atoms as well as displacements in other directions. In such a complete basis set, how to correctly combine

the symmetry adapted displacement vectors to form the true normal modes would be a problem. Additionally, some indication of the frequencies would be useful.

To do this, we have to treat the mechanical problem of molecular vibration seriously.

2.1 Diatomic Vibration

We begin by looking at the vibration of a diatomic molecule, and hopefully this can give us some insight on treating the general problem. Each atom in a diatomic can move in three independent directions (x , y and z), so there are in total six possible independent motions. We know that three of them are translations and rotations, leaving us with only one vibrational mode. It turns out that only the motion along the internuclear axis is useful for vibration. To label the positions of the atoms relative to their equilibrium positions, we define two basis vectors \mathbf{x}_1 and \mathbf{x}_2 . Then the configuration of the atom can be labelled by a vector

$$\mathbf{v} = x_1\mathbf{x}_1 + x_2\mathbf{x}_2, \quad (2.8)$$

where x_1 and x_2 are the components, meaning that atom 1 has displaced by length x_1 along the direction \mathbf{x}_1 , and atom 2 has displaced by x_2 along \mathbf{x}_2 . We can put the components into a single column vector $\mathbf{x} = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$.

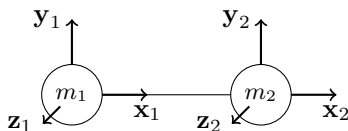


Figure 2: A basis set representing the motion of a diatomic molecule.

The simplest model for the internuclear potential is the harmonic oscillator, with the potential given by

$$V_{\text{HO}} = \frac{1}{2}k(x_1 - x_2)^2, \quad (2.9)$$

where k is the force constant. We can write the Hamiltonian as¹¹

$$\hat{H}(\mathbf{x}) = -\frac{\hbar^2}{2m_1}\frac{\partial^2}{\partial x_1^2} - \frac{\hbar^2}{2m_2}\frac{\partial^2}{\partial x_2^2} + \frac{1}{2}k(x_1 - x_2)^2, \quad (2.10)$$

where the first two terms are the kinetic energies of the two particles with masses of m_1 and m_2 respectively. Now this is a non-separable Hamiltonian — we have cross terms x_1x_2 in the potential energy, so that we can not write the Hamiltonian as $H(x_1) + H(x_2)$. We would not like to solve this kind of partial differential equations directly.

To make progress, we want to try some coordinate transformation that would make the cross terms vanishes. The transformation

$$\begin{aligned} w_1 &= \frac{1}{\sqrt{2}}(x_1 - x_2) \\ w_2 &= \frac{1}{\sqrt{2}}(x_1 + x_2) \end{aligned} \quad (2.11)$$

of the components seems promising, since it eliminates the cross terms in the potential energy by making it into a single term kw_1^2 . Moreover, these two coordinates have solid physical meaning — w_1 is the compression/extension along the internuclear axis, which is exactly the vibrational motion

¹¹We treat this problem using Hamiltonian. If you do Part IB Mathematics, you will solve this type of problems using Lagrangian — you will find that these two methods are closely related.

we are trying to model, and w_2 describes the translation along the internuclear axis, one of the other motion of the molecules. This is described by the unitary transformation matrix

$$\mathbf{U} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \quad (2.12)$$

generated by putting the components of the transformed components in terms of the original components in rows,¹² so that the components transforms as desired:

$$\begin{pmatrix} w_1 \\ w_2 \end{pmatrix} = \mathbf{U} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}, \quad (2.13)$$

or

$$\mathbf{w} = \mathbf{U}\mathbf{x}. \quad (2.14)$$

We can be satisfied that no physical properties will be altered by this unitary transformation.

However, we will see that the problem of this basis transformation is that although the potential terms is nicely simplified, the kinetic term is screwed up. From chain rule, we have

$$\begin{aligned} \frac{\partial}{\partial x_1} &= \frac{\partial w_1}{\partial x_1} + \frac{\partial}{\partial w_1} + \frac{\partial w_2}{\partial x_1} \frac{\partial}{\partial w_2} \\ &= \frac{1}{\sqrt{2}} \left(\frac{\partial}{\partial w_1} - \frac{\partial}{\partial w_2} \right), \end{aligned} \quad (2.15)$$

$$\begin{aligned} \frac{\partial}{\partial x_2} &= \frac{\partial w_1}{\partial x_2} + \frac{\partial}{\partial w_1} + \frac{\partial w_2}{\partial x_2} \frac{\partial}{\partial w_2} \\ &= \frac{1}{\sqrt{2}} \left(\frac{\partial}{\partial w_1} + \frac{\partial}{\partial w_2} \right). \end{aligned} \quad (2.16)$$

Therefore in this transformed basis, the Hamiltonian is

$$\hat{H}(\mathbf{w}) = -\frac{\hbar^2}{4m_1} \left(\frac{\partial}{\partial w_1} - \frac{\partial}{\partial w_2} \right)^2 - \frac{\hbar^2}{4m_2} \left(\frac{\partial}{\partial w_1} + \frac{\partial}{\partial w_2} \right)^2 + kw_1^2. \quad (2.17)$$

The kinetic part contains a mixed partial derivative

$$\frac{\hbar^2}{2m_1} \left(\frac{1}{m_1} - \frac{1}{m_2} \right) \frac{\partial^2}{\partial w_1 \partial w_2}, \quad (2.18)$$

which is non-vanishing for $m_1 \neq m_2$.

It seems that by doing a unitary transformation, we can only separate one of the kinetic and the potential part. Whenever we separate one of the terms, the other will necessarily be screwed up.

However, the above trial did provide us some inspiration. The mixed partial derivative term do vanish if the masses of the two particles are equal. What if we do some scaling to the coordinates based on the masses? In turns out that for this particular question, the useful scaling is

$$Q_1 = \sqrt{\frac{m_1 m_2}{m_1 + m_2}} (x_1 - x_2) \quad (2.19)$$

$$Q_2 = \frac{1}{\sqrt{m_1 + m_2}} (m_1 x_1 + m_2 x_2) \quad (2.20)$$

We will explain how we obtained this later, but now let's try this out. Again, the potential is straightforward to rewrite in the \mathbf{Q} basis, as

$$V_{\text{HO}} = \frac{k(m_1 + m_2)}{2m_1 m_2} Q_1^2. \quad (2.21)$$

¹²Then the basis vector would transform as \mathbf{U}^\dagger . Remember that the basis vectors and the components transform in the inverse way.

For the kinetic energies, we again need the chain rule, and we obtain

$$\frac{\partial}{\partial x_1} = \frac{1}{\sqrt{m_1 + m_2}} \left(\sqrt{m_1 m_2} \frac{\partial}{\partial Q_1} + m_1 \frac{\partial}{\partial Q_2} \right), \quad (2.22)$$

$$\frac{\partial}{\partial x_2} = \frac{1}{\sqrt{m_1 + m_2}} \left(-\sqrt{m_1 m_2} \frac{\partial}{\partial Q_1} + m_2 \frac{\partial}{\partial Q_2} \right). \quad (2.23)$$

If we substitute this into the expression of the Hamiltonian, we will see that all the mixed derivatives magically cancels out and we get

$$\hat{H}(Q) = -\frac{\hbar^2}{2} \frac{\partial^2}{\partial Q_1^2} + \frac{k(m_1 + m_2)}{2m_1 m_2} Q_1^2 - \frac{\hbar^2}{2} \frac{\partial^2}{\partial Q_2^2}. \quad (2.24)$$

This can be nicely separated into

$$\hat{H}(\mathbf{Q}) = \hat{H}(Q_1) + \hat{H}(Q_2), \quad (2.25)$$

where

$$\hat{H}(Q_1) = -\frac{\hbar^2}{2} \frac{\partial^2}{\partial Q_1^2} + \frac{k(m_1 + m_2)}{2m_1 m_2} Q_1^2, \quad (2.26)$$

$$\hat{H}(Q_2) = -\frac{\hbar^2}{2} \frac{\partial^2}{\partial Q_2^2}. \quad (2.27)$$

If we compare (2.26) with the Hamiltonian of a canonical harmonic oscillator, we see that this is an harmonic oscillator with a mass 1 and a modified force constant of

$$k' = \frac{k(m_1 + m_2)}{m_1 m_2} =: \frac{k}{\mu}, \quad (2.28)$$

where we defined the familiar reduced mass $\mu := m_1 m_2 / (m_1 + m_2)$. This gives an angular frequency

$$\omega = \sqrt{\frac{k'}{1}} = \sqrt{\frac{k}{\mu}}. \quad (2.29)$$

This is a familiar result. The vibration of a diatomic molecule is the same as the vibration of a single molecule with reduced mass of the system. The second equation (2.27) has only a kinetic term. This is the translation of the whole molecule along the internuclear axis — it can also be thought of as a harmonic oscillator with zero force constant, and so a zero frequency.

2.1.1 Mass-Weighted Coordinates

Now let's consider what is going on. The transformation we proposed can be expressed by the matrix

$$\mathbf{A} = \frac{1}{\sqrt{m_1 + m_2}} \begin{pmatrix} \sqrt{m_1 m_2} & -\sqrt{m_1 m_2} \\ m_1 & m_2 \end{pmatrix}. \quad (2.30)$$

You may verify that this is not a unitary matrix — the easiest way to see this is by checking its determinant. Therefore, physical observable do not have to be preserved by this transformation. For example, we can see that all masses has reduced to 1, and the actual masses has somehow been taken into the modified force constant. However, the observable we really care about, the (angular) frequency of the oscillator ω , is related to the ratio of these, and this is unchanged by our transformation.

To see what it really going on in our transformation, we can split our transformation into two phases. The first phase is to mass-weight the coordinates, defining $q_i = \sqrt{m_i} x_i$, which is a diagonal transform, but is not unitary. This is represented by the diagonal matrix

$$\mathbf{B} = \begin{pmatrix} \sqrt{m_1} & 0 \\ 0 & \sqrt{m_2} \end{pmatrix}. \quad (2.31)$$

The Hamiltonian in this mass-weighted basis set is

$$\hat{H}(\mathbf{q}) = -\frac{\hbar^2}{2} \left(\frac{\partial^2}{\partial q_1^2} + \frac{\partial^2}{\partial q_2^2} \right) + \frac{k}{2} \left(\frac{q_1}{\sqrt{m_1}} - \frac{q_2}{\sqrt{m_2}} \right)^2. \quad (2.32)$$

This transformation does not remove the cross term in the potential, but it has reduced all the kinetic terms to a nice and simple form where all the masses are unity. This is exactly the case that we wanted before — if the masses are equal, then when you do the unitary transformation to simplify the potential term, all the cross terms in the kinetic term after the transformation will automatically cancel out! We are then ready to do our second transformation defined by

$$Q_1 = \frac{1}{\sqrt{m_1 + m_2}} (\sqrt{m_2} q_1 - \sqrt{m_1} q_2), \quad (2.33)$$

$$Q_2 = \frac{1}{\sqrt{m_1 + m_2}} (\sqrt{m_1} q_1 + \sqrt{m_2} q_2), \quad (2.34)$$

which can be represented by the unitary matrix

$$\mathbf{C} = \frac{1}{\sqrt{m_1 + m_2}} \begin{pmatrix} \sqrt{m_2} & -\sqrt{m_1} \\ \sqrt{m_1} & \sqrt{m_2} \end{pmatrix}. \quad (2.35)$$

The combination of these two transformations is the one we claimed before:

$$\mathbf{A} = \mathbf{C}\mathbf{B}. \quad (2.36)$$

2.2 Quadratic Form

Before investigating more complicated cases, you may find that it is extremely useful to formulate the above process in matrices. Hence, we may rewrite the Hamiltonian in the following matrix form

$$\hat{H}(\mathbf{x}) = \frac{\hbar^2}{2} \begin{pmatrix} \frac{\partial}{\partial x_1} & \frac{\partial}{\partial x_2} \end{pmatrix} \begin{pmatrix} \frac{1}{m_1} & 0 \\ 0 & \frac{1}{m_2} \end{pmatrix} \begin{pmatrix} \frac{\partial}{\partial x_1} \\ \frac{\partial}{\partial x_2} \end{pmatrix} + \frac{1}{2} \begin{pmatrix} x_1 & x_2 \end{pmatrix} \begin{pmatrix} k & -k \\ -k & k \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \quad (2.37)$$

$$=: -\frac{\hbar^2}{2} \dot{\mathbf{x}}^T \mathbf{T}_x \dot{\mathbf{x}} + \frac{1}{2} \mathbf{x}^T \mathbf{H}_x \mathbf{x}. \quad (2.38)$$

The subscripts x here stands for the x basis, and \mathbf{H} is confusingly the canonical notation for the Hessian matrix which unfortunately happens to share its notation with the Hamiltonian.

