# Introduction to Quantum Mechanics by David J. Griffiths Problems

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## Contents

# Part I
# Theory

## 1 The Wave Function

### 1.1

(a)

$$\begin{aligned}
\langle j^2 \rangle &= \sum j^2 P(j) \\
&= 14^2 \frac{1}{14} + 15^2 \frac{1}{14} + 16^2 \frac{3}{14} + 22^2 \frac{2}{14} + 24^2 \frac{2}{14} + 25^2 \frac{5}{14} \\
&= \frac{3217}{7} \\
&\approx 459.571 \\
\langle j \rangle^2 &= \left( \sum j P(j) \right)^2 \\
&= 441
\end{aligned}$$

(b)

$$\begin{aligned}
\Delta j_{14} &= -7 \\
\Delta j_{15} &= -6 \\
\Delta j_{16} &= -5 \\
\Delta j_{22} &= 1 \\
\Delta j_{24} &= 3 \\
\Delta j_{25} &= 4 \\
\sigma^2 &= \sum (\Delta j)^2 P(j) \\
&= \frac{130}{7} \\
&\approx 18.571
\end{aligned}$$

(c)

$$\sigma^2 = \sqrt{\langle j^2 \rangle - \langle j \rangle^2} = 18.571$$

### 1.2

(a)

$$\begin{aligned}
\langle x^2\rangle &= \int_0^h x^2\rho(x)\,dx \\
&= \int_0^h \frac{x^{3/2}}{2\sqrt{h}}\,dx \\
&= \frac{1}{2\sqrt{h}}\left[\frac{2}{5}x^{5/2}\right]_0^h \\
&= \frac{h^2}{5} \\
\langle x\rangle^2 &= \frac{h^2}{9} \\
\sigma &= \sqrt{\langle x^2\rangle - \langle x\rangle^2} \\
&= \sqrt{\frac{h^2}{5} - \frac{h^2}{9}} \\
&= h\sqrt{\frac{4}{45}} \\
&= \frac{2}{3\sqrt{5}}h
\end{aligned}$$

(b)

$$\begin{aligned}
1 - \int_{\langle x\rangle-\sigma}^{\langle x\rangle+\sigma} \rho(x)\,dx &= 1 - \frac{1}{2\sqrt{h}}[2\sqrt{x}]_{\langle x\rangle-\sigma}^{\langle x\rangle+\sigma} \\
&= 1 - \frac{1}{\sqrt{h}}\left(\sqrt{\frac{1}{3}h + \frac{2}{3\sqrt{5}}h} - \sqrt{\frac{1}{3}h - \frac{2}{3\sqrt{5}}h}\right) \\
&= 1 - \left(\sqrt{\frac{1}{3} + \frac{2}{3\sqrt{5}}} - \sqrt{\frac{1}{3} - \frac{2}{3\sqrt{5}}}\right) \\
&\approx 0.393
\end{aligned}$$

## 1.3

(a)

$$\begin{aligned}
\rho(x) &= Ae^{-\lambda(x-a)^2} \\
1 &= \int_{-\infty}^{\infty} \rho(x)\, dx \\
&= A \int_{-\infty}^{\infty} e^{-\lambda(x-a)^2}\, dx \\
&= A\sqrt{\frac{\pi}{\lambda}} \\
A &= \sqrt{\frac{\lambda}{\pi}}
\end{aligned}$$

(b)

$$\begin{aligned}
\langle x \rangle &= \sqrt{\frac{\lambda}{\pi}} \int_{-\infty}^{\infty} xe^{-\lambda(x-a)^2}\, dx \\
&= a \\
\langle x^2 \rangle &= \sqrt{\frac{\lambda}{\pi}} \int_{-\infty}^{\infty} x^2 e^{-\lambda(x-a)^2}\, dx \\
&= a^2 + \frac{1}{2\lambda} \\
\sigma &= \sqrt{\langle x^2 \rangle - \langle x \rangle^2} \\
&= \sqrt{a^2 + \frac{1}{2\lambda} - a^2} \\
&= \frac{1}{\sqrt{2\lambda}}
\end{aligned}$$

## 1.4

(a)

$$
\begin{aligned}
1 &= \int_{-\infty}^{\infty} |\Psi(x,0)|^2 \, dx \\
&= \left(\frac{A}{a}\right)^2 \int_0^a x^2 \, dx + \left(\frac{A}{b-a}\right)^2 \int_a^b (b-x)^2 \, dx \\
&= \frac{1}{3}A^2 a + \left(\frac{A}{b-a}\right)^2 \left[-\frac{1}{3}(b-x)^3\right]_a^b \\
&= \frac{1}{3}A^2 a + \frac{1}{3}A^2(b-a) \\
&= \frac{1}{3}A^2 b \\
A &= \sqrt{\frac{3}{b}}
\end{aligned}
$$

(c) $x = a$

(d)

$$
\begin{aligned}
\int_0^a |\Psi(x,0)|^2 \, dx &= \frac{3}{a^2 b} \left[\frac{1}{3}x^3\right]_0^a \\
&= \frac{a}{b}
\end{aligned}
$$

(e)

$$
\begin{aligned}
\langle x \rangle &= \int_{-\infty}^{\infty} x|\Psi(x,0)|^2 \, dx \\
&= \frac{3}{a^2 b}\left[\frac{1}{4}x^4\right]_0^a + \frac{3}{b(b-a)^2}\int_a^b x(b-x)^2 \, dx \\
&= \frac{3a^2}{4b} + \frac{3}{b(b-a)^2}\int_a^b (b^2x - 2bx^2 + x^3) \, dx \\
&= \frac{3a^2}{4b} + \frac{3}{b(b-a)^2}\left[\frac{1}{2}b^2x^2 - \frac{2}{3}bx^3 + \frac{1}{4}x^4\right]_a^b \\
&= \frac{3a^2}{4b} + \frac{3}{b(b-a)^2}\left(\frac{1}{2}b^4 - \frac{2}{3}b^4 + \frac{1}{4}b^4 - \frac{1}{2}a^2b^2 + \frac{2}{3}a^3b - \frac{1}{4}a^4\right) \\
&= \frac{3a^2}{4b} + \frac{3}{b(b-a)^2}\frac{1}{12}(b-a)^3(3a+b) \\
&= \frac{3a^2}{4b} + \frac{1}{4b}(3ab + b^2 - 3a^2 - ab) \\
&= \frac{1}{2}a + \frac{1}{4}b
\end{aligned}
$$

### 1.5

(a)

$$
\begin{aligned}
\Psi(x,t) &= Ae^{-\lambda|x|}e^{-i\omega t} \\
\Psi(x,0) &= Ae^{-\lambda|x|} \\
1 &= A^2 \int_{-\infty}^{\infty} e^{-2\lambda|x|}\,dx \\
&= 2A^2 \int_0^{\infty} e^{-2\lambda x}\,dx \\
&= 2A^2 \left[-\frac{1}{2\lambda}e^{-2\lambda x}\right]_0^{\infty} \\
&= \frac{A^2}{\lambda} \\
A &= \sqrt{\lambda}
\end{aligned}
$$

