

PIMD Notes

Alan Robledo

11/14/19

I have created the following notes to better understand path integral molecular dynamics (PIMD) as applied to a harmonic oscillator and beyond. All the material in this paper can be found in multiple resources. The ones that I used are listed in the references. Notes are still in development.

1 Introduction

1.1 Quantum Harmonic Oscillator

Similar to the classical harmonic oscillator, we have a particle that is subject to a harmonic potential so that the 1D Hamiltonian looks like

$$\hat{H} = \hat{K} + \hat{U} = \frac{\hat{p}^2}{2m} + \frac{1}{2}m\omega^2\hat{x}^2 \quad (1)$$

where m is the particle's mass and ω is the angular frequency of the oscillator. We know that we can derive the properties of the harmonic oscillator from the canonical ensemble. To do this, we start with the canonical partition function,

$$Q = \sum_n e^{-\beta E_n} \quad (2)$$

where the sum is performed over all possible states of the system, which are discrete. [1] The energies E_n for a quantum harmonic oscillator are well known and can be obtained from solving Schrödinger's equation with the Hamiltonian in equation (1). Alternatively, the energies can be derived (see Appendix 1) using Dirac's ladder operators, \hat{a} and \hat{a}^\dagger . [2, 3] Doing so yields,

$$E_n = \hbar\omega(n + \frac{1}{2}). \quad (3)$$

Plugging our energies into equation (2) gives us the partition function.

$$Q = \sum_{n=0}^{\infty} e^{-\beta\hbar\omega(n+\frac{1}{2})} \quad (4)$$

The purpose of knowing the partition function is so that we can derive the thermodynamic properties of our system in the canonical ensemble. One property we can derive is the total energy. We already know the energies of the harmonic oscillator, but we can derive the energies in the canonical ensemble with the partition function using the relationship,

$$E = -\frac{\partial}{\partial\beta} \ln(Q). \quad (5)$$

Using equation (4), we find (see Appendix 2) that the energies are of the form,

$$E = \frac{\hbar\omega}{2} + \frac{\hbar\omega e^{-\beta\hbar\omega}}{1 - e^{-\beta\hbar\omega}}. \quad (6)$$

Remember that this is the exact form of the harmonic oscillator energies in the canonical ensemble and not an approximation. When we try to approximate the energies of a harmonic oscillator using PIMD, we will want to refer back to equation (28) and plug in our values for ω and β as a check to make sure that our code is working.

To understand what a PIMD code does, we have to first understand the idea of representing partition functions like equation (4) as a path integral.

1.2 Path Integral

We will consider the case of a single quantum particle moving in one dimension subject to some potential $U(x)$. Remember that our Hamiltonian is, in general,

$$\hat{H} = \hat{K} + \hat{U}. \quad (7)$$

We already know from classical statistical mechanics that the canonical partition function can be written as equation (4). In Quantum Statistical Mechanics, the partition function is written more formally as (see Appendix 3),

$$Q(N, V, T) = \text{Tr} \left[e^{-\beta \hat{H}} \right] \quad (8)$$

where $\beta = 1/k_B T$ and \hat{H} is the Hamiltonian of our system.

If we perform the trace in the coordinate basis, we obtain an integral

$$Q = \text{Tr} \left[e^{-\beta \hat{H}} \right] = \int dx \langle x | e^{-\beta \hat{H}} | x \rangle. \quad (9)$$

After going through a long process (see Appendix 4), equation (9) can be represented equivalently in terms of path integrals,

$$Q = \lim_{P \rightarrow \infty} \int dp_1 \cdots dp_P \int dx_P \cdots dx_1 \exp \left(-\beta \sum_{k=1}^P \left[\frac{p_k^2}{2m'} + \frac{1}{2} m \omega_P^2 (x_{k+1} - x_k)^2 + \frac{1}{P} U(x_k) \right] \right). \quad (10)$$

The interesting thing about the path integral representation is that equation (10) resembles the classical partition function for a cyclic chain of beads. Each bead can be thought of as having the same fictitious mass m' along with harmonic nearest neighbors. In other words, each bead is connected to one another with a spring that is defined by the chain frequency $\omega_P = \sqrt{P}/(\beta \hbar)$. Lastly, each bead is subjected to an external potential $U(x)$ that is defined by the quantum system.

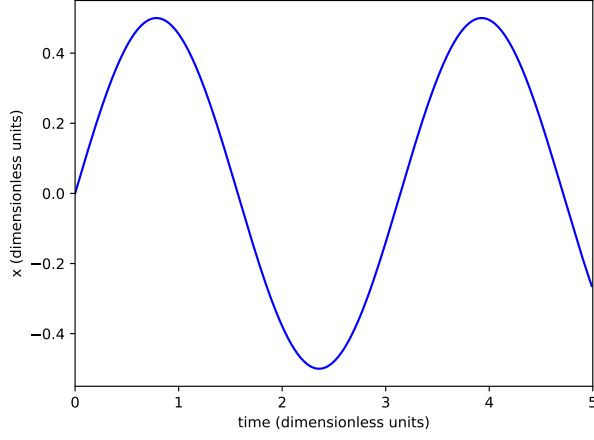
Therefore, the properties of our quantum system can be obtained directly from the classical system in the infinite bead limit. Alternatively, these quantities can be approximated by performing calculations with a finite number of beads and is the main idea behind a PIMD calculation. It is worth mentioning that quantum properties of interest can also be uncovered by decreasing the temperature of our system or the masses of our beads.