Now we can do the transformations. The first step is to mass-scale the coordinates by

$$\mathbf{q} = \mathbf{B}\mathbf{x}, \quad (2.39)$$

where

$$\mathbf{B} = \begin{pmatrix} \sqrt{m_1} & 0 \\ 0 & \sqrt{m_2} \end{pmatrix}. \quad (2.40)$$

Note that by chain rule, the derivatives transform in the opposite way as the coordinates, so

$$\dot{\mathbf{q}} = \mathbf{B}^{-1} \dot{\mathbf{x}}, \quad (2.41)$$

and so

$$\dot{\mathbf{x}}^T \mathbf{T}_x \dot{\mathbf{x}} = \dot{\mathbf{q}}^T \mathbf{B}^T \mathbf{T}_x \mathbf{B} \dot{\mathbf{q}} =: \dot{\mathbf{q}}^T \mathbf{T}_q \dot{\mathbf{q}}. \quad (2.42)$$

This transformation is designed to reduce the \mathbf{T} matrix to the identity matrix in this basis:

$$\mathbf{T}_q := \mathbf{B}^T \mathbf{T}_x \mathbf{B} = \mathbf{I}, \quad (2.43)$$

and so

$$\dot{\mathbf{x}}^T \mathbf{T}_x \dot{\mathbf{x}} = \dot{\mathbf{q}}^T \mathbf{I} \dot{\mathbf{q}} = \dot{\mathbf{q}}^T \dot{\mathbf{q}}. \quad (2.44)$$

Similarly for the Hessian matrix,

$$\mathbf{x}^T \mathbf{H}_x \mathbf{x} = \mathbf{q}^T (\mathbf{B}^{-1})^T \mathbf{H}_x \mathbf{B}^{-1} \mathbf{q} =: \mathbf{q}^T \mathbf{K} \mathbf{q}, \quad (2.45)$$

where the Hessian matrix in this mass-scaled coordinate is called the *dynamical matrix* and is given the special notation \mathbf{K} . We can calculate this as

$$\mathbf{K} := (\mathbf{B}^{-1})^T \mathbf{H}_x \mathbf{B}^{-1} = \begin{pmatrix} \frac{k}{m_1} & -\frac{k}{\sqrt{m_1 m_2}} \\ -\frac{k}{\sqrt{m_1 m_2}} & \frac{k}{m_2} \end{pmatrix}. \quad (2.46)$$

Similarly, we then do the unitary transformation that diagonalises \mathbf{K} as well, and we finally get

$$\mathbf{T}_Q = \mathbf{I}, \quad \mathbf{H}_Q = \begin{pmatrix} 0 & 0 \\ 0 & \frac{k}{\mu} \end{pmatrix} \quad (2.47)$$

in the \mathbf{Q} basis. Since both matrices are diagonal, we are then able to separate the Hamiltonian.

2.3 The General Case

Now we are ready to generalise the above method for all molecules. Consider a molecule consisting of M atoms. The position of each atom is described by a displacement vector $\mathbf{x}_i = (x_i, y_i, z_i)$ ($1 \leq i \leq N$) from its equilibrium position. We can compactly string them together as a $3N$ -dimensional vector

$$\mathbf{x} = (x_1, y_1, z_1, \dots, x_N, y_N, z_N). \quad (2.48)$$

A general Hamiltonian can be written as

$$\hat{H} = -\frac{\hbar^2}{2} \sum_i \frac{1}{m_i} \frac{\partial^2}{\partial x_i^2} + \frac{1}{2} \sum_i \sum_{j>1}^{3N} k_{ij} (x_i - x_j)^2. \quad (2.49)$$

Note that we sum over $i > j$ in the potential term to avoid double counting, and we allow a potential term to rise between any two coordinates, although in practise we can set most of them to be zero. We can write this into the matrix form introduced above

$$\hat{H} = -\frac{\hbar^2}{2} \dot{\mathbf{x}}^T \mathbf{T}_x \dot{\mathbf{x}} + \frac{1}{2} \mathbf{x}^T \mathbf{H}_x \mathbf{x}, \quad (2.50)$$

where \mathbf{T} is a diagonal matrix whose elements are the reciprocal masses

$$T_{x,ii} = \frac{1}{m_i}, \quad (2.51)$$

and the Hessian matrix elements are

$$H_{x,ij} = \frac{\partial^2 V}{\partial x_i \partial x_j} = \begin{cases} \sum_n k_{in} & \text{if } i = j \\ -k_{ij} & \text{if } i \neq j \end{cases}. \quad (2.52)$$

We first scale the Hamiltonian into the mass-weighted basis so that

$$\hat{H}(\mathbf{q}) = -\frac{\hbar^2}{2} \dot{\mathbf{q}}^T \dot{\mathbf{q}} + \frac{1}{2} \mathbf{q}^T \mathbf{K} \mathbf{q}. \quad (2.53)$$

The matrix \mathbf{T}_q in the mass-weighted basis is the identity matrix so we have omitted it, and the dynamical matrix is simply

$$K_{ij} = \frac{1}{\sqrt{m_i m_j}} H_{x,ij}. \quad (2.54)$$

We now need to transform the basis such that the \mathbf{K} is made diagonal. We can always do this because \mathbf{K} is a real symmetric matrix, which is always diagonalisable by a orthogonal matrix (a real unitary matrix). This transformation is guaranteed to keep \mathbf{T} matrix still diagonalised because the identity matrix is always the identity matrix in any basis. This is done by the orthogonal matrix \mathbf{C} such that

$$\mathbf{H}_Q = \mathbf{C}^\dagger \mathbf{K} \mathbf{C}, \quad (2.55)$$

where each column of \mathbf{C} is the normalised eigenvector of \mathbf{K} , and \mathbf{H}_Q is a diagonal matrix whose elements are eigenvalues $\{\lambda_i\}$ of \mathbf{K} in corresponding order. Finally in this basis, we have

$$\hat{H}(\mathbf{Q}) = -\frac{\hbar^2}{2} \dot{\mathbf{Q}}^\mathbf{T} \dot{\mathbf{Q}} + \frac{1}{2} \mathbf{Q}^\mathbf{T} \mathbf{H}_Q \mathbf{Q} \quad (2.56)$$

$$= \sum_i^{3N} \left(-\frac{\hbar^2}{2} \frac{\partial^2}{\partial Q_i^2} + \frac{1}{2} \lambda_i Q_i^2 \right) \quad (2.57)$$

separated into $3N$ one-dimensional harmonic oscillator with modified force constants $\{\lambda_i\}$. The angular frequencies of the modes are therefore

$$\omega_i = \sqrt{\lambda_i}. \quad (2.58)$$

The eigenvectors of \mathbf{K} are the normal modes in terms of the \mathbf{q} coordinates, which can be transformed into the \mathbf{x} coordinates. Note that although the normal modes are orthogonal in the \mathbf{q} coordinates, they are not necessarily so in the \mathbf{x} coordinates since the mass scaling is not unitary. However, we may still often find them to be orthogonal, as they must be so if they transform according to different irreducible representations.

Note that since we used all $3N$ displacement vectors, there will be 6 (or 5) normal modes corresponding to translations or rotations. If we use a restricted basis set, there may be less of them. They can be easily identified as modes with frequencies zero.

2.4 Example: AAA Linear Molecule

As an simple example, let's look at the AAA linear molecule of three identical atoms connected by two bonds of equal strengths. An example of this would be the azide anion. For simplicity, we only consider the motions along the internuclear axis.

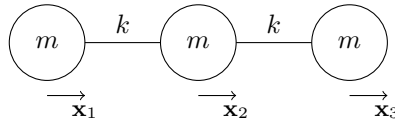


Figure 3: An AAA molecule.

The potential can be modelled as

$$V = \frac{k}{2}(x_1 - x_2)^2 + \frac{k}{2}(x_2 - x_3)^2. \quad (2.59)$$

The Hessian matrix can be found by either taking the partial derivative or by expanding the above function.

$$\mathbf{H}_x = \begin{pmatrix} k & -k & 0 \\ -k & 2k & -k \\ 0 & -k & k \end{pmatrix}. \quad (2.60)$$

The dynamical matrix is

$$\mathbf{K} = \begin{pmatrix} \frac{k}{m} & -\frac{k}{m} & 0 \\ -\frac{k}{m} & \frac{2k}{m} & -\frac{k}{m} \\ 0 & -\frac{k}{m} & \frac{k}{m} \end{pmatrix}. \quad (2.61)$$

We then simply need to diagonalise this matrix. The eigenvalues and the corresponding normal mode frequencies are

$$\lambda_1 = 0 \qquad \lambda_2 = \frac{k}{m} \qquad \lambda_3 = \frac{3k}{m} \quad (2.62)$$

$$\omega_1 = 0 \qquad \omega_2 = \sqrt{\frac{k}{m}} \qquad \omega_3 = \sqrt{\frac{3k}{m}}. \quad (2.63)$$

We can also find the normalised eigenvectors, which give the normal mode coordinates in the \mathbf{q} basis (which is also the normal coordinates in the \mathbf{x} basis since all atoms have equal masses)

$$Q_1 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \cdot \mathbf{q} \qquad Q_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} -1 \\ 0 \\ 1 \end{pmatrix} \cdot \mathbf{q} \qquad Q_3 = \frac{1}{\sqrt{6}} \begin{pmatrix} 1 \\ -2 \\ 1 \end{pmatrix} \cdot \mathbf{q}. \quad (2.64)$$

In mode 1, all atoms move in the same direction with the same magnitude. This is the translation. Mode 2 is the symmetric stretch, in which both bonds are simultaneously stretched/compressed, and mode 3 is the antisymmetric stretch, in which when one bond is stretched, the other is compressed.



Figure 4: Normal modes of an AAA molecule.

2.5 The Use of Symmetry

The dynamical matrix in the above example is 3×3 , which we can easily diagonalise directly. For larger molecules, we will encounter the same issue that we had when constructing MOs: any bigger matrix will be too tedious to diagonalise directly by hand. The solution is the same too: we can use an intermediate symmetry-adapted basis set to transform the dynamical matrix to a block diagonal form.

We will summarise the process of constructing normal modes by symmetry as well as molecular orbitals in the table below.

2.6 Example: ABBBA Linear Molecule

Consider the motions along the bond for a centrosymmetric ABBBA linear molecule, for example acetylene. The masses of the two types of atoms are now different, and we also allow the strength of the A – B bond to be different from the B – B bond.

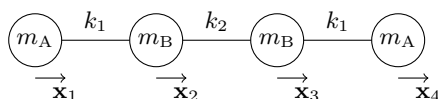


Figure 5: A centrosymmetric ABBBA linear molecule.