(b)

$$
\begin{aligned}
\langle x \rangle &= \int_{-\infty}^{\infty} x\lambda e^{-2\lambda|x|}\,dx \\
&= \lambda \int_{-\infty}^{\infty} xe^{-2\lambda|x|}\,dx \\
&= 0 \\
\langle x^2 \rangle &= \int_{-\infty}^{\infty} x^2\lambda e^{-2\lambda|x|}\,dx \\
&= 2\lambda \int_0^{\infty} x^2 e^{-2\lambda x}\,dx \\
&= \frac{1}{2\lambda^2}
\end{aligned}
$$

(c)

$$
\begin{aligned}
\sigma &= \sqrt{\langle x^2 \rangle - \langle x \rangle^2} \\
&= \frac{1}{\sqrt{2}\lambda} \\
1 - \int_{-\sigma}^{\sigma} \lambda e^{-2\lambda|x|}\,dx &= 1 - 2\lambda \int_0^{\sigma} e^{-2\lambda x}\,dx \\
&= 1 - 2\lambda \left[-\frac{1}{2\lambda}e^{-2\lambda x}\right]_0^{\sigma} \\
&= e^{-2\lambda\sigma} \\
&= e^{-\sqrt{2}} \\
&\approx 0.243
\end{aligned}
$$

## 1.6

The chain rule requires that you apply it to both $x$ and $|\Psi|^2$ which gives the same result

$$\begin{aligned}
\frac{d\langle x\rangle}{dt} &= \frac{d}{dt}\int x|\Psi|^2\,dx \\
&= \int \frac{d}{dt}(x|\Psi|^2)\,dx \\
&= \int \left(0\cdot|\Psi|^2 + x\frac{\partial|\Psi|^2}{\partial t}\right)dx \\
&= \int x\frac{\partial|\Psi|^2}{\partial t}\,dx
\end{aligned}$$

## 1.8

$$\begin{aligned}
i\hbar\frac{\partial}{\partial t}\left(e^{-iV_0t/\hbar}\Psi\right) &= -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\left(e^{-iV_0t/\hbar}\Psi\right) + (V+V_0)\left(e^{-iV_0t/\hbar}\Psi\right) \\
i\hbar\left(-\frac{iV_0}{\hbar}e^{-iV_0t/\hbar}\Psi + e^{-iV_0t/\hbar}\frac{\partial\Psi}{\partial t}\right) &= -\frac{\hbar^2}{2m}e^{-iV_0t/\hbar}\frac{\partial^2\Psi}{\partial x^2} + Ve^{-iV_0t/\hbar}\Psi + V_0e^{-iV_0t/\hbar}\Psi \\
V_0\Psi + i\hbar\frac{\partial\Psi}{\partial t} &= -\frac{\hbar^2}{2m}\frac{\partial^2\Psi}{\partial x^2} + V\Psi + V_0\Psi \\
i\hbar\frac{\partial\Psi}{\partial t} &= -\frac{\hbar^2}{2m}\frac{\partial^2\Psi}{\partial x^2} + V\Psi
\end{aligned}$$

$$\begin{aligned}
\langle Q(x,p)\rangle &= \int\left(e^{-iV_0t/\hbar}\Psi\right)^*\left[Q(x,-i\hbar\partial/\partial x)\right]e^{-iV_0t/\hbar}\Psi\,dx \\
&= \int e^{iV_0t/\hbar}\Psi^*\left[Q(x,-i\hbar\partial/\partial x)\right]e^{-iV_0t/\hbar}\Psi\,dx \\
&= \int \Psi^*[Q(x,-i\hbar\partial/\partial x)]\Psi\,dx
\end{aligned}$$

No effect on the expectation value.

## 1.9

(a)

$$
\begin{aligned}
\Psi(x,t) &= Ae^{-a[(mx^2/\hbar)+it]} \\
1 &= A^2 \int_{-\infty}^{\infty} e^{-2a(mx^2/\hbar)}\,dx \\
&= A^2 \int_{-\infty}^{\infty} e^{-2a(mx^2/\hbar)}\,dx \\
&= A^2 \sqrt{\frac{\pi\hbar}{2am}} \\
A^2 &= \sqrt{\frac{2am}{\pi\hbar}} \\
A &= \left(\frac{2am}{\pi\hbar}\right)^{1/4}
\end{aligned}
$$

(b)

$$
\begin{aligned}
\Psi &= Ae^{-a[(mx^2/\hbar)+it]} \\
\frac{\partial\Psi}{\partial t} &= -ia\Psi \\
\frac{\partial\Psi}{\partial x} &= -\frac{2amx}{\hbar}\Psi \\
\frac{\partial^2\Psi}{\partial x^2} &= -\frac{2am}{\hbar}\left(\Psi + x\frac{\partial\Psi}{\partial x}\right) \\
&= -\frac{2am}{\hbar}\left(1 - \frac{2amx^2}{\hbar}\right)\Psi \\
V\Psi &= i\hbar\frac{\partial\Psi}{\partial t} + \frac{\hbar^2}{2m}\frac{\partial^2\Psi}{\partial x^2} \\
&= a\hbar\Psi - a\hbar\left(1 - \frac{2amx^2}{\hbar}\right)\Psi \\
V &= a\hbar - a\hbar + 2a^2mx^2 \\
&= 2a^2mx^2
\end{aligned}
$$

(c)

$$\begin{aligned}
\langle x \rangle &= A^2 \int_{-\infty}^{\infty} e^{-2a(mx^2/\hbar)} x \, dx \\
&= 0 \\
\left\langle x^2 \right\rangle &= A^2 \int_{-\infty}^{\infty} e^{-2a(mx^2/\hbar)} x^2 \, dx \\
&= 2A^2 \int_{0}^{\infty} e^{-2a(mx^2/\hbar)} x^2 \, dx \\
&= \frac{\hbar}{4am} \\
\langle p \rangle &= \int_{-\infty}^{\infty} \Psi^* \left[ -i\hbar \frac{\partial}{\partial x} \right] \Psi \, dx \\
&= -i\hbar \int_{-\infty}^{\infty} A e^{-a[(mx^2/\hbar)-it]} \left( -\frac{2amx}{\hbar} A e^{-a[(mx^2/\hbar)+it]} \right) dx \\
&= 2iA^2 am \int_{-\infty}^{\infty} x e^{-2amx^2/\hbar} \, dx \\
&= 0 \\
\left\langle p^2 \right\rangle &= \int_{-\infty}^{\infty} \Psi^* \left[ -\hbar^2 \frac{\partial^2}{\partial x^2} \right] \Psi \, dx \\
&= -\hbar^2 \int_{-\infty}^{\infty} A e^{-a[(mx^2/\hbar)-it]} \left[ -\frac{2am}{\hbar} \left( 1 - \frac{2amx^2}{\hbar} \right) A e^{-a[(mx^2/\hbar)+it]} \right] dx \\
&= 2A^2 am\hbar \int_{-\infty}^{\infty} e^{-2amx^2/\hbar} \left( 1 - \frac{2amx^2}{\hbar} \right) dx \\
&= am\hbar
\end{aligned}$$

(d)

$$\begin{aligned}
\sigma_x &= \sqrt{\langle x^2 \rangle - \langle x \rangle^2} \\
&= \sqrt{\frac{\hbar}{4am}} \\
\sigma_p &= \sqrt{am\hbar} \\
\sigma_x \sigma_p &= \sqrt{\frac{1}{4}\hbar^2} \\
&= \frac{1}{2}\hbar \\
&\geq \frac{1}{2}\hbar
\end{aligned}$$

Yes, this is consistent with Heisenberg's uncertainty principle.