Going back to the 1D quantum harmonic oscillator, a PIMD calculation would consist of performing a molecular dynamics simulation on one chain of P beads with each bead subject to an external potential $U(x) = (1/2)m\omega^2 x^2$, which defines the quantum oscillator. The temperature of our system can be controlled by introducing a thermostat. Thermostats also allow us to make sure that we are sampling the canonical distribution when running a molecular dynamics code.

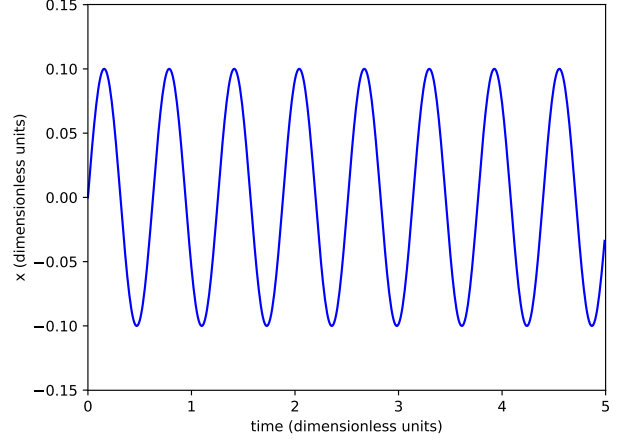
2 Results

Since a PIMD code consists of combining velocity verlet with a langevin thermostat, several tests were done to check that each piece of the PIMD code was implemented properly.

The first test case was writing a velocity verlet code for a one dimensional harmonic oscillator.



(a) Positions with $\omega = 2$.



(b) Positions with $\omega = 10$

Figure 1: Harmonic oscillator positions for different values of ω .

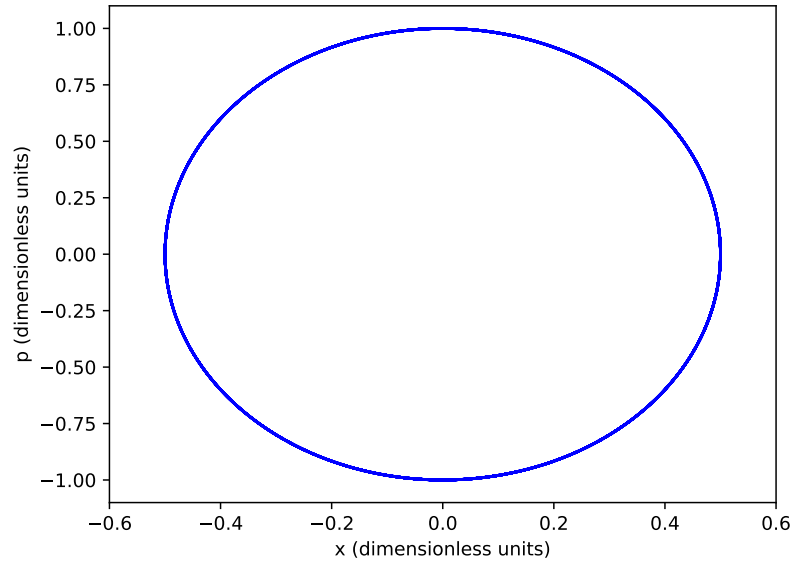


Figure 2: Phase space plot of the one dimensional harmonic oscillator with $\omega = 2$. The phase space curve should follow the shape of an ellipse since the Hamiltonian is $H = \frac{1}{2m}p^2 + \frac{m\omega^2}{2}x^2$.

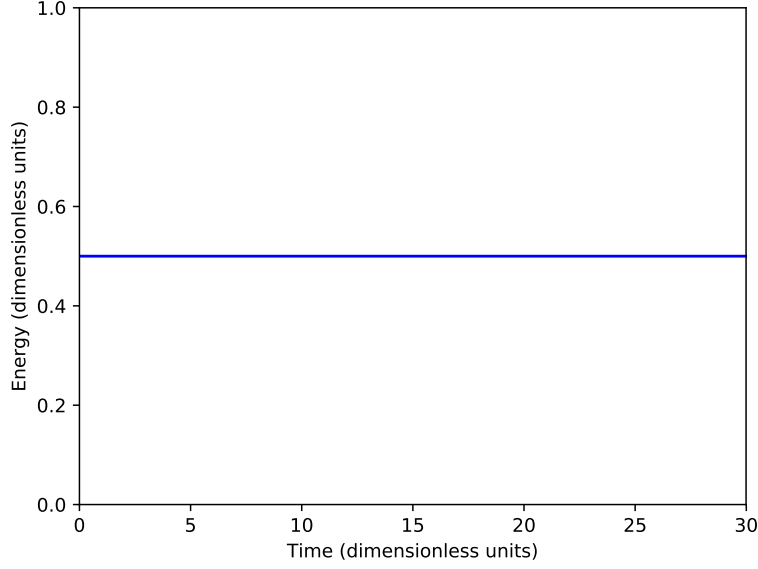


Figure 3: Plot of total energy over an MD trajectory. The energy remains constant throughout an MD trajectory because there are no other external forces acting on the potential, which conserves total energy.

3 Appendix

3.1 Quantum Harmonic Oscillator Energies

This section serves to derive the energies for a quantum harmonic oscillator using Dirac's ladder operators.

