Week 2

The Schrödinger Equation

2.1 Ehrenfest Theorem and Uncertainty Principle

1/8: • Announcement: PSet 1 due Friday at midnight.

- Recap.
  - $\psi(\vec{r}, t)$ is a wave function to which we associate a **probability density**.
    - Integrating this probability density over a volume yields the probability that the particle is in V.
    - Moreover, ψ is not arbitrary but must satisfy the Schrödinger equation.
  - $\hat{\vec{p}}$ is the momentum operator, defined as the differential operator $-i\hbar\vec{\nabla}$.
  - Expressing the Schrödinger equation in terms of $\hat{\vec{p}}$, we see that it represents the application of a Hamiltonian operator in the usual form from last quarter (i.e., kinetic plus potential energy) to a certain function.
  - $\langle\hat{\vec{r}}\rangle$ is the mean position, and $\langle\hat{\vec{p}}\rangle$ is the mean momentum.
    - The mean position and mean momentum satisfy the classical relation, i.e., $\mathrm{d}\langle\hat{\vec{r}}\rangle / \mathrm{d}t = \langle\hat{\vec{p}}\rangle/m$.
- **Probability density**: The quantity given as follows. *Given by*

$$|\psi(\vec{r}, t)|^2$$

- We now prove something even more amazing than the classical relation result: An analogy to the classical Newton's law.
- **Ehrenfest's theorem**: The time derivative of the expectation value of the momentum operator is related to the expectation value of the force $F := -\vec{\nabla}V$ on a massive particle moving in a scalar potential $V(\vec{r}, t)$ as follows.

$$\frac{\mathrm{d}\langle\hat{\vec{p}}\rangle}{\mathrm{d}t} = \langle-\vec{\nabla}V(\vec{r}, t)\rangle$$

Proof. Consider the Schrödinger equation:

$$-i\hbar\frac{\partial\psi}{\partial t} = \frac{\hbar^2}{2m}\vec{\nabla}^2\psi - V(\vec{r}, t)\psi$$

Take the complex conjugate of it. This means that we're sending $i \mapsto -i$, keeping V fixed (it's real), and sending $\psi \mapsto \psi^*$ (the inclusion of i in the Schrödinger equation means that ψ is complex in general and thus has a nontrivial complex conjugate).

$$-i\hbar\frac{\partial\psi^*}{\partial t} = -\frac{\hbar^2}{2m}\vec{\nabla}^2\psi^* + V(\vec{r}, t)\psi^*$$

We will use the above two equations to substitute into the following algebraic derivation.

$$
\begin{aligned}
\frac{\mathrm{d}\langle\hat{\vec{p}}\rangle}{\mathrm{d}t} &= \frac{\mathrm{d}}{\mathrm{d}t}\left(\int \mathrm{d}^3\vec{r}\ \psi^*(-i\hbar\vec{\nabla}\psi)\right) \\
&= \int \mathrm{d}^3\vec{r}\ \frac{\partial\psi^*}{\partial t}(-i\hbar\vec{\nabla}\psi) + \int \mathrm{d}^3\vec{r}\ \psi^*\left(-i\hbar\vec{\nabla}\frac{\partial\psi}{\partial t}\right) \\
&= \int \mathrm{d}^3\vec{r}\left[-i\hbar\frac{\partial\psi^*}{\partial t}(\vec{\nabla}\psi)\right] + \int \mathrm{d}^3\vec{r}\ \psi^*\vec{\nabla}\left(-i\hbar\frac{\partial\psi}{\partial t}\right) \\
&= \int \mathrm{d}^3\vec{r}\left[-\frac{\hbar^2}{2m}\vec{\nabla}^2\psi^*(\vec{\nabla}\psi)\right] + \int \mathrm{d}^3\vec{r}\ \psi^*\vec{\nabla}\left(\frac{\hbar^2}{2m}\vec{\nabla}^2\psi\right) \\
&\quad + \int \mathrm{d}^3\vec{r}\left[V(\vec{r},t)\psi^*(\vec{\nabla}\psi) + \psi^*\vec{\nabla}(-V(\vec{r},t)\psi)\right] \\
&= \int \mathrm{d}^3\vec{r}\ \psi^*\vec{\nabla}(-V(\vec{r},t)\psi) \\
&= \int \mathrm{d}^3\vec{r}\ \psi^*(-\vec{\nabla}V(\vec{r},t))\psi \\
&= \langle -\vec{\nabla}V(\vec{r},t)\rangle
\end{aligned}
$$

as desired. $\square$

- How does everything cancel from the long line to the following line in the above proof??
- In quantum mechanics, we have **observables** which are in one-to-one correspondence with operators.