## 1.10

(a)

$$
\begin{aligned}
P(0) &= 0 \\
P(1) &= \frac{2}{25} \\
&= 0.08 \\
P(2) &= \frac{3}{25} \\
&= 0.12 \\
P(3) &= \frac{1}{5} \\
&= 0.2 \\
P(4) &= \frac{3}{25} \\
&= 0.12 \\
P(5) &= \frac{3}{25} \\
&= 0.2 \\
P(6) &= \frac{3}{25} \\
&= 0.2 \\
P(7) &= \frac{1}{25} \\
&= 0.04 \\
P(8) &= \frac{2}{25} \\
&= 0.08 \\
P(9) &= \frac{3}{25} \\
&= 0.12
\end{aligned}
$$

(b) The most probable digit is 3, the median digit is 4, and the average value is $\frac{118}{25} = 4.72$.

(c) $\sigma = 2.474$

## 1.14

(a)

$$
\begin{aligned}
P_{ab}(t) &= \int_a^b |\Psi(x,t)|^2 \, dx \\
\frac{dP_{ab}}{dt} &= \frac{d}{dt} \int_a^b |\Psi(x,t)|^2 \, dx \\
&= \int_a^b \frac{d}{dt} \left( |\Psi(x,t)|^2 \right) \, dx \\
&= \int_a^b \frac{\partial}{\partial x} \left[ \frac{i\hbar}{2m} \left( \Psi^* \frac{\partial \Psi}{\partial x} - \frac{\partial \Psi^*}{\partial x} \Psi \right) \right] \, dx \\
&= J(a,t) - J(b,t)
\end{aligned}
$$

The units are $\mathrm{s}^{-1}$.

(b)

$$
\begin{aligned}
\Psi(x,t) &= Ae^{-a[(mx^2/\hbar)+it]} \\
\frac{\partial \Psi}{\partial x} &= -\frac{2amx}{\hbar} \Psi \\
\Psi^*(x,t) &= Ae^{-a[(mx^2/\hbar)-it]} \\
\frac{\partial \Psi^*}{\partial x} &= -\frac{2amx}{\hbar} \Psi^* \\
J(x,t) &= \frac{i\hbar}{2m} \left( \Psi \frac{\partial \Psi^*}{\partial x} - \Psi^* \frac{\partial \Psi}{\partial x} \right) \\
&= \frac{i\hbar}{2m} \left[ \Psi \left( -\frac{2amx}{\hbar} \Psi^* \right) - \Psi^* \left( -\frac{2amx}{\hbar} \Psi \right) \right] \\
&= 0
\end{aligned}
$$

**1.15**

$$
\begin{aligned}
\frac{d}{dt}\int_{-\infty}^{\infty}\Psi_1^*\Psi_2\,dx &= \int_{-\infty}^{\infty}\left(\frac{\partial\Psi_1^*}{\partial t}\Psi_2+\Psi_1^*\frac{\partial\Psi_2}{\partial t}\right)\,dx \\
&= \int_{-\infty}^{\infty}\left[\left(-i\frac{\hbar}{2m}\frac{\partial^2\Psi_1^*}{\partial x^2}+i\frac{V}{\hbar}\Psi_1^*\right)\Psi_2\right. \\
&\qquad \left. +\Psi_1^*\left(i\frac{\hbar}{2m}\frac{\partial^2\Psi_2}{\partial x^2}-i\frac{V}{\hbar}\Psi_2\right)\right]\,dx \\
&= i\frac{\hbar}{2m}\int_{-\infty}^{\infty}\left(\Psi_1^*\frac{\partial^2\Psi_2}{\partial x^2}-\frac{\partial^2\Psi_1^*}{\partial x^2}\Psi_2\right)\,dx \\
&= i\frac{\hbar}{2m}\left[\Psi_1^*\frac{\partial\Psi_2}{\partial x}\bigg|_{-\infty}^{\infty}-\int_{-\infty}^{\infty}\frac{\partial}{\partial x}(\Psi_1^*\Psi_2)\,dx\right. \\
&\qquad \left.\frac{\partial\Psi_1^*}{\partial x}\Psi_2\bigg|_{-\infty}^{\infty}-\int_{-\infty}^{\infty}\frac{\partial}{\partial x}(\Psi_1^*\Psi_2)\,dx\right] \\
&= 0
\end{aligned}
$$

**1.16**

(a)

$$
\begin{aligned}
1 &= \int_{-a}^{a}A^2(a^2-x^2)^2\,dx \\
&= A^2\int_{0}^{a}(a^2-x^2)^2\,dx \\
&= \frac{16}{15}A^2a^5 \\
A &= \sqrt{\frac{15}{16a^5}}
\end{aligned}
$$

(b)

$$
\begin{aligned}
\langle x\rangle &= \int_{-a}^{a}xA(a^2-x^2)\,dx \\
&= 0
\end{aligned}
$$

(c)

$$
\begin{aligned}
\langle p\rangle &= \int_{-a}^{a}\Psi^*\left(-i\hbar\frac{\partial}{\partial x}\right)\Psi\,dx \\
&= 2iA^2\hbar\int_{-a}^{a}x(a^2-x^2)\,dx \\
&= 0
\end{aligned}
$$

(d)

$$
\begin{aligned}
\left\langle x^2 \right\rangle &= \int_{-a}^{a} \Psi^* x^2 \Psi \, dx \\
&= A^2 \int_{-a}^{a} x^2 (a^2 - x^2)^2 \, dx \\
&= A^2 \frac{16}{105} a^7 \\
&= \frac{a^2}{7}
\end{aligned}
$$

(e)

$$
\begin{aligned}
\left\langle p^2 \right\rangle &= \int_{-a}^{a} \Psi^* \left( -\hbar^2 \frac{\partial^2}{\partial x^2} \right) \Psi \, dx \\
&= -\hbar^2 \int_{-a}^{a} A(a^2 - x^2)(-2A) \, dx \\
&= 4A^2\hbar^2 \int_{0}^{a} (a^2 - x^2) \, dx \\
&= 4A^2\hbar^2 \left[ a^2 x - \frac{1}{3} x^3 \right]_0^a \\
&= 4A^2\hbar^2 \left( a^3 - \frac{1}{3} a^3 \right) \\
&= \frac{8}{3} A^2 a^3 \hbar^2 \\
&= \frac{8}{3} \frac{15}{16a^5} a^3 \hbar^2 \\
&= \frac{5}{2} \frac{\hbar^2}{a^2}
\end{aligned}
$$