The "raising operator" \hat{a} and "lowering operator" \hat{a}^\dagger can be defined in terms of the position and momentum operators as

$$\begin{aligned}\hat{a} &= \sqrt{\frac{m\omega}{2\hbar}} \left(\hat{x} + \frac{i}{m\omega} \hat{p} \right) \\ \hat{a}^\dagger &= \sqrt{\frac{m\omega}{2\hbar}} \left(\hat{x} - \frac{i}{m\omega} \hat{p} \right)\end{aligned}\tag{11}$$

where the prefactors are such that they allow the math to work out nicely when deriving the energies for a harmonic oscillator. The ladder operators can then be used to obtain a function of the Hamiltonian by remembering the commutation relation $[\hat{x}, \hat{p}] = i\hbar$. The hats will be omitted from the operators to simplify notation.

$$\begin{aligned}aa^\dagger &= \sqrt{\frac{m\omega}{2\hbar}} \left(x + \frac{i}{m\omega} p \right) \sqrt{\frac{m\omega}{2\hbar}} \left(x - \frac{i}{m\omega} p \right) \\ &= \frac{m\omega}{2\hbar} \left(x + \frac{i}{m\omega} p \right) \left(x - \frac{i}{m\omega} p \right) \\ &= \frac{m\omega}{2\hbar} \left(x^2 - \frac{i}{m\omega} xp + \frac{i}{m\omega} px + \frac{p^2}{(m\omega)^2} \right) \\ &= \frac{m\omega}{2\hbar} \left(x^2 + \frac{p^2}{(m\omega)^2} \right) - \frac{i}{2\hbar} xp + \frac{i}{2\hbar} px\end{aligned}\tag{12}$$

We can turn everything in the paranthesis into the Hamiltonian after mutliplying by $1 = \frac{m\omega}{m\omega}$ and distributing the $\frac{1}{2}$.

$$\begin{aligned}
aa^\dagger &= \frac{m\omega}{2\hbar} \left(\frac{m\omega}{m\omega} \right) \left(x^2 + \frac{p^2}{(m\omega)^2} \right) - \frac{i}{2\hbar} xp + \frac{i}{2\hbar} px \\
&= \frac{1}{2\hbar} \left(\frac{p^2}{m\omega} + m\omega x^2 \right) - \frac{i}{2\hbar} [x, p] \\
&= \frac{1}{\hbar\omega} \left(\frac{p^2}{2m} + \frac{(m\omega x)^2}{2m} \right) - \frac{i}{2\hbar} (i\hbar) \\
&= \frac{1}{\hbar\omega} H + \frac{1}{2}
\end{aligned} \tag{13}$$

So rearranging to solve for the Hamiltonian gives us,

$$\hat{H} = \hbar\omega \left(\hat{a}\hat{a}^\dagger - \frac{1}{2} \right). \tag{14}$$

If we reverse the ladder operators and perform the same process as before we get,

$$\begin{aligned}
a^\dagger a &= \sqrt{\frac{m\omega}{2\hbar}} \left(x - \frac{i}{m\omega} p \right) \sqrt{\frac{m\omega}{2\hbar}} \left(x + \frac{i}{m\omega} p \right) \\
&= \frac{m\omega}{2\hbar} \left(x - \frac{i}{m\omega} p \right) \left(x + \frac{i}{m\omega} p \right) \\
&= \frac{m\omega}{2\hbar} \left(x^2 + \frac{i}{m\omega} xp - \frac{i}{m\omega} px + \frac{p^2}{(m\omega)^2} \right) \\
&= \frac{m\omega}{2\hbar} \left(x^2 + \frac{p^2}{(m\omega)^2} \right) + \frac{i}{2\hbar} xp - \frac{i}{2\hbar} px \\
&= \frac{m\omega}{2\hbar} \left(\frac{m\omega}{m\omega} \right) \left(x^2 + \frac{p^2}{(m\omega)^2} \right) + \frac{i}{2\hbar} xp - \frac{i}{2\hbar} px \\
&= \frac{1}{2\hbar} \left(\frac{p^2}{m\omega} + m\omega x^2 \right) + \frac{i}{2\hbar} [x, p] \\
&= \frac{1}{2\hbar m\omega} \left(p^2 + (m\omega x)^2 \right) + \frac{i}{2\hbar} (i\hbar) \\
&= \frac{1}{\hbar\omega} \left(\frac{p^2}{2m} + \frac{(m\omega x)^2}{2m} \right) - \frac{1}{2} \\
&= \frac{1}{\hbar\omega} H - \frac{1}{2}
\end{aligned} \tag{15}$$

So rearranging to solve for the Hamiltonian gives us,

$$\hat{H} = \hbar\omega \left(\hat{a}^\dagger \hat{a} + \frac{1}{2} \right). \tag{16}$$

We can imagine a set of vectors that make up the basis of eigenvectors $|\psi_n\rangle$ for the harmonic oscillator Hamiltonian that yield energies E_n . If we apply equation (14) to a vector that is one state higher $\hat{a}|\psi_n\rangle$, we obtain,

$$H\hat{a}|\psi\rangle = (E_n + \hbar\omega)\hat{a}|\psi\rangle. \tag{17}$$

eigenvalues equal to the energy in the previous state plus $\hbar\omega$. Likewise, if we apply equation (16) to a vector that is one state lower $\hat{a}^\dagger|\psi_n\rangle$, we obtain,

$$H\hat{a}^\dagger|\psi\rangle = (E_n - \hbar\omega)\hat{a}^\dagger|\psi\rangle. \tag{18}$$