MOs	Normal modes
1. Write down the Hamiltonian matrix in the AO basis.	1. Write down the dynamical matrix in the mass-weighted basis.
2. Determine the IRs spanned by the AO basis set.	2. Determine IRs spanned by the mass-weighted basis set.
3. Construct symmetry adapted combinations of the AOs.	3. Construct symmetry adapted combinations of the mass-weighted coordinates.
4. Transform the Hamiltonian matrix into the symmetry-adapted basis set.	4. Transform the dynamical matrix into the symmetry-adapted basis set.
5. The eigenvalues are the orbital energies and the eigenvectors are the MO coefficients in the symmetry-adapted basis set.	5. The eigenvalues are the frequencies squared and the eigenvectors are the normal mode coordinates in the symmetry-adapted basis set.
6. The eigenvectors can be transformed back to the AO basis set.	6. The eigenvectors can be transformed back to the coordinate displacement basis set.

If we proceed without using symmetry, then we have a 4×4 dynamical matrix to diagonalise

$$\mathbf{K} = \begin{pmatrix} \frac{k_1}{m_A} & -\frac{k_1}{\sqrt{m_A m_B}} & 0 & 0 \\ -\frac{k_1}{\sqrt{m_A m_B}} & \frac{k_1 + k_2}{m_B} & -\frac{k_2}{m_B} & 0 \\ 0 & -\frac{k_2}{m_B} & \frac{k_1 + k_2}{m_B} & -\frac{k_1}{\sqrt{m_A m_B}} \\ 0 & 0 & -\frac{k_1}{\sqrt{m_A m_B}} & \frac{k_1}{m_A} \end{pmatrix}. \quad (2.65)$$

To simplify things up, we will create a $\tilde{\mathbf{q}}$ basis from symmetry adapted combinations of \mathbf{q} . The point group of the molecule is $D_{\infty h}$, and we can split the basis into two two-dimensional sets $\{\mathbf{q}_1, \mathbf{q}_4\}$ and $\{\mathbf{q}_2, \mathbf{q}_3\}$. The irreducible representations and the symmetry adapted combinations of basis vectors should be easy to find¹³

$$\tilde{\mathbf{q}}_1 = \frac{1}{\sqrt{2}}(\mathbf{q}_1 - \mathbf{q}_4) \quad \Sigma_g^+ \quad (2.66)$$

$$\tilde{\mathbf{q}}_2 = \frac{1}{\sqrt{2}}(\mathbf{q}_2 - \mathbf{q}_3) \quad \Sigma_g^+ \quad (2.67)$$

$$\tilde{\mathbf{q}}_3 = \frac{1}{\sqrt{2}}(\mathbf{q}_1 + \mathbf{q}_4) \quad \Sigma_u^+ \quad (2.68)$$

$$\tilde{\mathbf{q}}_4 = \frac{1}{\sqrt{2}}(\mathbf{q}_2 + \mathbf{q}_3) \quad \Sigma_u^+ \quad (2.69)$$

This is the basis transformation represented by the unitary matrix

$$\tilde{\mathbf{C}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & -1 & 0 & 1 \\ -1 & 0 & 1 & 0 \end{pmatrix} \quad (2.70)$$

so that the components transforms as

$$\tilde{\mathbf{q}} = \tilde{\mathbf{C}}^\dagger \mathbf{q}. \quad (2.71)$$

¹³Recall when constructing a representation, we transform the basis, not the components.

We must have

$$\mathbf{q}^\dagger \mathbf{K} \mathbf{q} = \tilde{\mathbf{q}}^\dagger \tilde{\mathbf{K}} \tilde{\mathbf{q}} = \mathbf{q}^\dagger \tilde{\mathbf{C}} \tilde{\mathbf{K}} \tilde{\mathbf{C}}^\dagger \mathbf{q}, \quad (2.72)$$

and so

$$\tilde{\mathbf{K}} = \tilde{\mathbf{C}} \mathbf{K} \tilde{\mathbf{C}} \quad (2.73)$$

$$= \begin{pmatrix} \frac{k_1}{m_A} & -\frac{k_1}{\sqrt{m_A m_B}} & 0 & 0 \\ -\frac{k_1}{\sqrt{m_A m_B}} & \frac{k_1 + 2k_2}{m_B} & 0 & 0 \\ 0 & 0 & \frac{k_1}{m_A} & -\frac{k_1}{\sqrt{m_A m_B}} \\ 0 & 0 & -\frac{k_1}{\sqrt{m_A m_B}} & \frac{k_1}{m_A} \end{pmatrix}. \quad (2.74)$$

This is block diagonal as expected. For simplicity, we will only work out the Σ_u^+ (bottom right) block. The eigenvalues are

$$\lambda_3 = 0 \quad \lambda_4 = \frac{k_1(m_A + m_B)}{m_A m_B}, \quad (2.75)$$

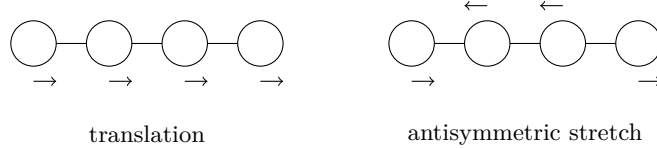
and the eigenvectors in the various basis sets are

$$Q_3 = \frac{1}{\sqrt{m_A + m_B}} \begin{pmatrix} \sqrt{m_A} \\ \sqrt{m_B} \end{pmatrix} \cdot \tilde{\mathbf{q}}_{\Sigma_u^+} \quad Q_4 = \frac{1}{\sqrt{m_A + m_B}} \begin{pmatrix} \sqrt{m_B} \\ -\sqrt{m_A} \end{pmatrix} \cdot \tilde{\mathbf{q}}_{\Sigma_u^+} \quad (2.76)$$

$$= \frac{1}{\sqrt{2(m_A + m_B)}} \begin{pmatrix} \sqrt{m_A} \\ \sqrt{m_B} \\ \sqrt{m_B} \\ \sqrt{m_A} \end{pmatrix} \cdot \mathbf{q} \quad = \frac{1}{\sqrt{2(m_A + m_B)}} \begin{pmatrix} \sqrt{m_B} \\ -\sqrt{m_A} \\ -\sqrt{m_A} \\ \sqrt{m_B} \end{pmatrix} \cdot \mathbf{q} \quad (2.77)$$

$$= \frac{1}{2} \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} \cdot \mathbf{x} \quad = \frac{\sqrt{m_A m_B}}{\sqrt{2(m_A^2 + m_B^2)}} \begin{pmatrix} \sqrt{\frac{m_B}{m_A}} \\ -\sqrt{\frac{m_A}{m_B}} \\ -\sqrt{\frac{m_A}{m_B}} \\ \sqrt{\frac{m_B}{m_A}} \end{pmatrix} \cdot \mathbf{x}. \quad (2.78)$$

Mode three is the uniform translation, and mode four is the antisymmetric stretch in which when one A – B bond is stretched, the other is compressed.



2.7 Beyond Harmonic Oscillators

Real molecules are not harmonic oscillators in general. We will have some complicated potential as a function of the nuclear coordinates, which defines the nuclear *potential energy surface* (PES). We can perform a Taylor expansion around an equilibrium position to get

$$V(\mathbf{R}) = V(\mathbf{R}_{\text{eq}}) + \sum_{i=1}^{3N} x_i \frac{\partial V}{\partial x_i} \Big|_{\mathbf{R}_{\text{eq}}} + \frac{1}{2} \sum_{i=1}^{3N} \sum_{j=1}^{3N} x_i x_j \frac{\partial^2 V}{\partial x_i \partial x_j} \Big|_{\mathbf{R}_{\text{eq}}} + O(x_i x_j x_k). \quad (2.79)$$

$V(\mathbf{R}_{\text{eq}})$ is the energy at the bottom of the potential well, which we can set to 0, and the first derivatives at the equilibrium positions should also be 0. For sufficiently small oscillations, the cubic terms and above are not significant, so we can truncate our expression at the quadratic term, which is equivalent to making a harmonic approximation. We are left with

$$V(\mathbf{R}) \approx \frac{1}{2} \sum_{i,j=1}^{3N} x_i x_j \frac{\partial^2 V}{\partial x_i \partial x_j} \Big|_{\mathbf{R}_{\text{eq}}} = \mathbf{x}^T \mathbf{H}_x \mathbf{x} \quad (2.80)$$

with Hessian matrix elements

$$H_{x,ij} = \left. \frac{\partial^2 V}{\partial x_i \partial x_j} \right|_{\mathbf{R}_{\text{eq}}} . \quad (2.81)$$

For harmonic potentials, this is equivalent to finding the quadratic coefficients of V . If we want to include the effect of cubic terms and above, we can do this by perturbation theory, which is the topic of the rest of this course.

2.8 Transition States

The eigenvalues of the Hessian matrix represents the second derivatives of the potential energies along the principal directions. Recall that a positive second derivative corresponds to a minimum. Ignoring the six directions that do not corresponds to an internal change of the molecule, we can classify a stationary point on the potential energy surface according to the number of negative Hessian eigenvalues. If there are no negative Hessian eigenvalues, then this is a minimum on the PES. If all the eigenvalues are negative, the point is a maximum.

The Murrell–Laidler definition of a *transition state* is an index-1 saddle point, that is a stationary point with only one negative Hessian value. Therefore a transition state is a maximum along one direction and a minimum in all other orthogonal directions. The normal mode corresponding to the negative Hessian eigenvalue is the reaction coordinate at the transition state. Since the vibrational frequency is the square root of the eigenvalue, the frequency in such a direction is imaginary.¹⁴

¹⁴This statement should make you question the derivation of transition state theory presented in the Part IB MELT course. A rigorous treatment of reaction kinetics will be left to Part III.

3 Non-degenerate Perturbation Theory

3.1 Non-degenerate Perturbation Theory

Often the Schrödinger equation of a Hamiltonian H will be too complicated to be solved directly:

$$\hat{H}\psi_n = E_n\psi_n, \quad (3.1)$$

where $n \in \mathbb{N}$ labelling the quantum states. Then we need to start to make approximations. The starting point of the perturbation theory is to find a simpler Hamiltonian, which we call $\hat{H}^{(0)}$, that somewhat resembles H but whose eigenfunctions $\psi_n^{(0)}$ and eigenvalues $E_n^{(0)}$ are known:

$$\hat{H}^{(0)}\psi_n^{(0)} = E_n^{(0)}\psi_n^{(0)}. \quad (3.2)$$

At this state we will assume that the states are non-degenerate.

The next thing we do to consider the whole one-parameter family of Hamiltonian

$$\hat{H}(\lambda) = \hat{H}^{(0)} + \lambda\hat{H}^{(1)} \quad (3.3)$$

such that

$$\hat{H}(\lambda^*) = \hat{H} \quad (3.4)$$

at some specific value of $\lambda = \lambda^*$. $\hat{H}^{(1)}$ is the *perturbation* to the reference Hamiltonian. Usually we would just let

$$\hat{H}^{(1)} = \hat{H} - \hat{H}^{(0)} \quad (3.5)$$

so that $\hat{H}(\lambda)$ becomes the Hamiltonian \hat{H} of interest at $\lambda = 1$. However, sometimes the perturbation to the reference Hamiltonian has a natural perturbation in it. For example, if we consider applying a small electric field $\mathcal{E}\hat{\mathbf{z}}$ to a molecule with dipole $\boldsymbol{\mu}$, then the strength of the electric field \mathcal{E} will be a natural perturbation parameter.