(f)

$$
\begin{aligned}
\sigma_x &= \sqrt{\langle x^2 \rangle - \langle x \rangle^2} \\
&= \sqrt{\frac{a^2}{7}} \\
&= \frac{a}{\sqrt{7}}
\end{aligned}
$$

(g)

$$
\begin{aligned}
\sigma_p &= \sqrt{\langle p^2 \rangle - \langle p \rangle^2} \\
&= \sqrt{\frac{5}{2}} \frac{\hbar}{a}
\end{aligned}
$$

(h)

$$\sigma_x \sigma_p = \sqrt{\frac{5}{14}}\hbar$$
$$\geq \frac{1}{2}\hbar$$

### 1.18

(a)

$$\begin{aligned}
\frac{h}{\sqrt{3mk_BT}} &> d \\
\frac{\sqrt{3mk_BT}}{h} &< \frac{1}{d} \\
T_{\text{electron}} &< \frac{h^2}{3d^2mk_B} \\
&< 1.3 \times 10^5\,\text{K} \\
T_{\text{nuclei}} &< 2.5\,\text{K}
\end{aligned}$$

(b)

$$\begin{aligned}
PV &= Nk_BT \\
\frac{V}{N} &= \frac{k_BT}{P} \\
d &= \left(\frac{k_BT}{P}\right)^{1/3} \\
\frac{h}{\sqrt{3mk_Bt}} &> \left(\frac{k_BT}{P}\right)^{1/3} \\
T &< \frac{1}{k_B}\left(\frac{h^2}{3m}\right)^{3/5} P^{2/5}
\end{aligned}$$

## 2 Time-Independent Schrödinger Equation

### 2.1

(a)

$$\begin{aligned}
\int_{-\infty}^{\infty} |\Psi|^2\,dx &= \int_{-\infty}^{\infty} \Psi^*\Psi\,dx \\
&= \int_{-\infty}^{\infty} \psi^* e^{i(E_0 - i\Gamma)t/\hbar}\psi e^{-i(E_0+i\Gamma)t/\hbar}\,dx \\
&= e^{2\Gamma t/\hbar}\int_{-\infty}^{\infty} |\psi|^2\,dx
\end{aligned}$$

In order for this to equal 1 for all $t$, $\Gamma$ must be 0.

(b) If $\psi(x)$ is a complex solution to the time-independent Schrödinger equation then so is $\psi^*(x)$ and $\psi(x) + \psi^*(x)$ which is real.

## 2.2

If $\psi$ and its second derivative always have the same sign, $\psi$ will increase or decrease without bound forever. This means there is no non-zero choice of constant $A$ such that

$$\int_{-\infty}^{\infty} |A\Psi|^2 \, dx = 1$$

and thus the equation can't be normalised.

The classical analog of this is statements is that the potential energy of a system can't exceed its total energy.

## 2.3

The time-independent Schrödinger equation in an infinite square well is

$$-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} = E\psi.$$

If $E = 0$ then $\psi = Ax + B$ which isn't normalisable.

If $E < 0$ then $\psi = Ae^{kt} + Be^{-kt}$ where $k \in \mathbb{R}$ which also isn't normalisable.

## 2.4

$$\begin{aligned}
\Psi_n(x,t) &= \sqrt{\frac{2}{a}}\sin\left(\frac{n\pi}{a}x\right)e^{-i(n^2\pi^2\hbar/2ma^2)t} \\
\langle x\rangle &= \int_0^a \Psi_n^* x \Psi_n \, dx \\
&= \frac{2}{a}\int_0^a x\sin^2\left(\frac{n\pi}{a}x\right)\, dx \\
&= \frac{a}{2} \\
\left\langle x^2\right\rangle &= \int_0^a \Psi_n^* x^2 \Psi_n \, dx \\
&= \frac{2}{a}\int_0^a x^2\sin^2\left(\frac{n\pi}{a}x\right)\, dx \\
&= a^2\left(\frac{1}{3} - \frac{1}{2n^2\pi^2}\right) \\
\langle p\rangle &= \int_0^a \Psi_n^* \left(-i\hbar\frac{\partial}{\partial x}\right)\Psi_n \, dx \\
&= -i\frac{2\hbar n\pi}{a^2}\int_0^a \sin\left(\frac{n\pi}{a}x\right)\cos\left(\frac{n\pi}{a}x\right)\, dx \\
&= 0 \\
\left\langle p^2\right\rangle &= \int_0^a \Psi_n^* \left(-\hbar^2\frac{\partial^2}{\partial x^2}\right)\Psi_n \, dx \\
&= \frac{2\hbar^2 n^2\pi^2}{a^3}\int_0^a \sin^2\left(\frac{n\pi}{a}x\right)\, dx \\
&= \left(\frac{n\pi\hbar}{a}\right)^2 \\
\sigma_x &= \sqrt{\langle x^2\rangle - \langle x\rangle^2} \\
&= \frac{a}{2}\sqrt{\frac{1}{3} - \frac{2}{n^2\pi^2}} \\
\sigma_p &= \sqrt{\langle p^2\rangle - \langle p\rangle^2} \\
&= \frac{n\pi\hbar}{a}
\end{aligned}$$

**2.5**

(a)

$$
\begin{aligned}
1 &= \int_0^a A^2(\psi_1 + \psi_2)^2\,dx \\
&= A^2 \int_0^a (\psi_1^2 + 2\psi_1\psi_2 + \psi_2^2)\,dx \\
&= \frac{2A^2}{a}\left[\int_0^a \sin^2\left(\frac{\pi}{a}x\right)\,dx + \int_0^a \sin^2\left(\frac{2\pi}{a}x\right)\,dx\right] \\
&= 2A^2 \\
A &= \frac{1}{\sqrt{2}}
\end{aligned}
$$