It is for this reason that the operators \hat{a} and \hat{a}^\dagger are called ladder operators because they allow us to go up and down in energy. [2, 3] When we consider that there is a ground state $|\psi_0\rangle$ such that $\hat{a}^\dagger|\psi_0\rangle = 0$, we can plug in the defintion for \hat{a}^\dagger in position space,

$$\hat{a}^\dagger|\psi_0\rangle = \sqrt{\frac{m\omega}{2\hbar}} \left(\hat{x} - \frac{i}{m\omega} \hat{p} \right) |\psi_0\rangle = 0 \quad \Rightarrow \quad \sqrt{\frac{m\omega}{2\hbar}} \left(x - \frac{i}{m\omega} (-i\hbar) \frac{\partial}{\partial x} \right) \psi_0(x) = \sqrt{\frac{m\omega}{2\hbar}} \left(x - \frac{\hbar}{m\omega} \frac{\partial}{\partial x} \right) \psi_0(x) = 0 \tag{19}$$

and solve for $|\psi_0\rangle = \psi_0(x)$ by solving the differential equation,

$$\sqrt{\frac{m\omega}{2\hbar}} \left(x - \frac{\hbar}{m\omega} \frac{\partial}{\partial x} \right) \psi_0(x) \quad \Rightarrow \quad \frac{\partial \psi_0(x)}{\partial x} - \frac{m\omega}{\hbar} x \psi_0(x) = 0. \tag{20}$$

The solution to this ODE is a gaussian which looks like, with proper normalization,

$$\psi_0(x) = \left(\frac{m\omega}{\pi\hbar}\right)^{1/4} e^{-\frac{m\omega x^2}{2\hbar}}. \quad (21)$$

Plugging the solution into the Schrödinger equation gives us the ground state energy,

$$E_0 = \frac{\hbar\omega}{2}. \quad (22)$$

Since we know that applying the raising operator \hat{a} increases the energy by $\hbar\omega$, applying \hat{a} n times increases the energy by $n\hbar\omega$. So the energy at the n th state can be defined as,

$$E_n = \hbar\omega\left(n + \frac{1}{2}\right). \quad (23)$$

3.2 Energies from the Partition Function

This section serves to derive the energy for a quantum harmonic oscillator in the canonical ensemble starting from equation (4).

We can evaluate the sum in equation (4) to get a more compact form by remembering that \hbar , ω , β , are just constants and $\sum_{n=0}^{\infty} x^n = \frac{1}{1-x}$ when $0 < x < 1$.

$$\begin{aligned} Q &= \sum_{n=0}^{\infty} e^{-\beta\hbar\omega(n+\frac{1}{2})} \\ &= e^{-\frac{\beta\hbar\omega}{2}} \sum_{n=0}^{\infty} e^{-\beta\hbar\omega n} \\ &= e^{-\frac{\beta\hbar\omega}{2}} \sum_{n=0}^{\infty} \left(e^{-\beta\hbar\omega}\right)^n \\ &= \frac{e^{-\frac{\beta\hbar\omega}{2}}}{1 - e^{-\beta\hbar\omega}} \end{aligned} \quad (24)$$

It would be perfectly fine to use the last line for Q , but one could also obtain Q in terms of hyperbolic sine to make the derivative slightly easier to manage. To do this, we can simply multiply by 1 and distribute terms. Then we use the relationship between sinh and exponentials, $2 \sinh(x) = e^x - e^{-x}$.

$$\begin{aligned} Q &= \left(\frac{e^{\frac{\beta\hbar\omega}{2}}}{e^{\frac{\beta\hbar\omega}{2}}}\right) \frac{e^{-\frac{\beta\hbar\omega}{2}}}{1 - e^{-\beta\hbar\omega}} \\ &= \frac{1}{e^{\frac{\beta\hbar\omega}{2}} - e^{-\frac{\beta\hbar\omega}{2}}} \\ &= \frac{1}{2 \sinh(\frac{\beta\hbar\omega}{2})} \end{aligned} \quad (25)$$

Using this form of Q , we can find an expression for the energies.

$$\begin{aligned} E &= -\frac{\partial}{\partial\beta} \ln Q \\ &= -\frac{\partial}{\partial\beta} \ln \left(\frac{1}{2 \sinh(\frac{\beta\hbar\omega}{2})} \right) \\ &= -\frac{\partial}{\partial\beta} \left[\ln(1) - \ln \left(2 \sinh\left(\frac{\beta\hbar\omega}{2}\right) \right) \right] \\ &= \frac{\partial}{\partial\beta} \ln \left(2 \sinh\left(\frac{\beta\hbar\omega}{2}\right) \right) \end{aligned} \quad (26)$$

Lastly, we use the chain rule for computing the derivative.

$$\begin{aligned}
E &= \frac{1}{2 \sinh(\frac{\beta \hbar \omega}{2})} \frac{\partial}{\partial \beta} 2 \sinh(\frac{\beta \hbar \omega}{2}) \\
&= \frac{2 \cosh(\frac{\beta \hbar \omega}{2})}{2 \sinh(\frac{\beta \hbar \omega}{2})} \frac{\partial}{\partial \beta} \frac{\beta \hbar \omega}{2} \\
&= \frac{\cosh(\frac{\beta \hbar \omega}{2})}{\sinh(\frac{\beta \hbar \omega}{2})} \left(\frac{\hbar \omega}{2} \right) \\
&= \frac{\hbar \omega}{2 \tanh(\frac{\hbar \omega}{2})}
\end{aligned} \tag{27}$$