Then the fundamental assumption in perturbation theory is to assume that both the energies and the quantum states are analytic near $\lambda = 0$, so that if we gradually turn on the perturbation from the reference state where $\lambda = 0$ to some small non-zero λ , the energies and the wavefunctions will also change smoothly given by the power series

$$\psi_n(\lambda) = \psi_n^{(0)} + \lambda\psi_n^{(1)} + \lambda^2\psi_n^{(2)} + \dots \quad (3.6)$$

$$E_n(\lambda) = E_n^{(0)} + \lambda E_n^{(1)} + \lambda^2 E_n^{(2)} + \dots \quad (3.7)$$

In hope that these series do converge to the true values, we can then evaluate these power series expansions (usually the first few correction terms only) at the desired value of λ to get a approximation of the true E_n and ψ_n .

We will employ the conventional *intermediate normalisation*, where the unperturbed wavefunction will be normalised

$$\langle \psi_n^{(0)} | \psi_n^{(0)} \rangle \equiv \langle n | n \rangle = 0. \quad (3.8)$$

This choice means that the perturbed wavefunctions $\psi_n(\lambda)$ will not be normalised. However, since $\psi_n^{(1)}, \psi_n^{(2)}, \dots$ are correction to $\psi_n^{(0)}$, we may require that

$$\langle n | \psi_n^{(i)} \rangle = 0 \quad (3.9)$$

for all $i > 0$, from which it follows that

$$\langle n | \psi_n \rangle = 1. \quad (3.10)$$

We can claim this because if $\psi_n^{(i)}$ has some non-zero $\psi_n^{(0)}$ component for $i > 0$, we can absorb it into $\psi_n^{(0)}$ and renormalise ψ_n to make the coefficient of $\psi_n^{(0)}$ to be 1 again.

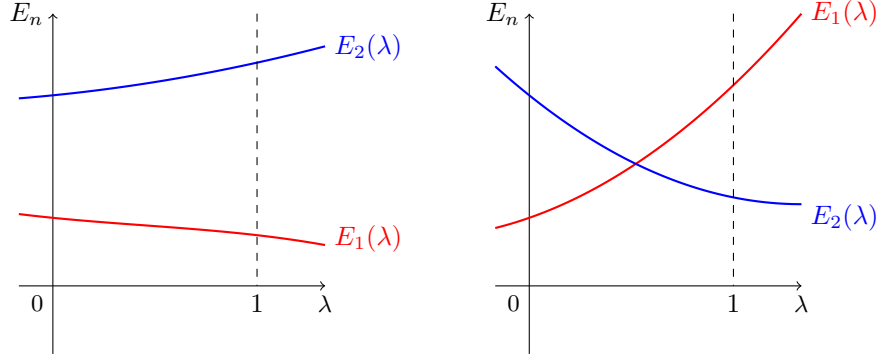


Figure 6: The perturbation theory is appropriate in the first case, in which the reference Hamiltonian is “close enough” to the true Hamiltonian such that the perturbation only leads to small changes in the energies and wavefunctions. The perturbation theory may not work in the second case where the changes in energy levels is comparable with the energy level separations. The reference Hamiltonian is too far away from the true Hamiltonian. Either we will then need too many terms in the series expansion to get a satisfactory result, or the series just may not converge.

3.1.1 The Perturbation Equations

To work out the coefficients $E_n^{(i)}$ and $\psi_n^{(i)}$ of the power series, we simply need to plug the expansion ansatz (3.7) and (3.6) into the Schrödinger equation (3.1) to get

$$(\hat{H}^{(0)} + \lambda \hat{H}^{(1)} - E_n^{(0)} - \lambda E_n^{(1)} - \lambda^2 E_n^{(2)} + \dots)(\psi_n^{(0)} + \lambda \psi_n^{(1)} + \lambda^2 \psi_n^{(2)} + \dots) = 0 \quad (3.11)$$

For this equation to be satisfied for all λ sufficiently small such that the series converges, the coefficients of all powers of λ must be zero. Gathering the terms in $\lambda^0, \lambda^1, \lambda^2, \dots$, we get a series of equations

$$(\hat{H}^{(0)} - E_n^{(0)}) \left| \psi_n^{(0)} \right\rangle = 0 \quad (3.12)$$

$$(\hat{H}^{(0)} - E_n^{(0)}) \left| \psi_n^{(1)} \right\rangle + (\hat{H}^{(1)} - E_n^{(1)}) \left| \psi_n^{(0)} \right\rangle = 0 \quad (3.13)$$

$$(\hat{H}^{(0)} - E_n^{(0)}) \left| \psi_n^{(2)} \right\rangle + (\hat{H}^{(1)} - E_n^{(1)}) \left| \psi_n^{(1)} \right\rangle - E_n^{(2)} \left| \psi_n^{(0)} \right\rangle = 0 \quad (3.14)$$

\vdots

The zeroth-order equation (3.12) is exactly the unperturbed Schrödinger equation (3.2), which we should have already solved. The next equation of interest is the first-order equation (3.13). If we contract it with $\langle \psi_n^{(0)} | \equiv \langle n |$, we get

$$\langle n | H^{(0)} - E_n^{(0)} | \psi_n^{(1)} \rangle + \langle n | \hat{H}^{(1)} - E_n^{(1)} | n \rangle = 0. \quad (3.15)$$

Since $\hat{H}^{(0)}$ is Hermitian, the first term vanishes:

$$\langle n | H^{(0)} - E_n^{(0)} | \psi_n^{(1)} \rangle = \langle \psi_n^{(1)} | H^{(0)} - E_n^{(0)} | n \rangle^* = 0, \quad (3.16)$$

and we are left with

$$E_n^{(1)} = \langle n | \hat{H}^{(1)} | n \rangle. \quad (3.17)$$

This is the key result in perturbation theory. The first-order correction in energy is simply the expectation value of the perturbation for the unperturbed state. This also implies that

$$E_n^{(0)} + \lambda E_n^{(1)} = \langle n | \hat{H}^{(0)} + \lambda \hat{H}^{(1)} | n \rangle = \langle n | \hat{H} | n \rangle. \quad (3.18)$$

The energy corrected to first order is the expectation value of the complete Hamiltonian with the unperturbed wavefunction.

A similar procedure yields the second-order energy. If we contract the second-order perturbation equation (3.14) with $\langle n|$, we get

$$\langle n|\hat{H}^{(0)} - E_n^{(0)}|\psi_n^{(2)}\rangle + \langle n|\hat{H}^{(1)} - E_n^{(1)}|\psi_n^{(1)}\rangle - \langle n|E_n^{(2)}|n\rangle = 0. \quad (3.19)$$

The first term again vanishes since $\hat{H}^{(0)}$ is Hermitian. By the intermediate normalisation, we also have $E_n^{(1)}\langle n|\psi_n^{(1)}\rangle$ in the second term vanishes and the third term $\langle n|E_n^{(2)}|n\rangle = E_n^{(2)}$. Therefore, the second-order energy is

$$E_n^{(2)} = \langle n|\hat{H}^{(1)}|\psi_n^{(1)}\rangle. \quad (3.20)$$

To use this expression we will need to obtain the first-order wavefunction $\psi_n^{(1)}$. This can be obtained by solving the complicated first-order equation (3.13), which we don't expect to have a simple closed form solution in general unless in very simple cases. We will introduce alternative methods to work this out later.

3.1.2 Higher-order Energies and Wigner's $2n + 1$ Theorem

By expanding higher order terms of (3.11), one can show that the n^{th} -order correction in energy is given by

$$E_n^{(i)} = \langle n|\hat{H}^{(1)}|\psi_n^{(i-1)}\rangle, \quad (3.21)$$

so it seems that we need to know the wavefunction to the order $i - 1$ to calculate the energy to order i . In fact, we can do better than this

Theorem 3.1 (Wigner's $2n + 1$ rule). The $2n + 1^{\text{th}}$ -order correction of energy can be calculated from the first n^{th} -order perturbation of wavefunctions.

This is more easily seen in a different formulation of the perturbation theory called the *Wigner-Brillouin perturbation theory*, but it is a far more complicated topic. A brief proof of this is in appendix section A, and here we will only show explicitly how to construct $E_n^{(3)}$ from $\psi_n^{(1)}$.

If we contract the first-order perturbation equation (3.13) with the second-order wavefunction $\langle \psi_n^{(2)}|$, we get a overall third-order expression

$$\langle \psi_n^{(2)}|\hat{H}^{(0)} - E_n^{(0)}|\psi_n^{(1)}\rangle + \langle \psi_n^{(2)}|\hat{H}^{(1)} - E_n^{(1)}|n\rangle = 0. \quad (3.22)$$

By (3.21) and the intermediate normalisation, we identify the second term as $E_n^{(3)}$, and so

$$E_n^{(3)} = -\langle \psi_n^{(2)}|\hat{H}^{(0)} - E_n^{(0)}|\psi_n^{(1)}\rangle. \quad (3.23)$$

We can get another third-order expression by contracting the second-order equation (3.14) with the first-order wavefunction $\langle \psi_n^{(1)}|$

$$\langle \psi_n^{(1)}|\hat{H}^{(0)} - E_n^{(0)}|\psi_n^{(2)}\rangle + \langle \psi_n^{(1)}|\hat{H}^{(1)} - E_n^{(1)}|\psi_n^{(1)}\rangle = 0. \quad (3.24)$$

We identify the first term in the above expression as the negative third-order energy by (3.23), and so

$$E_n^{(3)} = \langle \psi_n^{(1)}|\hat{H}^{(1)} - E_n^{(1)}|\psi_n^{(1)}\rangle, \quad (3.25)$$

which contains only the first-order wavefunction as claimed.

We can obtain higher order expression using the same trick as above, but they will be much more complicated to derive and are rarely needed. For a problem to be properly treated using perturbation theory, the higher order corrections should be small and so the series should converge quickly.

3.2 The Hellmann–Feynman Theorem

We have formulated the perturbation problem as the eigenvalue problem of a family of one-parameter Hamiltonians

$$\hat{H}(\lambda)\psi(\lambda) = E(\lambda)\psi(\lambda). \quad (3.26)$$

How the energy $E(\lambda)$ changes against λ actually tells us something more about the system.

Theorem 3.2 (Hellmann–Feynman theorem). Let $E(\lambda)$ and $\psi(\lambda)$ be the eigenvalues and eigenstates of the of one-parameter family of Hamiltonians

$$\hat{H}(\lambda)\psi(\lambda) = E(\lambda)\psi(\lambda), \quad (3.27)$$

then

$$\frac{dE(\lambda)}{d\lambda} = \left\langle \psi(\lambda) \left| \frac{d\hat{H}(\lambda)}{d\lambda} \right| \psi(\lambda) \right\rangle. \quad (3.28)$$

Proof. Let $\psi(\lambda)$ be normalised. Then by the product rule,

$$\begin{aligned} \frac{dE(\lambda)}{d\lambda} &= \frac{d}{d\lambda} \left\langle \psi(\lambda) \left| \hat{H}(\lambda) \right| \psi(\lambda) \right\rangle \\ &= \left\langle \frac{d\psi(\lambda)}{d\lambda} \left| \hat{H}(\lambda) \right| \psi(\lambda) \right\rangle + \left\langle \psi(\lambda) \left| \frac{d\hat{H}(\lambda)}{d\lambda} \right| \psi(\lambda) \right\rangle + \left\langle \psi(\lambda) \left| \hat{H}(\lambda) \right| \frac{d\psi(\lambda)}{d\lambda} \right\rangle \\ &= \left\langle \psi(\lambda) \left| \frac{d\hat{H}(\lambda)}{d\lambda} \right| \psi(\lambda) \right\rangle + E(\lambda) \left[\left\langle \frac{d\psi(\lambda)}{d\lambda} \left| \psi(\lambda) \right\rangle + \left\langle \psi(\lambda) \left| \frac{d\psi(\lambda)}{d\lambda} \right\rangle \right] \right. \\ &= \left\langle \psi(\lambda) \left| \frac{d\hat{H}(\lambda)}{d\lambda} \right| \psi(\lambda) \right\rangle + E(\lambda) \frac{d}{d\lambda} \|\psi(\lambda)\| \\ &= \left\langle \psi(\lambda) \left| \frac{d\hat{H}(\lambda)}{d\lambda} \right| \psi(\lambda) \right\rangle. \end{aligned} \quad (3.29)$$