(b)

$$
\begin{aligned}
\Psi(x,t) &= \frac{1}{\sqrt{2}}\left[\sqrt{\frac{2}{a}}\sin\left(\frac{\pi}{a}x\right)e^{-i\omega t} + \sqrt{\frac{2}{a}}\sin\left(\frac{2\pi}{a}x\right)e^{-4i\omega t}\right] \\
|\Psi(x,t)|^2 &= \Psi^*\Psi \\
&= \frac{1}{a}\left[\sin\left(\frac{\pi}{a}x\right)e^{i\omega t} + \sin\left(\frac{2\pi}{a}x\right)e^{4i\omega t}\right] \\
&\quad \left[\sin\left(\frac{\pi}{a}x\right)e^{-i\omega t} + \sin\left(\frac{2\pi}{a}x\right)e^{-4i\omega t}\right] \\
&= \frac{1}{a}\left[\sin^2\left(\frac{\pi}{a}x\right) + \sin\left(\frac{\pi}{a}x\right)\sin\left(\frac{2\pi}{a}x\right)e^{-3i\omega t}\right. \\
&\quad \left. + \sin\left(\frac{\pi}{a}x\right)\sin\left(\frac{2\pi}{a}x\right)e^{3i\omega t} + \sin^2\left(\frac{2\pi}{a}x\right)\right] \\
&= \frac{1}{a}\left[\sin^2\left(\frac{\pi}{a}x\right) + \sin^2\left(\frac{2\pi}{a}x\right)\right. \\
&\quad \left. + 2\sin\left(\frac{\pi}{a}x\right)\sin\left(\frac{2\pi}{a}x\right)\cos(3\omega t)\right]
\end{aligned}
$$

(c)

$$
\begin{aligned}
\langle x \rangle &= \int_0^a \Psi^* x \Psi\,dx \\
&= \int_0^a x|\Psi|^2\,dx \\
&= \frac{a}{2}\left[1 - \frac{32}{9\pi^2}\cos(3\omega t)\right]
\end{aligned}
$$

(d)

$$\begin{aligned}
\langle p \rangle &= m\frac{d\langle x \rangle}{dt} \\
&= \frac{16am\omega}{3\pi^2}\sin(3\omega t) \\
&= \frac{8\hbar}{3a}\sin(3\omega t)
\end{aligned}$$

(e) You can get $E_1$ or $E_2$ and the probability of getting each is 1/2. $H = \frac{1}{2}(E_1 + E_2)$ is the mean of the two possible energy values.

## 2.6

$$\begin{aligned}
\Psi(x,0) &= A[\psi_1 + e^{i\phi}\psi_2] \\
1 &= \int_0^a |\Psi|^2\,dx \\
&= \int_0^a \Psi^*\Psi\,dx \\
&= A^2\int_0^a (\psi_1 + e^{-i\phi}\psi_2)(\psi_1 + e^{i\phi}\psi_2)\,dx \\
&= A^2\int_0^a (\psi_1^2 + e^{i\phi}\psi_1\psi_2 + e^{-i\phi}\psi_1\psi_2 + \psi_2^2)\,dx \\
&= \frac{2A^2}{a}\int_0^a \left[\sin^2\left(\frac{\pi}{a}x\right) + e^{i\phi}\sin\left(\frac{\pi}{a}x\right)\sin\left(\frac{2\pi}{a}x\right)\right. \\
&\qquad \left. e^{-i\phi}\sin\left(\frac{\pi}{a}x\right)\sin\left(\frac{2\pi}{a}x\right) + \sin^2\left(\frac{2\pi}{a}x\right)\right]\,dx \\
&= \frac{2A^2}{a}\int_0^a \left[\sin^2\left(\frac{\pi}{a}x\right) + \sin\left(\frac{\pi}{a}x\right)\sin\left(\frac{2\pi}{a}x\right)\cos\phi\right. \\
&\qquad \left. + \sin^2\left(\frac{2\pi}{a}x\right)\right]\,dx \\
&= 2A^2 \\
A &= \frac{1}{\sqrt{2}} \\
\Psi(x,t) &= \frac{1}{\sqrt{a}}\left[\sin\left(\frac{\pi}{a}x\right)e^{-i\omega t} + \sin\left(\frac{2\pi}{a}x\right)e^{i(\phi-4\omega t)}\right]
\end{aligned}$$

$$
\begin{aligned}
|\Psi|^2 &= \Psi^*\Psi \\
&= \frac{1}{a}\left[\sin\left(\frac{\pi}{a}x\right)e^{i\omega t} + \sin\left(\frac{2\pi}{a}x\right)e^{-i(\phi-4\omega t)}\right] \\
&\quad \left[\sin\left(\frac{\pi}{a}x\right)e^{-i\omega t} + \sin\left(\frac{2\pi}{a}x\right)e^{i(\phi-4\omega t)}\right] \\
&= \frac{1}{a}\left[\sin^2\left(\frac{\pi}{a}x\right) + \sin\left(\frac{\pi}{a}x\right)\sin\left(\frac{2\pi}{a}x\right)e^{i(\phi-3\omega t)}\right. \\
&\quad \left.\sin\left(\frac{\pi}{a}x\right)\sin\left(\frac{2\pi}{a}x\right)e^{-i(\phi-3\omega t)} + \sin^2\left(\frac{2\pi}{a}x\right)\right] \\
&= \frac{1}{a}\left[\sin^2\left(\frac{\pi}{a}x\right) + \sin^2\left(\frac{2\pi}{a}x\right)\right. \\
&\quad \left. +2\sin\left(\frac{\pi}{a}x\right)\sin\left(\frac{2\pi}{a}x\right)\cos(\phi - 3\omega t)\right] \\
\langle x\rangle &= \int_0^a \Psi^* x\Psi\,dx \\
&= \int_0^a x|\Psi|^2\,dx \\
&= \frac{a}{2}\left[1 - \frac{32}{9\pi^2}\cos(3\omega t - \phi)\right]
\end{aligned}
$$

## 2.7

(a)

$$
\begin{aligned}
1 &= \int_0^a |\Psi|^2\,dx \\
&= A^2\left[\int_0^{a/2} x^2\,dx + \int_{a/2}^a (a-x)^2\,dx\right] \\
&= A^2\left\{\frac{1}{3}\left[\frac{a}{2}\right]^3 + \left[-\frac{1}{3}(a-x)^3\right]_{a/2}^a\right\} \\
&= A^2\left(\frac{a^3}{24} + \frac{a^3}{24}\right) \\
&= \frac{A^2a^3}{12} \\
A &= \frac{2\sqrt{3}}{\sqrt{a^3}}
\end{aligned}
$$

(b)

$$
\begin{aligned}
c_n &= \sqrt{\frac{2}{a}}\int_0^a \sin\left(\frac{n\pi}{a}x\right)\Psi(x,0)\,dx \\
&= \sqrt{\frac{2}{a}}\left[\int_0^{a/2} \sin\left(\frac{n\pi}{a}x\right)Ax\,dx + \int_{a/2}^a \sin\left(\frac{n\pi}{a}x\right)A(a-x)\,dx\right] \\
&= \frac{2\sqrt{6}}{a^2}\left[\int_0^{a/2} x\sin\left(\frac{n\pi}{a}x\right)\,dx + \int_{a/2}^a (a-x)\sin\left(\frac{n\pi}{a}x\right)\,dx\right] \\
&= \frac{8\sqrt{6}}{n^2\pi^2}\sin^2\left(\frac{n\pi}{4}\right)\sin\left(\frac{n\pi}{2}\right) \\
&= \begin{cases} 0 & n \text{ even} \\ (-1)^{(n-1)/2}\frac{4\sqrt{6}}{n^2\pi^2} & n \text{ odd} \end{cases} \\
\Psi(x,t) &= \frac{4\sqrt{6}}{\pi^2}\sqrt{\frac{2}{a}}\sum_{n=1,3,5,\ldots}^{\infty}(-1)^{(n-1)/2}\frac{1}{n^2}\sin\left(\frac{n\pi}{a}x\right)e^{-i(n^2\pi^2\hbar/2ma^2)t}
\end{aligned}
$$