The last line comes from remembering that $\tanh(x) = \frac{\sinh(x)}{\cosh(x)}$. The equation for the total energy can be made exactly the same as in equation (6) by expressing the tanh function in terms of exponentials, $\tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}}$, and, again, multiplying by 1 and distributing terms.

$$\begin{aligned}
E &= \frac{\hbar \omega}{2 \tanh(\frac{\hbar \omega}{2})} \\
&= \left(\frac{\hbar \omega}{2} \right) \frac{e^{\frac{\beta \hbar \omega}{2}} + e^{-\frac{\beta \hbar \omega}{2}}}{e^{\frac{\beta \hbar \omega}{2}} - e^{-\frac{\beta \hbar \omega}{2}}} \\
&= \left(\frac{\hbar \omega}{2} \right) \left(\frac{e^{-\frac{\beta \hbar \omega}{2}}}{e^{-\frac{\beta \hbar \omega}{2}}} \right) \frac{e^{\frac{\beta \hbar \omega}{2}} + e^{-\frac{\beta \hbar \omega}{2}}}{e^{\frac{\beta \hbar \omega}{2}} - e^{-\frac{\beta \hbar \omega}{2}}} \\
&= \left(\frac{\hbar \omega}{2} \right) \frac{1 + e^{-\beta \hbar \omega}}{1 - e^{-\beta \hbar \omega}} \\
&= \left(\frac{\hbar \omega}{2} \right) \frac{(1 - e^{-\beta \hbar \omega} + 2e^{-\beta \hbar \omega})}{1 - e^{-\beta \hbar \omega}} \\
&= \left(\frac{\hbar \omega}{2} \right) \frac{1 - e^{-\beta \hbar \omega}}{1 - e^{-\beta \hbar \omega}} + \left(\frac{\hbar \omega}{2} \right) \frac{2e^{-\beta \hbar \omega}}{1 - e^{-\beta \hbar \omega}} \\
&= \frac{\hbar \omega}{2} + \frac{\hbar \omega e^{-\beta \hbar \omega}}{1 - e^{-\beta \hbar \omega}}
\end{aligned} \tag{28}$$

3.3 Quantum Partition Function

This section serves to show that the canonical partition function can be written as a sum over states or equivalently as a trace of the density matrix.

We can obtain the form of the partition function in equation (4) by writing the density matrix as a power series in \hat{H} (remember that $e^x = \sum_{n=0}^{\infty} \frac{x^n}{n!}$).

$$e^{-\beta \hat{H}} = \sum_{n=0}^{\infty} \frac{(-\beta)^n \hat{H}^n}{n!} \tag{29}$$

Next, we perform a unitary transformation on \hat{H} so that it becomes a diagonal matrix of its eigenvalues with $\hat{H} = \mathbf{U} \mathbf{D} \mathbf{U}^{-1}$, where \mathbf{D} is the diagonal matrix of eigenvalues and \mathbf{U} is a matrix with the i th column being the eigenvector corresponding to the i th eigenvalue on the diagonal matrix.

$$e^{-\beta \hat{H}} = \sum_{n=0}^{\infty} \frac{(-\beta)^n (\mathbf{U} \mathbf{D} \mathbf{U}^{-1})^n}{n!} \tag{30}$$

If we write out the first few terms we can see that the \mathbf{U}^{-1} and \mathbf{U} can be taken out of the sum,

$$\begin{aligned}
e^{-\beta\hat{H}} &= [\mathbf{I} + \frac{(-\beta)^1}{1!}(\mathbf{U}\mathbf{D}\mathbf{U}^{-1}) + \frac{(-\beta)^2}{2!}(\mathbf{U}\mathbf{D}\mathbf{U}^{-1})^2 + \dots] \\
&= [\mathbf{I} + \frac{(-\beta)^1}{1!}(\mathbf{U}\mathbf{D}\mathbf{U}^{-1}) + \frac{(-\beta)^2}{2!}(\mathbf{U}\mathbf{D}\mathbf{U}^{-1})(\mathbf{U}\mathbf{D}\mathbf{U}^{-1}) + \dots] \\
&= [\mathbf{I} + \frac{(-\beta)^1}{1!}(\mathbf{U}\mathbf{D}\mathbf{U}^{-1}) + \frac{(-\beta)^2}{2!}(\mathbf{U}\mathbf{D}\mathbf{D}\mathbf{U}^{-1}) + \dots] \\
&= [\mathbf{U}\mathbf{U}^{-1} + \frac{(-\beta)^1}{1!}(\mathbf{U}\mathbf{D}\mathbf{U}^{-1}) + \frac{(-\beta)^2}{2!}(\mathbf{U}\mathbf{D}\mathbf{D}\mathbf{U}^{-1}) + \dots] \\
&= \mathbf{U}[\mathbf{I} + \frac{(-\beta)^1}{1!}\mathbf{D} + \frac{(-\beta)^2}{2!}\mathbf{D}^2 + \dots]\mathbf{U}^{-1} \\
&= \mathbf{U}e^{-\beta\mathbf{D}}\mathbf{U}^{-1}
\end{aligned} \tag{31}$$

exploiting the property of unitary matrices $\mathbf{U}\mathbf{U}^{-1} = \mathbf{I}$. Then we use the cyclic property of the trace to show that the trace of a matrix is independent of the basis we choose to represent the matrix in,

$$\begin{aligned}
\text{Tr}[e^{-\beta\hat{H}}] &= \text{Tr}[\mathbf{U}e^{-\beta\mathbf{D}}\mathbf{U}^{-1}] \\
&= \text{Tr}[e^{-\beta\mathbf{D}}\mathbf{U}\mathbf{U}^{-1}] \\
&= \text{Tr}[e^{-\beta\mathbf{D}}]
\end{aligned} \tag{32}$$