□

Let's make a connection with the perturbation theory. We can expand $E(\lambda)$ in a Taylor series

$$E(\lambda) = E(0) + \left. \frac{dE}{d\lambda} \right|_{\lambda=0} \lambda + \frac{1}{2} \left. \frac{d^2E}{d\lambda^2} \right|_{\lambda=0} \lambda^2 + \dots \quad (3.30)$$

Then we may identify the n^{th} derivatives of $E(\lambda)$ at $\lambda = 0$ as the n^{th} -order correction in energy

$$E^{(1)} = \left. \frac{dE}{d\lambda} \right|_{\lambda=0} \quad (3.31)$$

$$E^{(2)} = \left. \frac{1}{2} \frac{d^2E}{d\lambda^2} \right|_{\lambda=0} \quad (3.32)$$

⋮

Now, for example, consider a molecule/atom in an electric field of strength \mathcal{E} parallel to the z axis, for which the Hamiltonian is

$$\hat{H}(\mathcal{E}) = \hat{H}^{(0)} - \mathcal{E}\hat{\mu}_z, \quad (3.33)$$

where $\hat{H}^{(0)}$ is the molecular Hamiltonian without external fields and $\hat{\mu}_z = z$ is the z component of the dipole moment operator. We have

$$\frac{d\hat{H}(\mathcal{E})}{d\mathcal{E}} = -\hat{\mu}_z. \quad (3.34)$$

Using the Hellmann–Feynman theorem, we can write

$$E^{(1)} = \left. \frac{dE}{d\mathcal{E}} \right|_{\mathcal{E}=0} = - \langle \psi(\mathcal{E}=0) | \hat{\mu}_z | \psi(\mathcal{E}=0) \rangle . \quad (3.35)$$

This is the expectation value of the dipole moment in the unperturbed state, which is, by definition, the permanent dipole moment,

$$E^{(1)} = -\mu_z^0 . \quad (3.36)$$

Looking at the second-order contribution, we have

$$E^{(2)} = \left. \frac{1}{2} \frac{d^2 E}{d\mathcal{E}^2} \right|_{\mathcal{E}=0} = \left. \frac{1}{2} \frac{d}{d\mathcal{E}} (-\mu_z) \right|_{\mathcal{E}=0} . \quad (3.37)$$

The definition of the polarisability is exactly

$$\alpha_{ij} := \left. \frac{d\mu_i}{d\mathcal{E}_j} \right|_{\mathcal{E}_j=0} , \quad (3.38)$$

and so

$$E^{(2)} = -\frac{1}{2} \alpha_{zz} . \quad (3.39)$$

Example. Quadratic Stark Effect and the Polarisability of Hydrogen

Consider the ground electronic state of the hydrogen atom, where the electronic Hamiltonian, ground state wavefunction and energy are

$$\hat{H}^{(0)} = -\frac{1}{2} \nabla^2 - \frac{1}{r} \quad (3.40)$$

$$\psi_0^{(0)} = \frac{1}{\sqrt{\pi}} e^{-r} \quad (3.41)$$

$$E_0^{(0)} = -\frac{1}{2} . \quad (3.42)$$

We again consider the perturbation of a external electric field of strength \mathcal{E} in the z direction, giving a perturbing Hamiltonian

$$\lambda = \mathcal{E} \quad \hat{H}^{(1)} = z . \quad (3.43)$$

The first-order energy is

$$E_0^{(1)} = \langle 0 | z | 0 \rangle = 0 , \quad (3.44)$$

which can easily be evaluated by symmetry. This shows that a ground state hydrogen atom has no permanent dipole moment. Using the first-order perturbation equation (3.13), one can obtain the differential equation

$$\left(-\frac{1}{2} \nabla^2 - \frac{1}{r} + \frac{1}{2} \right) \psi_0^{(1)} + \frac{1}{\sqrt{\pi}} z e^{-r} = 0 . \quad (3.45)$$

This is one of the extremely rare cases where the first-order wavefunction can be solved analytically in a closed form,¹⁵ which gives

$$\psi_0^{(1)} = -\frac{1}{\sqrt{\pi}} \left(1 + \frac{r}{2} \right) z e^{-r} . \quad (3.46)$$

One can then obtain the exact second-order energy

$$E_0^{(2)} = \langle 0 | z | \psi_0^{(1)} \rangle = -\frac{9}{4} . \quad (3.47)$$

¹⁵Even in this case, this equation is not easy to solve at all! You need to change to parabolic coordinates and do fancy stuffs.

Hence, the electronic energy of hydrogen in an electric field of strength \mathcal{E} is given by

$$E = -\frac{1}{2} - \frac{9}{4}\mathcal{E}^2 + O(\mathcal{E}^4), \quad (3.48)$$

where one can actually argue that only even power terms are permitted by symmetry. This tells us that the ground state hydrogen atom has a polarisability of $\alpha = 9/2$ exactly.

This is a particularly important example, which we will use as a benchmark for the methods introduced later since we know the answer exactly.

3.3 Matrix Formulation

Let's say we have an unperturbed wavefunction expressed in some orthonormal basis $\{\phi_i\}$

$$|\psi_n^{(0)}\rangle = \sum_i c_{ni} \phi_i = \boldsymbol{\phi}^T \mathbf{c}_n. \quad (3.49)$$

Then if $|\psi_n^{(0)}\rangle$ and hence \mathbf{c}_n is normalised, we can express the first-order energy as

$$\begin{aligned} E_n^{(1)} &= \left\langle \sum_i c_{ni} \phi_i \left| \hat{H}^{(1)} \right| \sum_j c_{nj} \phi_j \right\rangle \\ &= \sum_{i,j} c_{ni}^* c_{nj} \langle \phi_i | \hat{H}^{(1)} | \phi_j \rangle \\ &= \mathbf{c}_n^\dagger \mathbf{H}^{(1)} \mathbf{c}_n, \end{aligned} \quad (3.50)$$

where $\mathbf{H}^{(1)}$ is the matrix representation of $\hat{H}^{(1)}$ in the $\{\phi_i\}$ basis

$$H_{ij}^{(1)} = \langle \phi_i | \hat{H}^{(1)} | \phi_j \rangle. \quad (3.51)$$

3.4 Perturbations to Normal Modes

The Hamiltonian of a (unperturbed) molecular vibration is

$$\hat{H}^{(0)}(\mathbf{q}) = -\frac{\hbar^2}{2} \dot{\mathbf{q}}^T \dot{\mathbf{q}} + \frac{1}{2} \mathbf{q}^T \mathbf{K}^{(0)} \mathbf{q}. \quad (3.52)$$

in the mass-weighted basis. If we perturb the system by changing some of the bond strengths or the masses, then this will lead to a change in the dynamical matrix

$$\mathbf{K} = \mathbf{K}^{(0)} + \mathbf{K}^{(1)}. \quad (3.53)$$

If the first order change in the eigenvalue of \mathbf{H} (energy) is given by $\mathbf{c}^\dagger \mathbf{H}^{(1)} \mathbf{c}$, where \mathbf{c} is the eigenvectors of $\mathbf{H}^{(0)}$ (eigenstates), then we can equally show that the first order change in the eigenvalues of \mathbf{K} (frequency squared) is given by $\mathbf{Q}^\dagger \mathbf{K}^{(1)} \mathbf{Q}$, where \mathbf{Q} is the eigenvectors of $\mathbf{K}^{(0)}$ (normal modes).¹⁶ Therefore, we can write

$$(\omega_n^2)^{(1)} = \lambda_n^{(1)} = \mathbf{Q}_n^\dagger \mathbf{K}^{(1)} \mathbf{Q}_n. \quad (3.55)$$

¹⁶Can be seen by replacing all the H to K and ψ to Q in the above derivation of perturbation theory. Or equally, you can see

$$\mathbf{H}^{(1)}(\mathbf{q}) = \frac{1}{2} \mathbf{q}^T \mathbf{K}^{(1)} \mathbf{q}, \quad (3.54)$$

so the matrix representation of $\mathbf{H}^{(1)}$ in the $\{\mathbf{q}_i\}$ basis is $\frac{1}{2} \mathbf{K}^{(1)}$. Since $\mathbf{H}^{(0)}$ and $\mathbf{K}^{(0)}$ share the same set of eigenvectors (normal modes), the first order change in the eigenvalues of $\mathbf{K}^{(0)}$ will be a twice the change in the eigenvalues of $\mathbf{H}^{(0)}$. Hence, if $E_n^{(1)} = \mathbf{Q}_n^\dagger \mathbf{H}^{(1)} \mathbf{Q}_n$, we naturally have $(\omega_n^2)^{(1)} = \lambda_n^{(1)} = \mathbf{Q}_n^\dagger \mathbf{K}^{(1)} \mathbf{Q}_n$.

Example. AAB linear triatomic.

We will consider a AAB triatomic linear molecule as a perturbation of the AAA linear molecule which we have already solved. We will let atom B have a different mass than atom A, and let the bond strength of A – B and A – A be different. Of course this still leads to a 3×3 dynamical matrix, which we can directly diagonalise. However, the algebra will be very tedious, so we will try to treat it using perturbation theory.

The dynamical matrices of interest are

$$\mathbf{K} = \begin{pmatrix} \frac{k_1}{m_A} & -\frac{k_1}{m_A} & 0 \\ -\frac{k_1}{m_A} & \frac{k_1+k_2}{m_A} & -\frac{k_2}{m_A m_B} \\ 0 & -\frac{k_2}{\sqrt{m_A m_B}} & \frac{k_2}{m_B} \end{pmatrix} \quad (3.56)$$

$$\mathbf{K}^{(0)} = \begin{pmatrix} \frac{k_1}{m_A} & -\frac{k_1}{m_A} & 0 \\ -\frac{k_1}{m_A} & \frac{2k_1}{m_A} & -\frac{k_1}{m_A} \\ 0 & -\frac{k_1}{m_A} & \frac{k_1}{m_A} \end{pmatrix} \quad (3.57)$$

$$\begin{aligned} \mathbf{K}^{(1)} &= \mathbf{K} - \mathbf{K}^{(0)} \\ &= \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{k_2-k_1}{m_A} & \frac{k_1}{m_A} - \frac{k_2}{m_A m_B} \\ 0 & \frac{k_1}{m_A} - \frac{k_2}{m_A m_B} & \frac{k_2}{m_B} - \frac{k_1}{m_A} \end{pmatrix}. \end{aligned} \quad (3.58)$$

We also know that for the reference system, the three modes are

$$\lambda_1^{(0)} = 0 \quad \mathbf{Q}_1 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \quad (3.59)$$

$$\lambda_2^{(0)} = \frac{k_1}{m_A} \quad \mathbf{Q}_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} -1 \\ 0 \\ 1 \end{pmatrix} \quad (3.60)$$

$$\lambda_3^{(0)} = \frac{3k_1}{m_A} \quad \mathbf{Q}_3 = \frac{1}{\sqrt{6}} \begin{pmatrix} 1 \\ -2 \\ 1 \end{pmatrix}. \quad (3.61)$$

Therefore, the first-order eigenvalues are

$$\lambda_1^{(1)} = \mathbf{Q}_1^\dagger \mathbf{K}^{(1)} \mathbf{Q}_1 = \frac{k_2}{3m_A m_B} (\sqrt{m_A} - \sqrt{m_B})^2 \quad (3.62)$$

$$\lambda_2^{(1)} = \mathbf{Q}_2^\dagger \mathbf{K}^{(1)} \mathbf{Q}_2 = \frac{1}{2} \left(\frac{k_2}{m_B} - \frac{k_1}{m_A} \right) \quad (3.63)$$

$$\lambda_3^{(1)} = \mathbf{Q}_3^\dagger \mathbf{K}^{(1)} \mathbf{Q}_3 = \frac{1}{6m_A} \left(\frac{k_2}{m_B} (2\sqrt{m_B} + \sqrt{m_A})^2 - 9k_1 \right). \quad (3.64)$$