(c)

$$
\begin{aligned}
|c_1|^2 &= \left(\frac{4\sqrt{6}}{\pi^2}\right)^2 \\
&\approx 0.985
\end{aligned}
$$

(d)

$$
\begin{aligned}
E_n &= \frac{n^2\pi^2\hbar^2}{2ma^2} \\
\langle H\rangle &= \sum_{n=0}^{\infty}|c_{2n+1}|^2 E_{2n+1} \\
&= \sum_{n=0}^{\infty}\left(\frac{4\sqrt{6}}{(2n+1)^2\pi^2}\right)^2\frac{(2n+1)^2\pi^2\hbar^2}{2ma^2} \\
&= \sum_{n=0}^{\infty}\frac{48\hbar^2}{(2n+1)^2ma^2\pi^2} \\
&= \frac{48\hbar^2}{ma^2\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2} \\
&= \frac{6\hbar^2}{ma^2}
\end{aligned}
$$

## 2.8

$$
\begin{aligned}
1 &= \int_0^{a/2} |\Psi|^2 \, dx \\
&= A^2 \int_0^{a/2} \, dx \\
&= \frac{aA^2}{2} \\
A &= \sqrt{\frac{2}{a}} \\
c_n &= \frac{2}{a} \int_0^{a/2} \sin\left(\frac{n\pi}{a} x\right) \, dx \\
|c_1|^2 &= \left(\frac{2}{\pi}\right)^2 \\
&\approx 0.405
\end{aligned}
$$

## 2.9

$$
\begin{aligned}
\Psi(x,0) &= Ax(a-x) \\
\langle H \rangle &= \int_0^a \Psi(x,0)^* \hat{H} \Psi(x,0) \, dx \\
&= \int_0^a \Psi(x,0)^* \left(-\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2}\right) \Psi(x,0) \, dx \\
&= \frac{A^2 \hbar^2}{m} \int_0^a x(a-x) \, dx \\
&= \frac{30\hbar^2}{ma^5} \frac{a^3}{6} \\
&= \frac{5\hbar^2}{ma^2}
\end{aligned}
$$

## 2.10

(a)

$$\begin{aligned}
\psi_2(x) &= \frac{1}{\sqrt{2!}}(\hat{a}_+)\psi_1 \\
&= \frac{1}{\sqrt{2}}\frac{1}{\sqrt{2\hbar m\omega}}\left(-\hbar\frac{d}{dx}+m\omega x\right)\left(\frac{m\omega}{\pi\hbar}\right)^{1/4}\sqrt{\frac{2m\omega}{\hbar}}xe^{-\frac{m\omega}{2\hbar}x^2} \\
&= \frac{1}{\sqrt{2}\hbar}\left(\frac{m\omega}{\pi\hbar}\right)^{1/4}\left(-\hbar\frac{d}{dx}+m\omega x\right)xe^{-\frac{m\omega}{2\hbar}x^2} \\
&= \frac{1}{\sqrt{2}\hbar}\left(\frac{m\omega}{\pi\hbar}\right)^{1/4}\left[-\hbar\left(e^{-\frac{m\omega}{2\hbar}x^2}-\frac{m\omega}{\hbar}x^2e^{-\frac{m\omega}{2\hbar}x^2}\right)+m\omega x^2e^{-\frac{m\omega}{2\hbar}x^2}\right] \\
&= \frac{1}{\sqrt{2}}\left(\frac{m\omega}{\pi\hbar}\right)^{1/4}\left(\frac{2m\omega}{\hbar}x^2-1\right)e^{-\frac{m\omega}{2\hbar}x^2}
\end{aligned}$$

## 2.11

(a)

$$
\begin{aligned}
\langle x \rangle &= \int_{-\infty}^{\infty} \psi_0^* x \psi_0 \, dx \\
&= \alpha^2 \int_{-\infty}^{\infty} x e^{-\frac{m\omega}{\hbar}x^2} \, dx \\
&= 0 \\
\langle p \rangle &= m \frac{d\langle x \rangle}{dt} \\
&= 0 \\
\langle x^2 \rangle &= \int_{-\infty}^{\infty} \psi_0^* x^2 \psi_0 \, dx \\
&= \alpha^2 \int_{-\infty}^{\infty} x^2 e^{-\frac{m\omega}{\hbar}x^2} \, dx \\
&= \frac{\hbar}{2m\omega} \\
\langle p^2 \rangle &= \int_{-\infty}^{\infty} \psi_0^* \left( -\hbar^2 \frac{d^2}{dx^2} \right) \psi_0 \, dx \\
&= -\hbar^2 \left( \frac{m\omega}{\pi\hbar} \right)^{1/2} \int_{-\infty}^{\infty} e^{-\frac{m\omega}{2\hbar}x^2} \frac{d}{dx} \left( -\frac{m\omega}{\hbar} x e^{-\frac{m\omega}{2\hbar}x^2} \right) dx \\
&= \hbar^2 \left( \frac{m\omega}{\pi\hbar} \right)^{1/2} \frac{m\omega}{\hbar} \int_{-\infty}^{\infty} e^{-\frac{m\omega}{2\hbar}x^2} \left( e^{-\frac{m\omega}{2\hbar}x^2} - \frac{m\omega}{\hbar} x^2 e^{-\frac{m\omega}{2\hbar}x^2} \right) dx \\
&= \hbar^2 \left( \frac{m\omega}{\pi\hbar} \right)^{1/2} \frac{m\omega}{\hbar} \int_{-\infty}^{\infty} \left( 1 - \frac{m\omega}{\hbar} x^2 \right) e^{-\frac{m\omega}{\hbar}x^2} \, dx \\
&= \hbar^2 \left( \frac{m\omega}{\pi\hbar} \right)^{1/2} \frac{m\omega}{\hbar} \frac{\hbar\sqrt{\pi}}{2\sqrt{\hbar m\omega}} \\
&= \frac{1}{2} m\hbar\omega
\end{aligned}
$$