And since \mathbf{D} is a diagonal matrix of the Hamiltonian eigenvalues E_i , the exponential matrix is just a diagonal matrix with the i th diagonal entry being $e^{-\beta E_n}$. So the trace just becomes a sum of exponentials,

$$\text{Tr}[e^{-\beta\hat{H}}] = \sum_n e^{-\beta E_n} \tag{33}$$

giving us equation (4). Anybody who has a background in physics and believes that this is trivial will simply say that if the Hamiltonian is written in the basis of its eigenvectors then its trace becomes a sum of its eigenvalues, rather than show why that is the case. I have chosen to show this to make a point that it is completely valid to work with the trace of $e^{-\beta\hat{H}}$ when we consider the quantum partition function.

3.4 Path Integral Derivation

This section serves to derive the path integral representation of the partition function starting from the definition (equation 9),

$$Q = \int dx \langle x | e^{-\beta\hat{H}} | x \rangle \tag{34}$$

The first thing we need to do is separate the Hamiltonian into its kinetic and potential energy components, $\hat{H} = \hat{K} + \hat{U}$. However, we cannot split the exponentials because for two operators that do not commute $\exp(\hat{H}) \neq \exp(\hat{K})\exp(\hat{U})$. To get around this we employ the trotter decomposition

$$e^{-\beta\hat{H}} = e^{-\beta(\hat{K}+\hat{U})} = \lim_{P \rightarrow \infty} \left[e^{-\beta\hat{U}/2P} e^{-\beta\hat{K}/P} e^{-\beta\hat{U}/2P} \right]^P. \tag{35}$$

Substituting this into equation (9) gives us,

$$Q = \lim_{P \rightarrow \infty} \int dx \langle x | \left[e^{-\beta\hat{U}/2P} e^{-\beta\hat{K}/P} e^{-\beta\hat{U}/2P} \right]^P | x \rangle \tag{36}$$

which can be condensed by defining another operator Ω as

$$\Omega = e^{-\beta\hat{U}/2P} e^{-\beta\hat{K}/P} e^{-\beta\hat{U}/2P}. \tag{37}$$

So our partition function becomes,

$$Q = \lim_{P \rightarrow \infty} \int dx \langle x | \Omega^P | x \rangle \tag{38}$$

We can insert the resolution of identity in terms of the position basis $P-1$ times between each of the omegas, remembering that $\Omega^P = \Omega\Omega\cdots\Omega$.

$$Q = \lim_{P \rightarrow \infty} \int \cdots \int dx_P \cdots dx_2 dx_1 \langle x|\Omega|x_P\rangle \langle x_P|\Omega|x_{P-1}\rangle \langle x_{P-1}|\cdots|x_3\rangle \langle x_3|\Omega|x_2\rangle \langle x_2|\Omega|x_1\rangle \quad (39)$$

In order to ensure that we obtain all the diagonal elements in the trace, we set $x_{P+1} = x_1 = x$,

$$Q = \lim_{P \rightarrow \infty} \int \cdots \int dx_P \cdots dx_2 dx_1 \langle x_1|\Omega|x_P\rangle \langle x_P|\Omega|x_{P-1}\rangle \langle x_{P-1}|\cdots|x_3\rangle \langle x_3|\Omega|x_2\rangle \langle x_2|\Omega|x_1\rangle \quad (40)$$

which gives us the reason for why the system in path integral molecular dynamics is often portrayed as a periodic lattice of beads. If we think of each x_i as the coordinate for the i th bead, then the only way for the condition $x_{P+1} = x_1$ to make sense physically is if the beads are arranged as a necklace.

In order to evaluate Ω we want to consider an element of the matrix,

$$\langle x_{k+1}|\Omega|x_k\rangle = \langle x_{k+1}|e^{-\beta\hat{U}/2P}e^{-\beta\hat{K}/P}e^{-\beta\hat{U}/2P}|x_k\rangle. \quad (41)$$

We can recognize that the set of $|x_k\rangle$ are eigenvectors of $e^{-\beta\hat{U}/2P}$ with eigenvalue $e^{-\beta U(x_k)/2P}$ because $\hat{U} = U(\hat{x})$ is a function of the coordinate operator. [2,3] This can be shown easily by writing the exponential as a power series in \hat{U} .