The frequencies correct to first order are

$$\omega_i = \sqrt{\lambda_i^{(0)} + \lambda_i^{(1)}}. \quad (3.65)$$

3.5 Rayleigh–Schrödinger Perturbation Theory

Since the eigenstates of a Hermitian operator forms an complete orthonormal set, we can try to expand the first order wavefunction $|\psi_n^{(1)}\rangle$ in the basis of the unperturbed wavefunction $\{|k\rangle\}$. As we have shown above, $|\psi_n^{(1)}\rangle$ should have no component of $|n\rangle$, so we can write

$$|\psi_n^{(1)}\rangle = \sum_{k \neq n} c_k |k\rangle. \quad (3.66)$$

If we substitute this into the first order equation (3.13), we get

$$\sum_{k \neq n} c_k (E_k^{(0)} - E_n^{(0)}) |k\rangle + (\hat{H}^{(1)} - E_n^{(1)}) |n\rangle = 0. \quad (3.67)$$

To find the coefficient c_j of a particular $|j\rangle$, we contract the above equation with $\langle j|$ and get

$$\sum_{k \neq n} \langle j | E_k^{(0)} - E_n^{(0)} | k \rangle + \langle j | \hat{H}^{(1)} - E_n^{(1)} | n \rangle = 0, \quad (3.68)$$

and then by orthogonality, we have¹⁷

$$c_j = - \frac{\langle j | \hat{H}^{(1)} | n \rangle}{E_j^{(0)} - E_n^{(0)}} = - \frac{H_{jn}^{(1)}}{E_j^{(0)} - E_n^{(0)}}. \quad (3.69)$$

If we substitute this back (3.66), we get an expansion of the first order wavefunction

$$|\psi_n^{(1)}\rangle = - \sum_{j \neq n} \frac{H_{jn}^{(1)}}{E_j^{(0)} - E_n^{(0)}} |j\rangle. \quad (3.70)$$

We can also substitute this into (3.20) to get an expansion of the second order energy

$$\begin{aligned} E_n^{(2)} &= \langle n | \hat{H}^{(2)} | \psi_n^{(1)} \rangle \\ &= - \sum_{j \neq n} \frac{H_{nj}^{(1)} H_{jn}^{(1)}}{E_j^{(0)} - E_n^{(0)}} \\ &= - \sum_{j \neq n} \frac{|H_{jn}^{(1)}|^2}{E_j^{(0)} - E_n^{(0)}}, \end{aligned} \quad (3.71)$$

where notice that $H^{(1)}$ is Hermitian. This is the ket result of Rayleigh–Schrödinger perturbation theory. Higher-order results may be obtained in analogous ways, but they are rarely needed.¹⁸

Example. Polarisability of Hydrogen Revisited.

Last time using the exact result of the first order wavefunction, we have worked out that the polarisability of hydrogen is $\alpha = 4.5$ exactly. Now let's see what Rayleigh–Schrödinger gives us.

Since we have identified $\alpha = -2E^{(2)}$ from Hellmann–Feynman theorem, the ground state polarisability of hydrogen is given by

$$\alpha = 2 \sum_{k \neq 0} \frac{|\langle 0 | z | k \rangle|^2}{E_k^{(0)} - E_0^{(0)}}. \quad (3.72)$$

The ground state $|0\rangle$ is totally symmetric, so for the integral $\langle 0 | z | k \rangle$ to be non-zero, k should transform the same as the irreducible representation as the Cartesian function z — these are exactly the $2p_z, 3p_z, \dots$ orbitals.¹⁹ The first of these is

$$\psi_{2p_z}^{(0)} = \frac{1}{\sqrt{32\pi}} z e^{-r/2} \quad (3.74)$$

¹⁷This expression goes well with our assumption that $|n\rangle$ is non-degenerate. If $|n\rangle$ is degenerate with some $|j\rangle$, then this expression will diverge. We will comment a bit more on this when discussing the degenerate perturbation theory.

¹⁸In fact due to some converging issue that we will discuss later, stopping at the first or the second order correction is usually a better choice.

¹⁹Since the wavefunction $|k\rangle \equiv |n, \ell, m\rangle = R_{n,\ell}(r) Y_{\ell,m}(\theta, \varphi)$ is a product of totally symmetric radial wavefunction and a spherical harmonic $|\ell, m\rangle = Y_{\ell,m}(\theta, \varphi)$, we need $Y_{\ell,m}(\theta, \varphi)$ to transform as the Cartesian function z . These are the $|1, 0\rangle = Y_{1,0}(\theta, \varphi)$ spherical harmonics, which combines with the radial wavefunctions $R_{n,1}(r)$, $n \geq \ell = 1$ to give np_z orbitals, $n \geq 1$.

More generally, we have

$$\langle n', \ell', m' | z | n \ell m \rangle = 0 \quad \text{unless} \quad \begin{cases} \ell' = \ell \pm 1 \\ m' = m. \end{cases} \quad (3.73)$$

This comes from the Wigner–Eckart theorem with $T_{q=0}^{(1)}$ and parity consideration. See my notes on Mathematical Tripos Part II: *Principles of Quantum Mechanics* for more detail.

with energy $-\frac{1}{8}$. This gives a contribution 2.96 to α . Clearly this is a poor estimate of α since we have only calculated the first term. You will evaluate the $3p_z$ contribution in the exercises. As you include more and more contributions, the result should converge, albeit very slowly since the denominator of (3.72) does not get any larger than $\frac{1}{2}$, so we are only relying on the numerator for convergence.

However, if you really calculate this series, summing up over all np_z orbitals, you will find that it actually converges to a wrong value! This is because there are also continuum (unbounded) states above the bounded energy levels. We also need to include these into our summation. This is very tricky to do, and goes far beyond our course, but you can actually do it if you try really hard using a method due to A. Dalgarno and J.T. Lewis²⁰, and you will find that it converges correctly to $\alpha = 4.5$.

A much easier thing to do is to give an upper bound for this series. Since $E_k^{(0)} - E_0^{(0)} > E_{n=2}^{(0)} - E_0^{(0)} = \frac{3}{8}$ for all (bounded and unbounded) states k , we have

$$\alpha < \frac{16}{3} \sum_{k \neq 0} |\langle 0|z|k \rangle|^2. \quad (3.75)$$

If we write

$$\sum_{k \neq 0} \langle 0|z|k \rangle \langle k|z|0 \rangle, \quad (3.76)$$

we see something very similar to the resolution of identity in the middle of this expression, except have excluded $k = 0$ from all possible k values. This is actually not a problem, since $\langle 0|z|0 \rangle$ is exactly the first order energy, which we have identified to be zero. Therefore,

$$\sum_{k \neq 0} \langle 0|z|k \rangle \langle k|z|0 \rangle = \sum_k \langle 0|z|k \rangle \langle k|z|0 \rangle = \langle 0|z^2|0 \rangle. \quad (3.77)$$

We have reduced this infinite series into a single term! Due to the spherical symmetry of $|0\rangle$, this can also be easily evaluated

$$\langle 0|z^2|0 \rangle = a_0^2 = 1 \quad (3.78)$$

in atomic units. Hence, we have an upper bound

$$\alpha < \frac{16}{3}. \quad (3.79)$$

The exact value $\alpha = 4.5$ does sit in this range.

Despite its practical difficulty, Rayleigh–Schrödinger perturbation theory provides some useful physical insight. The expression (3.72) shows that an atom will have a large polarisability if it possess low-lying excited states with an appropriate symmetry.

3.6 Ladder Operators

A *ladder operator* in quantum mechanics is an operator that acts on an eigenstate of another operator to produce an eigenfunction with a different value. Since the changes to the quantum number are usually $+1$ (raising operator) or -1 (lowering operator), they got their names by imaging stepping up or down onw ‘rung’ on the ‘ladder’ of eigenstates.

If we have an Hermitian operator \hat{B} , and another operator \hat{a}^{21} which satisfy the commuting relationship

$$[\hat{B}, \hat{a}] = c\hat{a} \quad (3.80)$$

²⁰See Merzbacher (1970), p. 424, for example

²¹The a here stands for *annihilation*, due to the use of ladder operators for creating or destroying particles in quantum field theory.

for some real constant c , then \hat{a} is a ladder operator for \hat{B} . To show this, consider acting \hat{a} on the eigenstate of \hat{B} , $|b\rangle$ with eigenvalue b . We have

$$\begin{aligned}\hat{B}\hat{a}|b\rangle &= \hat{a}\hat{B}|b\rangle + [\hat{B}, \hat{a}]|b\rangle \\ &= b\hat{a}|b\rangle + c\hat{a}|b\rangle \\ &= (b+c)\hat{a}|b\rangle ,\end{aligned}\tag{3.81}$$

and so $\hat{a}|b\rangle$ is an eigenstate of \hat{B} with eigenvalue $b+c$. Depending on the sign of c , this state is either raised or lowered.

By taking the adjoint of (3.80), we have

$$[\hat{B}, \hat{a}^\dagger] = -c\hat{a}^\dagger .\tag{3.82}$$

Hence, if \hat{a} is a raising (lowering) operator, then its Hermitian conjugate \hat{a}^\dagger will be a lowering (raising) operator, changing the magnitude of the eigenvalue by the same amount.

3.6.1 Angular Momentum Ladder Operators

By the commutation relationship of angular momentum operator

$$[\hat{J}_i, \hat{J}_j] = \sum_k \epsilon_{ijk} \hat{J}_k \quad [\hat{\mathbf{J}}^2, \hat{J}_i] = 0\tag{3.83}$$

for $i, j, k \in \{x, y, z\}$, one can show that the operators

$$\hat{J}_+ = \hat{J}_x + i\hat{J}_y\tag{3.84}$$

$$\hat{J}_- = \hat{J}_x - i\hat{J}_y\tag{3.85}$$

satisfies the commutation relationships

$$[\hat{J}_z, \hat{J}_\pm] = \pm \hat{J}_\pm\tag{3.86}$$

$$[\hat{\mathbf{J}}^2, \hat{J}_\pm] = 0 ,\tag{3.87}$$

and so they are ladder operators for \hat{J}_z . We have

$$\hat{J}_z \hat{J}_\pm |J, M\rangle = (M \pm 1) \hat{J}_\pm |J, M\rangle ,\tag{3.88}$$

$$\hat{\mathbf{J}}^2 \hat{J}_\pm |J, M\rangle = J(J+1) \hat{J}_\pm |J, M\rangle ,\tag{3.89}$$

where $|J, M\rangle = Y_{JM}$ is the angular momentum eigenstates. Therefore,

$$\hat{J}_\pm |J, M\rangle \propto |J, M \pm 1\rangle .\tag{3.90}$$

3.6.2 Harmonic Oscillator Ladder Operator

The Hamiltonian of a standard harmonic oscillator takes the form

$$\hat{H} = -\frac{1}{2} \frac{d^2}{dq^2} + \frac{1}{2} q^2 .\tag{3.91}$$

We will first show how to use the ladder operators to infer the eigenvalues of harmonic oscillator without needing to solve any differential equations. The ladder operators of the Harmonic oscillator are given by

$$\hat{a} = \sqrt{\frac{1}{2}} \left(q + \frac{d}{dq} \right)\tag{3.92}$$

$$\hat{a}^\dagger = \sqrt{\frac{1}{2}} \left(q - \frac{d}{dq} \right) .\tag{3.93}$$

It is easy to see that \hat{a} lowers the eigenvalue of an eigenstate by 1, and \hat{a}^\dagger raise the eigenvalue by 1. Additionally, we find that the ladder operators nicely “factor out” the Hamiltonian

$$\hat{a}\hat{a}^\dagger = \hat{H} + \frac{1}{2} \quad \hat{a}^\dagger\hat{a} = \hat{H} - \frac{1}{2}. \quad (3.94)$$

We define the *numbering operator* $\hat{N} = \hat{a}^\dagger\hat{a} = \hat{H} - \frac{1}{2}$, with $\hat{N}|n\rangle = n|n\rangle$. Then $|n\rangle$ is also an eigenstate of \hat{H} , with $\hat{H}|n\rangle = (n + \frac{1}{2})|n\rangle$. However, since

$$n = \langle n|\hat{N}|n\rangle = \langle n|\hat{a}^\dagger\hat{a}|n\rangle = \|\hat{a}|n\rangle\|^2 \geq 0, \quad (3.95)$$

we find that we cannot lower the eigenstate $|n\rangle$ infinitely. We must have $n \geq 0$, so the lowering process must somehow terminate at some point to avoid negative values of n . This will be our ground state, and is given by $\hat{a}|n\rangle = 0$. Therefore, we must have $n = 0$ to be the ground state. The excited states can be obtained by repeatedly acting \hat{a}^\dagger on $|0\rangle$, so the eigenvalues of \hat{H} are given by $k + \frac{1}{2}$, where $k \in \mathbb{N}_0$.