Observables	**Operators ($\hat{O}$)**
$\vec{r}$	$\hat{\vec{r}}$
$V(\vec{r},t)$	$\hat{V}(\vec{r},t)$
$\hat{\vec{p}}$	$-i\hbar\vec{\nabla}$
$\hat{H}$	$-\frac{\hbar^2}{2m}\vec{\nabla}^2 + V(\vec{r},t)$

Table 2.1: Observables vs. operators.

  - Recall that any Hermitian operator has a real observable.
- Define
$$\hat{O}_{ij} := \int \mathrm{d}^3\vec{r}\ \psi_i^*\hat{O}\psi_j$$
  - Then note that
$$\hat{O}_{ij} = (\hat{O}_{ji})^*$$
  - Thus, an equivalent definition of a Hermitian operator is one such that the above equation is satisfied for all relevant i,j.
- Recall that the Schrödinger equation is linear.
  - Let $\psi = \sum_i c_i\psi_i$.
  - Then
$$\int \mathrm{d}^3\vec{r}\ \psi^*\hat{O}\psi = \sum_{i,j}\int \mathrm{d}^3\vec{r}\ c_i^*\psi_i^*\hat{O}c_j\psi_j = \sum_{i,j} c_i^*c_j\hat{O}_{ij}$$
    is real.

- Takeaway: Averages over arbitrary wavefunctions are real.
- Similarly, suppose that $\vec{r}$ is Hermitian. Then any function $V(\vec{r})$ of it is also Hermitian.
- Once again,

$$\int \mathrm{d}^3\vec{r}\ \psi_i^*(-i\hbar\vec{\nabla}\psi_j) = \left(\int \mathrm{d}^3\vec{r}\ \psi_j^*(-i\hbar\vec{\nabla}\psi_i)\right)^* = \int \mathrm{d}^3\vec{r}\ \psi_j(i\hbar\vec{\nabla}\psi_i^*) \to -\int \mathrm{d}^3\vec{r}\ \vec{\nabla}\psi_j(i\hbar\psi_i^*)$$

  Involves integration by parts?? Perhaps via

$$\begin{aligned}\int \mathrm{d}^3\vec{r}\ \psi_j(i\hbar\vec{\nabla}\psi_i^*) &= i\hbar\int \mathrm{d}^3\vec{r}\ \vec{\nabla}(\psi_j\psi_i^*) - \int \mathrm{d}^3\vec{r}\ \vec{\nabla}\psi_j(i\hbar\psi_i^*)\\ &= i\hbar\vec{\nabla}\int \mathrm{d}^3\vec{r}\ (\psi_j\psi_i^*) - \int \mathrm{d}^3\vec{r}\ \vec{\nabla}\psi_j(i\hbar\psi_i^*)\\ &= i\hbar\vec{\nabla}0 - \int \mathrm{d}^3\vec{r}\ \vec{\nabla}\psi_j(i\hbar\psi_i^*)\\ &= -\int \mathrm{d}^3\vec{r}\ \vec{\nabla}\psi_j(i\hbar\psi_i^*)\end{aligned}$$

  What is the takeaway??

- Linear algebra analogy.
  - Recall that we can write any vector $\vec{v}$ componentwise as $\vec{v} = v_x\vec{x} + v_y\vec{y} + v_z\vec{z}$.
  - We can apply matrices A to such vectors to generate other vectors via $A\vec{v} = \vec{v}\,'$ and the like.
  - Lastly, we have an inner product $\cdot$ such that $\vec{a}\cdot\vec{b} = \delta_{ab}$, where $a, b = x, y, z$.
  - On an infinite-dimensional vector space, such as that containing all the ψ, we still can decompose $\psi = \sum_n c_n\psi_n$ into an infinite sum of basis components, apply operators $\hat{O}\psi = \psi'$, and have an inner product $\int \mathrm{d}^3\vec{r}\ \psi_m^*\psi_n = \delta_{mn}$.
  - Another analogy: Like the inner product of a vector and unit vector is the component of the vector in that direction (e.g., $\vec{v}\cdot\vec{x} = v_x$), we have

$$\int \mathrm{d}^3\vec{r}\ \psi_m^*\psi = \int \mathrm{d}^3\vec{r}\psi_m^*\sum_n c_n\psi_n = c_m$$

  - One more analogy: $\vec{x}^T A\vec{x} = A_{xx}$ is like $\langle\psi_i|\hat{O}|\psi_i\rangle = \hat{O}_{ii}$.