$$e^{-\beta\hat{U}/2P} = \sum_{n=0}^{\infty} \frac{\beta^n (2P)^{-n} \hat{U}^n}{n!} \quad (42)$$

and if we operate on an eigenvector $|x_k\rangle$, we get

$$\begin{aligned} e^{-\beta\hat{U}/2P} |x_k\rangle &= \sum_{n=0}^{\infty} \frac{\beta^n (2P)^{-n}}{n!} \hat{U}^n |x_k\rangle \\ &= \sum_{n=0}^{\infty} \frac{\beta^n (2P)^{-n}}{n!} (U(x_k))^n |x_k\rangle \\ &= e^{-\beta U(x_k)/2P} |x_k\rangle \end{aligned} \quad (43)$$

So equation (41) simplifies to

$$\langle x_{k+1}|\Omega|x_k\rangle = e^{-\beta U(x_{k+1})/2P} \langle x_{k+1}|e^{-\beta\hat{K}/P}|x_k\rangle e^{-\beta U(x_k)/2P}. \quad (44)$$

We know that \hat{K} is a function of the momentum operator, $\hat{K} = \hat{p}^2/2m$. [2,3] So we can use the same technique as we did with \hat{U} and the position eigenvectors by introducing the resolution of identity in terms of the momentum basis,

$$\begin{aligned} \langle x_{k+1}|\Omega|x_k\rangle &= \int e^{-\beta U(x_{k+1})/2P} \langle x_{k+1}|e^{-\beta\hat{K}/P}|p\rangle \langle p|x_k\rangle e^{-\beta U(x_k)/2P} \\ &= \int e^{-\beta U(x_{k+1})/2P} e^{-\beta p^2/2mP} \langle x_{k+1}|p\rangle \langle p|x_k\rangle e^{-\beta U(x_k)/2P} dp \end{aligned} \quad (45)$$

where $\langle x_{k+1}|p\rangle$ is the momentum wavefunction expressed in the coordinate basis x_{k+1} , and $\langle p|x_k\rangle$ is the complex conjugate of the momentum wavefunction expressed in the coordinate basis x_k , i.e. $\langle p|x_k\rangle = \langle x_k|p\rangle^*$.

We can obtain a functional form of these wavefunctions by recalling the eigenvalue problem for the momentum operator,

$$\hat{p}|p\rangle = p|p\rangle \quad (46)$$

If we project this equation on the coordinate basis, we can make use of the hermitian property of the momentum operator to obtain

$$\langle x|\hat{p}|p\rangle = p\langle x|p\rangle \Rightarrow \langle \hat{p}x|p\rangle = p\langle x|p\rangle \Rightarrow -i\hbar \frac{\partial}{\partial x} \langle x|p\rangle = p\langle x|p\rangle \quad (47)$$

And if we write $\langle x|p\rangle = \psi_p(x)$, then we just have a first order differential equation. The solution to this equation can easily be found

$$-i\hbar \frac{\partial}{\partial x} \psi_p(x) = p\psi_p(x) \Rightarrow \int \frac{d\psi_p}{\psi_p} dx = \int \frac{ip}{\hbar} dx \Rightarrow \ln \psi_p(x) = \frac{ipx}{\hbar} + C_1 \Rightarrow \psi_p(x) = C_2 e^{ipx/\hbar} \quad (48)$$

where C_2 is a normalization constant. With proper normalization, the momentum wavefunction looks like

$$\langle x|p\rangle = \psi_p(x) = \frac{1}{\sqrt{2\pi\hbar}} e^{ipx/\hbar}. \quad (49)$$

And its complex conjugate looks like,

$$\langle x|p\rangle^* = \langle p|x\rangle = \frac{1}{\sqrt{2\pi\hbar}} e^{-ipx/\hbar} \quad (50)$$

Our matrix elements for Ω can be rewritten as

$$\begin{aligned} \langle x_{k+1}|\Omega|x_k\rangle &= \int e^{-\beta U(x_{k+1})/2P} e^{-\beta p^2/2mP} \langle x_{k+1}|p\rangle \langle p|x_k\rangle e^{-\beta U(x_k)/2P} dp \\ &= \frac{1}{2\pi\hbar} \int e^{-\beta p^2/2mP} e^{-\beta(U(x_{k+1})+U(x_k))/2P} e^{ip(x_{k+1}-x_k)/\hbar} dp \end{aligned} \quad (51)$$

We can move the exponential without the momenta outside of the integral and combine the exponentials with the momenta to obtain

$$\langle x_{k+1}|\Omega|x_k\rangle = \frac{1}{2\pi\hbar} e^{-\beta(U(x_{k+1})+U(x_k))/2P} \int e^{-\beta p^2/2mP + ip(x_{k+1}-x_k)/\hbar} dp \quad (52)$$

Since our momentum basis extends from $+\infty$ to $-\infty$, we end up having an integral of a gaussian if we complete the square,

$$\begin{aligned} \frac{-\beta p^2}{2mP} + \frac{(x_{k+1}-x_k)ip}{\hbar} &= \frac{-\beta}{2mP} \left[p^2 - \frac{2imP(x_{k+1}-x_k)}{\beta\hbar} \right] \\ &= \frac{-\beta}{2mP} \left[\left(p - \frac{imP(x_{k+1}-x_k)}{\beta\hbar} \right)^2 - \left(\frac{imP(x_{k+1}-x_k)}{\beta\hbar} \right)^2 \right] \\ &= \frac{-\beta}{2mP} \left[\left(p - \frac{imP(x_{k+1}-x_k)}{\beta\hbar} \right)^2 + \frac{m^2 P^2 (x_{k+1}-x_k)^2}{\beta^2 \hbar^2} \right] \\ &= \frac{-\beta}{2mP} \left(p - \frac{imP(x_{k+1}-x_k)}{\beta\hbar} \right)^2 - \frac{mP(x_{k+1}-x_k)^2}{2\beta\hbar^2} \end{aligned} \quad (53)$$