Using this method, we can also easily find the eigenfunctions of \hat{H} . If we directly solve the Schrödinger equation, then this is a second order inhomogeneous differential equation, which we can't easily solve. The standard method would then be to solve this using an infinite series. However, we have claimed that the ground state satisfies

$$\hat{a}\psi(q) = \sqrt{\frac{1}{2}} \left(q\psi + \frac{d\psi}{dq} \right) = 0. \quad (3.96)$$

This is now a first order, linear, homogeneous equation, which we know the general solution. The ground state wavefunction is therefore

$$\psi(q) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}q^2}. \quad (3.97)$$

The wavefunction of the excited state can be obtained by acting \hat{a}^\dagger repeatedly.

Example. Harmonic Oscillator with Cubic Perturbation Potential.

Now consider adding a cubic perturbation $\hat{H}^{(1)} = \lambda q^3$ to the harmonic oscillator Hamiltonian. We anticipate to evaluate integrals like $\langle j|q^3|n\rangle$, which seems algebraically tedious. However, this can be much easily done using ladder operators.

From the definition of ladder operators, one can write

$$q = \frac{1}{\sqrt{2}}(\hat{a} + \hat{a}^\dagger). \quad (3.98)$$

You will show in the exercises that

$$\hat{a}|n\rangle = \sqrt{n}|n-1\rangle \quad \hat{a}^\dagger|n\rangle = \sqrt{n+1}|n+1\rangle, \quad (3.99)$$

so if we act it on some eigenstate of \hat{H} , we will get

$$q|n\rangle = \sqrt{\frac{n+1}{2}}|n+1\rangle + \sqrt{\frac{n}{2}}|n-1\rangle. \quad (3.100)$$

Now, let's consider what $q^3|n\rangle$ will give us. By taking the cube of (3.98), we see that q^3 constitutes of 8 different combination raising and lowering operators. One of the combinations is triple raising operator $\hat{a}^\dagger\hat{a}^\dagger\hat{a}^\dagger$ which will raise $|n\rangle$ by three quanta, and another is triple lowering operator $\hat{a}\hat{a}\hat{a}$. There will be three combinations that raise $|n\rangle$ by one quantum ($\hat{a}^\dagger\hat{a}^\dagger\hat{a}, \hat{a}^\dagger\hat{a}\hat{a}^\dagger, \hat{a}\hat{a}^\dagger\hat{a}^\dagger$), and three that lowers $|n\rangle$ by one quantum ($\hat{a}^\dagger\hat{a}\hat{a}, \hat{a}\hat{a}^\dagger\hat{a}, \hat{a}\hat{a}\hat{a}^\dagger$). Therefore, when acting on $|n\rangle$, we expect to see a mixture of four states: $|n \pm 3\rangle$ and $|n \pm 1\rangle$.

Let's first consider the first order variation in energy, given by

$$E_n^{(1)} = \langle n | q^3 | n \rangle . \quad (3.101)$$

Since $q^3 |n\rangle$ is only a combination of $|n \pm 3\rangle$ and $|n \pm 1\rangle$, it will be zero by orthogonality.

Next, we will consider the second order energy

$$E_n^{(2)} = -\lambda^2 \sum_{j \neq n} \frac{|\langle j | q^3 | n \rangle|^2}{j - n} . \quad (3.102)$$

For simplicity, we will consider the ground state $|n\rangle = |0\rangle$. Since we cannot lower $|0\rangle$ anymore, all the single lowering and triple contributions vanishes. Of the remaining four terms, we find that

$$\hat{a}^\dagger \hat{a}^\dagger \hat{a} |0\rangle = 0 \quad (3.103)$$

also vanishes since it firsts lowers $|0\rangle$. The other three terms are then

$$\hat{a}^\dagger \hat{a} \hat{a}^\dagger |0\rangle = \sqrt{1}\sqrt{1}\sqrt{1} |1\rangle = |1\rangle \quad (3.104)$$

$$\hat{a} \hat{a}^\dagger \hat{a}^\dagger |0\rangle = \sqrt{1}\sqrt{2}\sqrt{2} |1\rangle = 2 |1\rangle \quad (3.105)$$

$$\hat{a}^\dagger \hat{a}^\dagger \hat{a}^\dagger |0\rangle = \sqrt{1}\sqrt{2}\sqrt{3} |3\rangle = 2 |3\rangle , \quad (3.106)$$

and so

$$\langle 1 | q^3 | 0 \rangle = \frac{1}{\sqrt{8}} (2 + 1) \langle 1 | 1 \rangle = \frac{3}{2\sqrt{2}} \quad (3.107)$$

$$\langle 3 | q^3 | 0 \rangle = \frac{1}{\sqrt{8}} \sqrt{6} \langle 3 | 3 \rangle = \frac{\sqrt{3}}{2} . \quad (3.108)$$

Therefore, the second order energy is

$$E_0^{(2)} = -\lambda^2 \left(\frac{|\langle 1 | q^3 | 0 \rangle|^2}{1 - 0} + \frac{|\langle 3 | q^3 | 0 \rangle|^2}{3 - 0} \right) = -\frac{11}{8} \lambda^2 . \quad (3.109)$$

This is an exact result. Although the Rayleigh–Schrödinger sum runs over an infinite series of excited states, only two of them have non-zero contributions. In contrast to the polarisability example, the series converges really fast here.

Using a similar approach, one can find the exact first-order wavefunction of the ground state to be

$$\psi_0^{(1)} = -\lambda \left(q + \frac{1}{3} q^3 \right) \psi_0^{(0)} . \quad (3.110)$$

3.7 Variational Perturbation Theory

You should be familiar with the variational principles.

Lemma 3.3 (Variational principles). Let \hat{H} be a Hamiltonian with ground state wavefunction ψ_0 with energy E_0 . Let $\tilde{\psi}$ be any trial wavefunction, then

$$\tilde{E} = \frac{\langle \tilde{\psi} | \hat{H} | \tilde{\psi} \rangle}{\langle \tilde{\psi} | \tilde{\psi} \rangle} \geq E_0 , \quad (3.111)$$

where the equality holds if and only if $\tilde{\psi} = \psi_0$.

Now consider the ground state energy corrected to the first order,

$$E_0^{(0)} + \lambda E_0^{(1)} = \langle 0 | \hat{H}^{(0)} | 0 \rangle + \langle 0 | \lambda \hat{H}^{(1)} | 0 \rangle = \langle 0 | \hat{H} | 0 \rangle. \quad (3.112)$$

This can be seen as using the unperturbed ground state $|0\rangle$ as a trial function for the perturbed Hamiltonian, so we must have

$$E_0^{(0)} + \lambda E_0^{(1)} \geq E_0. \quad (3.113)$$

The ground state energy corrected to first order is greater than the true ground state energy.

However, if we consider the second order energy

$$E_0^{(2)} = \langle \psi_0^{(1)} | \hat{H}^{(1)} | 0 \rangle, \quad (3.114)$$

we see that it is not a expectation value. Therefore, the variational principles do not apply, and the energy corrected to the second order $E_0^{(0)} + \lambda E_0^{(1)} + \lambda^2 E_0^{(2)}$ may be lower than the true ground state energy E_0 .

3.7.1 An Upper Bound to the Second Order Energy

Although the variational principles do not apply, we can get an upper bound for $E_0^{(2)}$ using some trial first order wavefunction. This will be helpful if we can't solve the first order wavefunction exactly, nor do we want to expand it as a series, but we have some intuitive guess of what its form might be.

Let φ be a trial function that approximates the true (unknown) ground-state first-order wavefunction $\psi_0^{(1)}$. Let $\eta = \varphi - \psi_0^{(1)}$. As usual, we require the first-order wavefunctions to be orthogonal to the zeroth-order wavefunction, and we also impose this property on the trial function

$$\langle \varphi | 0 \rangle = \langle \eta | 0 \rangle = 0. \quad (3.115)$$

Now consider the quantity

$$X^{(2)} = \langle \varphi | \hat{H}^{(0)} - E_0^{(0)} | \varphi \rangle + \langle \varphi | \hat{H}^{(1)} | 0 \rangle + \langle 0 | \hat{H}^{(1)} | \varphi \rangle. \quad (3.116)$$

Substituting $\varphi = \psi_0^{(1)} + \eta$ and expanding, we have

$$\begin{aligned} X^{(2)} &= \langle \eta | \hat{H}^{(0)} - E_0^{(0)} | \eta \rangle + \langle \psi_0^{(1)} | \hat{H}^{(0)} - E_0^{(0)} | \eta \rangle \\ &\quad + \langle \eta | \hat{H}^{(0)} - E_0^{(0)} | \psi_0^{(1)} \rangle + \langle \psi_0^{(1)} | \hat{H}^{(0)} - E_0^{(0)} | \psi_0^{(1)} \rangle \\ &\quad + \langle \psi_0^{(1)} | \hat{H}^{(1)} | 0 \rangle + \langle \eta | \hat{H}^{(1)} | 0 \rangle + \langle 0 | \hat{H}^{(1)} | \psi_0^{(1)} \rangle + \langle 0 | \hat{H}^{(1)} | \eta \rangle. \end{aligned} \quad (3.117)$$

We can use the first order perturbation equation (3.13) to replace $(\hat{H}^{(0)} - E_0^{(0)}) | \psi_0^{(1)} \rangle$ by $-(\hat{H}^{(1)} - E_0^{(1)}) | 0 \rangle$, and then a lot of terms cancels out or vanishes by orthogonality, and we are left with

$$X^{(2)} = \langle \eta | \hat{H}^{(0)} - E_0^{(0)} | \eta \rangle + \langle 0 | \hat{H}^{(1)} | \psi_0^{(1)} \rangle. \quad (3.118)$$

The first term is positive by the variational principle, and the second term is the second order energy. Hence we can conclude that

$$X^{(2)} \geq E_0^{(2)}, \quad (3.119)$$

so $X^{(2)}$ is an upper bound to the second-order energy of the ground state. As usual, we can include some parameters in φ , and minimise $X^{(2)}$ to get the tightest upper bound.

Example. Polarisability of Hydrogen Revisited.