$$
\begin{aligned}
\psi_1(x) &= \left(\frac{m\omega}{\pi\hbar}\right)^{1/4}\sqrt{\frac{2m\omega}{\hbar}}xe^{-\frac{m\omega}{2\hbar}x^2} \\
\langle x\rangle &= 0 \\
\langle p\rangle &= m\frac{d\langle x\rangle}{dt} \\
&= 0 \\
\left\langle x^2\right\rangle &= \int_{-\infty}^{\infty}\psi_1^* x^2\psi_1\,dx \\
&= \left(\frac{m\omega}{\pi\hbar}\right)^{1/2}\frac{2m\omega}{\hbar}\int_{-\infty}^{\infty}x^4e^{-\frac{m\omega}{\hbar}x^2}\,dx \\
&= \left(\frac{m\omega}{\pi\hbar}\right)^{1/2}\frac{2m\omega}{\hbar}\frac{3}{4}\sqrt{\pi}\left(\frac{\hbar}{m\omega}\right)^{5/2} \\
&= \frac{3}{2}\frac{\hbar}{m\omega} \\
\left\langle p^2\right\rangle &= \int_{-\infty}^{\infty}\psi_1^*\left(-\hbar^2\frac{d^2}{dx^2}\right)\psi_1\,dx \\
&= -\hbar^2\left(\frac{m\omega}{\pi\hbar}\right)^{1/2}\frac{2m\omega}{\hbar}\int_{-\infty}^{\infty}xe^{-\frac{m\omega}{2\hbar}x^2}\frac{d}{dx}\left(e^{-\frac{m\omega}{2\hbar}x^2}-\frac{m\omega}{\hbar}x^2e^{-\frac{m\omega}{2\hbar}x^2}\right)\,dx \\
&= -\hbar^2\left(\frac{m\omega}{\pi\hbar}\right)^{1/2}\frac{2m\omega}{\hbar}\int_{-\infty}^{\infty}xe^{-\frac{m\omega}{2\hbar}x^2}\left[-\frac{m\omega}{\hbar}xe^{-\frac{m\omega}{2\hbar}x^2}\right. \\
&\qquad\left.-\frac{2m\omega}{\hbar}xe^{-\frac{m\omega}{2\hbar}x^2}+\left(\frac{m\omega}{\hbar}\right)^2x^3e^{-\frac{m\omega}{2\hbar}x^2}\right]\,dx \\
&= 2\hbar^2\left(\frac{m\omega}{\pi\hbar}\right)^{1/2}\left(\frac{m\omega}{\hbar}\right)^2\int_{-\infty}^{\infty}x^2e^{-\frac{m\omega}{\hbar}x^2}\left(3-\frac{m\omega}{\hbar}x^2\right)\,dx \\
&= 2\hbar^2\left(\frac{m\omega}{\pi\hbar}\right)^{1/2}\left(\frac{m\omega}{\hbar}\right)^2\frac{3}{4}\sqrt{\pi}\left(\frac{h}{m\omega}\right)^{3/2} \\
&= \frac{3}{2}m\hbar\omega
\end{aligned}
$$

(b)

$$\begin{aligned}
\sigma_x &= \sqrt{\langle x^2 \rangle - \langle x \rangle^2} \\
&= \sqrt{\frac{\hbar}{2m\omega}} \\
\sigma_p &= \sqrt{\langle p^2 \rangle - \langle p \rangle^2} \\
&= \sqrt{\frac{m\hbar\omega}{2}} \\
\sigma_x \sigma_p &= \frac{\hbar}{2} \\
\sigma_x &= \sqrt{\frac{3\hbar}{2m\omega}} \\
\sigma_p &= \sqrt{\frac{3m\hbar\omega}{2}} \\
\sigma_x \sigma_p &= \frac{3}{2}\hbar
\end{aligned}$$

(c)

$$\begin{aligned}
\langle T \rangle &= \frac{\left\langle p^2 \right\rangle}{2m} \\
&= \frac{\hbar\omega}{4} \\
\langle V \rangle &= \frac{1}{2} m\omega^2 \left\langle x^2 \right\rangle \\
&= \frac{1}{4}\hbar\omega \\
\langle T \rangle &= \frac{\left\langle p^2 \right\rangle}{2m} \\
&= \frac{3}{4}\hbar\omega \\
\langle V \rangle &= \frac{1}{2} m\omega^2 \left\langle x^2 \right\rangle \\
&= \frac{3}{4}\hbar\omega
\end{aligned}$$

## 2.12

$$
\begin{aligned}
\langle x \rangle &= \int_{-\infty}^{\infty} \psi_n^* x \psi_n \, dx \\
&= \sqrt{\frac{\hbar}{2m\omega}} \int_{-\infty}^{\infty} \psi_n^* (\hat{a}_+ + \hat{a}_-) \psi_n \, dx \\
&= \sqrt{\frac{\hbar}{2m\omega}} \int_{-\infty}^{\infty} \psi_n^* (\sqrt{n+1}\psi_{n+1} + \sqrt{n}\psi_{n-1}) \, dx \\
&= 0 \\
\langle p \rangle &= \int_{-\infty}^{\infty} \psi_n^* p \psi_n \, dx \\
&= i\sqrt{\frac{\hbar m\omega}{2}} \int_{-\infty}^{\infty} \psi_n^* (\hat{a}_+ - \hat{a}_-) \psi_n \, dx \\
&= i\sqrt{\frac{\hbar m\omega}{2}} \int_{-\infty}^{\infty} \psi_n^* (\sqrt{n+1}\psi_{n+1} - \sqrt{n}\psi_{n-1}) \, dx \\
&= 0 \\
\left\langle x^2 \right\rangle &= \int_{-\infty}^{\infty} \psi_n^* x^2 \psi_n \, dx \\
&= \frac{\hbar}{2m\omega} \int_{-\infty}^{\infty} \psi_n^* (\hat{a}_+^2 + \hat{a}_+\hat{a}_- + \hat{a}_-\hat{a}_+ + \hat{a}_-^2) \psi_n \, dx \\
&= \frac{\hbar}{2m\omega} (2n+1) \int_{-\infty}^{\infty} |\psi_n|^2 \, dx \\
&= \frac{\hbar}{m\omega} \left( n + \frac{1}{2} \right) \\
\left\langle p^2 \right\rangle &= \int_{-\infty}^{\infty} \psi_n^* p^2 \psi_n \, dx \\
&= -\frac{\hbar m\omega}{2} \int_{-\infty}^{\infty} \psi_n^* (\hat{a}_+^2 - \hat{a}_+\hat{a}_- - \hat{a}_-\hat{a} - +\hat{a}_-^2) \psi_n \, dx \\
&= \frac{\hbar m\omega}{2} (2n+1) \int_{-\infty}^{\infty} |\psi_n|^2 \, dx \\
&= \hbar m\omega \left( n + \frac{1}{2} \right) \\
\langle T \rangle &= \left\langle \frac{p^2}{2m} \right\rangle \\
&= \frac{1}{2}\hbar\omega \left( n + \frac{1}{2} \right)
\end{aligned}
$$

$$
\begin{aligned}
\sigma_x &= \sqrt{\langle x^2\rangle - \langle x\rangle^2} \\
&= \sqrt{\frac{\hbar}{m\omega}\left(n+\frac{1}{2}\right)} \\
\sigma_p &= \sqrt{\hbar m\omega\left(n+\frac{1}{2}\right)} \\
\sigma_x\sigma_p &= (2n+1)\frac{\hbar}{2} \\
&\geq \frac{\hbar}{2}
\end{aligned}
$$