and make a variable substitution,

$$u = p - \frac{imP(x_{k+1}-x_k)}{\beta\hbar}. \quad (54)$$

Our integral is now,

$$\langle x_{k+1}|\Omega|x_k\rangle = \frac{1}{2\pi\hbar} \exp\left[\frac{-\beta(U(x_{k+1})+U(x_k))}{2P}\right] \exp\left[\frac{-mP(x_{k+1}-x_k)^2}{2\beta\hbar^2}\right] \int e^{\frac{-\beta u^2}{2mP}} du \quad (55)$$

which evaluates to,

$$\begin{aligned} \langle x_{k+1}|\Omega|x_k\rangle &= \frac{1}{2\pi\hbar} \exp\left[-\frac{\beta}{2P}(U(x_{k+1})+U(x_k))\right] \exp\left[-\frac{mP}{2\beta\hbar^2}(x_{k+1}-x_k)^2\right] \left(\frac{2\pi mP}{\beta}\right)^{1/2} \\ &= \left(\frac{mP}{2\pi\beta\hbar^2}\right)^{1/2} \exp\left[-\frac{mP}{2\beta\hbar^2}(x_{k+1}-x_k)^2 - \frac{\beta}{2P}(U(x_{k+1})+U(x_k))\right] \end{aligned} \quad (56)$$

Plugging in our matrix elements into equation (40) P times for each element gives us the discretized path integral representation of the quantum partition function.

$$Q = \lim_{P \rightarrow \infty} \left(\frac{mP}{2\pi\beta\hbar^2}\right)^{P/2} \int \cdots \int dx_P \cdots dx_1 \exp\left(\sum_{k=1}^P \left[-\frac{mP}{2\beta\hbar^2}(x_{k+1}-x_k)^2 - \frac{\beta}{2P}(U(x_{k+1})+U(x_k))\right]\right). \quad (57)$$

For PIMD, we take advantage of the constant in front of equation (57) by considering an integral over momentum variables that would evaluate to the constant. It turns out that such an integral exists as a P dimensional gaussian integral.

$$\int \cdots \int dp_1 \cdots dp_P \exp\left(\sum_{k=1}^P \frac{-\beta p_k^2}{2m}\right) = \left(\frac{mP}{2\pi\beta\hbar^2}\right)^{P/2} \quad (58)$$

where $m' = mP/(2\pi\hbar)^2$. The integral can be easily evaluated by noticing that it is just the same integral multiplied P times.

$$\begin{aligned}
\int \cdots \int dp_1 \cdots dp_P \exp\left(\sum_{k=1}^P \frac{-\beta p_k^2}{2m'}\right) &= \int \cdots \int dp_1 \cdots dp_P \exp\left(\frac{-\beta p_1^2}{2m'}\right) \exp\left(\frac{-\beta p_2^2}{2m'}\right) \cdots \exp\left(\frac{-\beta p_P^2}{2m'}\right) \\
&= \left[\int dp_1 \exp\left(\frac{-\beta p_1^2}{2m'}\right) \right]^P \\
&= \left[\left(\frac{2\pi m'}{\beta}\right)^{1/2} \right]^P \\
&= \left[\left(\frac{2\pi mP}{(2\pi\hbar)^2 \beta}\right)^{1/2} \right]^P \\
&= \left(\frac{mP}{2\pi\beta\hbar^2}\right)^{P/2}
\end{aligned} \tag{59}$$

Finally, substituting the momentum integrals into equation (57) with more clever manipulation gives us,

$$\begin{aligned}
Q &= \lim_{P \rightarrow \infty} \int dp_1 \cdots dp_P \int dx_P \cdots dx_1 \exp\left(\sum_{k=1}^P \left[\frac{-\beta p_k^2}{2m'} - \frac{mP}{2\beta\hbar^2}(x_{k+1} - x_k)^2 - \frac{\beta}{2P}(U(x_{k+1}) + U(x_k)) \right]\right) \\
&= \lim_{P \rightarrow \infty} \int dp_1 \cdots dp_P \int dx_P \cdots dx_1 \exp\left(-\beta \sum_{k=1}^P \left[\frac{p_k^2}{2m'} + \frac{mP}{2\beta^2\hbar^2}(x_{k+1} - x_k)^2 + \frac{1}{2P}(U(x_{k+1}) + U(x_k)) \right]\right) \\
&= \lim_{P \rightarrow \infty} \int dp_1 \cdots dp_P \int dx_P \cdots dx_1 \exp\left(-\beta \sum_{k=1}^P \left[\frac{p_k^2}{2m'} + \frac{1}{2}m\omega_P^2(x_{k+1} - x_k)^2 + \frac{1}{P}U(x_k) \right]\right)
\end{aligned} \tag{60}$$

References

- [1] M.E. Tuckerman. *Statistical Mechanics: Theory and Molecular Simulation*. Oxford graduate texts. Oxford University Press, 2011.
- [2] D.J. Griffiths and P.D.J. Griffiths. *Introduction to Quantum Mechanics*. Pearson international edition. Pearson Prentice Hall, 2005.
- [3] R. Shankar. *Principles of Quantum Mechanics*. Springer US, 1995.