Let's consider again the polarisability of hydrogen. Since we are applying an electric field along the z direction, we might reasonably choose a trial function

$$\varphi = Az\psi_0^{(0)} \quad (3.120)$$

for the first-order wavefunction, where A is some constant. Note that $\langle\varphi|0\rangle = 0$ as we imposed before. If we substitute this ansatz into (3.116), we get

$$X^{(2)} = A^2 \left\langle z\psi_0^{(0)} \left| \hat{H}^{(0)} - E_0^{(0)} \right| z\psi_0^{(0)} \right\rangle + 2A \langle 0 | z^2 | 0 \rangle. \quad (3.121)$$

This is evaluated to be

$$X^{(2)} = \frac{1}{2}A^2 + 2A. \quad (3.122)$$

$X^{(2)}$ is minimised when $A = -2$, taking the value $X^{(2)} = -2$, which is our upper bound to the second-order energy. Recalling that the polarisability is $\alpha = -2E^{(2)}$, we conclude that $\alpha = 4$ is an lower bound to the ground state polarisability of the hydrogen atom.

Comparing with the exact value $\alpha = 4.5$, we see that this is a really good one-term estimation, significantly better than the first term estimation in the Rayleigh–Schrödinger.

3.8 Multiple Perturbations

- 4 Degenerate Perturbation Theory
- 5 Time-Dependent Perturbation Theory
- 6 Intermolecular Forces
- 7 Relativistic Effects

Appendices

A Proof of Wigner's $2n + 1$ Theorem

Let's first reformulate our problem a little bit. We know that the energy of a normalised state ψ is given by the expectation value of the Hamiltonian $E = \langle \psi | \hat{H} | \psi \rangle$. This allows to consider the energy as a functional

$$E[\psi, \lambda] = \langle \psi | \hat{H} | \psi \rangle = \langle \psi | \hat{H}^{(0)} + \lambda \hat{H}^{(1)} | \psi \rangle. \quad (\text{A.1})$$

For example, in the unperturbed situation where $\lambda = 0$, the ground state energy is given by the minimum of the energy functional

$$E_{\min} = E[\psi_0^{(0)}, 0], \quad (\text{A.2})$$

where $\psi_0^{(0)}$ is the ground state wavefunction of the unperturbed Hamiltonian. By the Rayleigh–Ritz variational principles, all eigenstates of the Hamiltonian \hat{H} are the stationary values of the energy functional. Therefore, to find the k^{th} eigenstate of \hat{H} for any λ , we can write $\psi_k = \psi_k^{(0)} + \Delta\psi_k$, and find the $\Delta\psi_k$ which satisfies

$$\frac{\partial E[\psi_k^{(0)} + \Delta\psi_k, \lambda]}{\partial(\Delta\psi_k)} = 0, \quad (\text{A.3})$$

and then the eigenvalue (energy) will given by $E_k(\lambda) = E[\psi_k^{(0)} + \Delta\psi_k, \lambda]$. From now on, we will drop the subscript k to refer to any eigenstate. If the perturbation λ is small, then we can expand the eigenstates and the eigenvalues as a Taylor series (as what we did in the normal perturbation theory)

$$\Delta\psi = \sum_{n=1}^{\infty} \frac{1}{n!} \frac{\partial^n \psi}{\partial \lambda^n} \Big|_{\lambda=0} \equiv \sum_{n=1}^{\infty} \psi^{(n)} \lambda^n \quad (\text{A.4})$$

$$E = \sum_{n=0}^{\infty} \frac{1}{n!} \frac{\partial^n E}{\partial \lambda^n} \Big|_{\lambda=0} \equiv \sum_{n=0}^{\infty} E^{(n)} \lambda^n. \quad (\text{A.5})$$

Then the what we want to claim is that we only need to know $\psi^{(i)}$ for $i = 1, \dots, n$ to calculate $E^{(2n+1)}$. Before proving this, we need some preparations.

First, let's expand the functional $E[\psi^{(0)} + \Delta\psi, \lambda]$ in both $\Delta\psi$ and λ . We get the double series

$$E = E[\psi^{(0)} + \Delta\psi, \lambda] = \sum_{k=0}^{\infty} \sum_{p=0}^{\infty} \frac{1}{k!} \frac{1}{p!} \frac{\delta^{k+p} E[\psi^{(0)} + \Delta\psi, \lambda]}{\delta(\Delta\psi)^k \delta \lambda^p} \Big|_{\Delta\psi=0, \lambda=0} (\Delta\psi)^k \lambda^p. \quad (\text{A.6})$$

Then for $\psi = \psi^{(0)} + \Delta\psi$ to be an eigenstate, we need to set $\partial E[\psi^{(0)} + \Delta\psi, \lambda] / \partial(\Delta\psi)$ to zero, which is evaluated as

$$\frac{\partial E[\psi^{(0)} + \Delta\psi, \lambda]}{\partial(\Delta\psi)} = \sum_{k=1}^{\infty} \sum_{p=0}^{\infty} \frac{1}{(k-1)!} \frac{1}{p!} \frac{\delta^{k+p} E[\psi^{(0)} + \Delta\psi, \lambda]}{\delta(\Delta\psi)^k \delta \lambda^p} \Big|_{\Delta\psi=0, \lambda=0} (\Delta\psi)^{k-1} \lambda^p. \quad (\text{A.7})$$

For simplicity, we denote

$$f^{(p)} := \sum_{k=1}^{\infty} \frac{1}{(k-1)!} \frac{1}{p!} \frac{\delta^{k+p} E[\psi^{(0)} + \Delta\psi, \lambda]}{\delta(\Delta\psi)^k \delta \lambda^p} \Big|_{\Delta\psi=0, \lambda=0} (\Delta\psi)^{k-1}, \quad (\text{A.8})$$

and so the above expression reduces to

$$\frac{\partial E[\psi^{(0)} + \Delta\psi, \lambda]}{\partial(\Delta\psi)} = \sum_{p=0}^{\infty} f^{(p)} \lambda^p = 0. \quad (\text{A.9})$$

For this to hold for all λ , we must have $f^{(p)} = 0$ for all p .

Next, let's have a closer look at our energy expansion

$$E = \sum_{n=0}^{\infty} E^{(n)} \lambda^n = \sum_{k=0}^{\infty} \sum_{p=0}^{\infty} c_{kp} (\Delta\psi)^k \lambda^p \quad (\text{A.10})$$

for some complicated coefficients c_{kp} given in (A.6). Here we can use the series expansion (A.4) for $\Delta\psi$

$$\Delta\psi = \sum_{n=1}^{\infty} \psi^{(n)} \lambda^n \quad (\text{A.11})$$

so that

$$E = \sum_{n=0}^{\infty} E^{(n)} \lambda^n = \sum_{k=0}^{\infty} \sum_{p=0}^{\infty} c_{kp} \left(\sum_{n=1}^{\infty} \psi^{(n)} \lambda^n \right)^k \lambda^p \quad (\text{A.12})$$

Now consider the terms contributing to $E^{(2n+1)} \lambda^{2n+1}$ in the above expansion. We claim that the terms must be linear in $\psi^{(G)} \lambda^G$ for all $G > n$. This is because if there is any quadratic (or above) term, then

$$E^{(2n+1)} \lambda^{2n+1} \sim [\psi^{(G)} \lambda^G]^2 \sum_{p=0}^{\infty} \lambda^p = \psi^{(2G)} \underbrace{\lambda^{2G} \sum_{p=0}^{\infty} \lambda^p}_{\lambda^{2n+2} \text{ or higher}}. \quad (\text{A.13})$$

The power of λ is at least $2n+2$, so it cannot contribute to $E^{(2n+1)} \lambda^{2n+1}$. Then, we can write $(\Delta\psi)^k$ in the following way:

$$\begin{aligned} (\Delta\psi)^k &= \left[\sum_{n=1}^k \psi^{(n)} \lambda^n \right]^k = [\psi^{(1)} \lambda + \psi^{(2)} \lambda^2 + \dots + \psi^{(G)} \lambda^G + \dots] [\psi^{(1)} \lambda + \psi^{(2)} \lambda^2 + \dots] \dots \\ &= \sum_{a=k}^{nk} P^{(a)}(\psi^{(1)}, \psi^{(2)}, \dots, \psi^{(n)}) \lambda^a + k \psi^{(G)} \lambda^G (\Delta\psi)^{k-1} + [\text{higher order terms.}] \end{aligned} \quad (\text{A.14})$$

The first term is a polynomial P of $\psi^{(1)}$ up until $\psi^{(n)}$, coming from picking a lower-than- $\psi^{(n)} \lambda^n$ term from each of the square brackets in the first line. The second term pulls out a single $\psi^{(G)} \lambda^G$ from one of the brackets, and there should be k terms like that. Technically this term is at least linear in $\psi^{(G)} \lambda^G$, since $(\Delta\psi)^{k-1}$ will certainly contain $\psi^{(G)} \lambda^G$ in each factor of $\Delta\psi$, but this expansion is good enough to prove what we want. Finally, we are left with terms in which $\psi^{(G)} \lambda^G$ appears twice or more often, and we are not interested in those.

Finally, to prove $2n+1$ theorem, we only need to plug this horrible-looking expansion of $(\Delta\psi)^k$ into our Taylor expansion of E (A.6).

$$\begin{aligned} E &= \sum_{k=0}^{\infty} \sum_{p=0}^{\infty} \frac{1}{k!} \frac{1}{p!} \frac{\delta^{k+p} E[\psi^{(0)} + \Delta\psi, \lambda]}{\delta(\Delta\psi)^k \delta \lambda^p} \Big|_{\Delta\psi=0, \lambda=0} \\ &\quad \left[\sum_{a=k}^{nk} P^{(a)}(\psi^{(1)}, \dots, \psi^{(n)}) \lambda^a + k \psi^{(G)} \lambda^G (\Delta\psi)^{k-1} + [\text{H.O.T.}] \right] \lambda^p, \end{aligned} \quad (\text{A.15})$$

where $G > n$. Now consider terms contributing to $E^{(2n+1)} \lambda^{2n+1}$. They are

$$\begin{aligned} E^{(2n+1)} \lambda^{2n+1} &= \sum_{k=0}^{\infty} \sum_{p=0}^{\infty} \frac{1}{k! p!} \frac{\delta^{k+p} E[\psi^{(0)} + \Delta\psi, \lambda]}{\delta(\Delta\psi)^k \delta \lambda^p} \Big|_{\Delta\psi=0, \lambda=0} \sum_{a=k}^{nk} P^{(a)}(\psi^{(1)}, \dots, \psi^{(n)}) \lambda^{a+p} \Big|_{a+p=2n+1} \\ &\quad + \underbrace{\sum_{p=0}^{\infty} \sum_{k=1}^{\infty} \frac{1}{(k-1)! p!} \frac{\delta^{k+p} E[\psi^{(0)} + \Delta\psi, \lambda]}{\delta(\Delta\psi)^k \delta \lambda^p} \Big|_{\Delta\psi=0, \lambda=0}}_{f^{(p)}} \frac{(\Delta\psi)^{k-1} \psi^{(G)} \lambda^{G+1}}{\Big|_{p+G=2n+1}}. \end{aligned} \quad (\text{A.16})$$

Since $f^{(p)} = 0$, the second term vanishes, and we are only left with

$$E^{(2n+1)} \lambda^{2n+1} = \sum_{k=0}^{\infty} \sum_{p=0}^{\infty} \frac{1}{k!p!} \frac{\delta^{k+p} E[\psi^{(0)} + \Delta\psi, \lambda]}{\delta(\Delta\psi)^k \delta\lambda^p} \Big|_{\Delta\psi=0, \lambda=0} \sum_{a=k}^{nk} P^{(a)}(\psi^{(1)} \dots, \psi^{(n)}) \lambda^{a+p} \Big|_{a+p=2n+1}. \quad (\text{A.17})$$

Only $\psi^{(1)}, \dots, \psi^{(n)}$ are present in this expression. This completes the proof. \square