## 2.13

(a)

$$
\begin{aligned}
\Psi(x,0) &= A[3\psi_0(x) + 4\psi_1(x)] \\
1 &= \int_{-\infty}^{\infty} |\Psi(x,0)|^2\,dx \\
&= A^2\int_{-\infty}^{\infty}[9\psi_0(x)^2 + 24\psi_0(x)\psi_1(x) + 16\psi_1(x)^2]\,dx \\
&= 25A^2 \\
A &= \frac{1}{5}
\end{aligned}
$$

(b)

$$
\begin{aligned}
\Psi(x,t) &= \frac{1}{5}[3\psi_0(x)e^{-i\omega t/2} + 4\psi_1(x)e^{-3i\omega t/2}] \\
|\Psi(x,t)|^2 &= \Psi(x,t)^*\Psi(x,t) \\
&= \frac{1}{25}[3\psi_0(x)e^{i\omega t/2} + 4\psi_1(x)e^{3i\omega t/2}][3\psi_0(x)e^{-i\omega t/2} + 4\psi_1(x)e^{-3i\omega t/2}] \\
&= \frac{1}{25}[9\psi_0(x)^2 + 12\psi_0(x)\psi_1(x)e^{-i\omega t} + 12\psi_0(x)\psi_1(x)e^{i\omega t} + 16\psi_1(x)^2] \\
&= \frac{1}{25}[9\psi_0(x)^2 + 16\psi_1(x)^2 + 24\psi_0(x)\psi_1(x)\cos\omega t]
\end{aligned}
$$

(c)

$$
\begin{aligned}
\langle x \rangle &= \int_{-\infty}^{\infty} \Psi^* x \Psi \, dx \\
&= \frac{1}{25} \int_{-\infty}^{\infty} x(9\psi_0^2 + 16\psi_1^2 + 24\psi_0\psi_1 \cos\omega t) \, dx \\
&= \frac{24}{25} \int_{-\infty}^{\infty} x\psi_0\psi_1 \cos(\omega t) \, dx \\
&= \frac{24}{25} \left(\frac{m\omega}{\pi\hbar}\right)^{1/2} \sqrt{\frac{2m\omega}{\hbar}} \cos(\omega t) \int_{-\infty}^{\infty} x^2 e^{-\frac{m\omega}{\hbar}x^2} \, dx \\
&= \frac{24}{25} \left(\frac{m\omega}{\pi\hbar}\right)^{1/2} \sqrt{\frac{2m\omega}{\hbar}} \cos(\omega t) \frac{1}{2}\sqrt{\pi} \left(\frac{\hbar}{m\omega}\right)^{3/2} \\
&= \frac{24}{25} \sqrt{\frac{\hbar}{2m\omega}} \cos(\omega t) \\
\langle p \rangle &= m\frac{d\langle x \rangle}{dt} \\
&= -\frac{24}{25} \sqrt{\frac{\hbar m\omega}{2}} \sin(\omega t) \\
\frac{d\langle p \rangle}{dt} &= -\frac{24}{25} \sqrt{\frac{\hbar m\omega}{2}} \omega \cos(\omega t) \\
V &= \frac{1}{2} m\omega^2 x^2 \\
\frac{\partial V}{d\partial} &= m\omega^2 x \\
\left\langle -\frac{\partial V}{\partial x} \right\rangle &= -m\omega^2 \langle x \rangle \\
&= -\frac{24}{25} \sqrt{\frac{\hbar m\omega}{2}} \omega \cos(\omega t) \\
&= \frac{d\langle p \rangle}{dt}
\end{aligned}
$$

(d)

$$
\begin{aligned}
E_0 &= \frac{\hbar\omega}{2} \\
P(E_0) &= \frac{9}{25} \\
E_1 &= \frac{3\hbar\omega}{2} \\
P(E_1) &= \frac{16}{25}
\end{aligned}
$$

## 2.14

$$1 - \left(\frac{m\omega}{\pi\hbar}\right)^{1/2} \int_{-\sqrt{\hbar/m\omega}}^{\sqrt{\hbar/m\omega}} e^{-m\omega x^2/\hbar}\, dx = 1 - \left(\frac{m\omega}{\pi\hbar}\right)^{1/2} \sqrt{\frac{\pi\hbar}{m\omega}}\, \mathrm{erf}\, 1$$
$$= 0.157$$

## 2.15

$$\begin{aligned}
a_{j+2} &= \frac{-2(n-j)}{(j+1)(j+2)} a_j \\
a_3 &= -\frac{4}{3} a_1 \\
a_5 &= \frac{4}{15} a_1 \\
H_5(\xi) &= a_1 \left( \xi - \frac{4}{3}\xi^3 + \frac{4}{15}\xi^5 \right) \\
&= \frac{1}{120} a_1 (120\xi - 160\xi^3 + 32\xi^5) \\
&= 32\xi^5 - 160\xi^3 + 120\xi \\
a_2 &= -6a_0 \\
a_4 &= \frac{-8}{12} a_2 \\
&= 4a_0 \\
a_6 &= \frac{-4}{30} a_4 \\
&= -\frac{8}{15} a_0 \\
H_6(\xi) &= a_0 \left( 1 - 6\xi^2 + 4\xi^4 - \frac{8}{15}\xi^6 \right) \\
&= \frac{1}{120} a_0 (120 - 720\xi^2 + 480\xi^4 - 64\xi^6) \\
&= 64\xi^6 - 480\xi^4 + 720\xi^2 - 120
\end{aligned}$$

## 2.17

$$
\begin{aligned}
Ae^{ikx} + Be^{-ikx} &= A[\cos(kx) + i\sin(kx)] + B[\cos(kx) - i\sin(kx)] \\
&= (A+B)\cos(kx) + i(A-B)\sin(kx) \\
C &= A + B \\
D &= i(A - B) \\
-iD &= A - B \\
A &= \frac{C - iD}{2} \\
B &= \frac{C + iD}{2}
\end{aligned}
$$

## 2.18

$$
\begin{aligned}
\Psi_k(x,t) &= Ae^{i\left(kx - \frac{\hbar k^2}{2m}t\right)} \\
J(x,t) &= \frac{i\hbar}{2m}\left(\Psi\frac{\partial\Psi^*}{\partial x} - \Psi^*\frac{\partial\Psi}{\partial x}\right) \\
&= \frac{\hbar k|A|^2}{m}
\end{aligned}
$$

The probability travels in the same direction as the wave.

## 2.20

(a)

$$
\begin{aligned}
\Psi(x,0) &= Ae^{-a|x|} \\
1 &= \int_{-\infty}^{\infty} \Psi^*\Psi\,dx \\
&= |A|^2\int_{-\infty}^{\infty} e^{-2a|x|}\,dx \\
&= 2|A|^2\int_{0}^{\infty} e^{-2ax}\,dx \\
&= \frac{|A|^2}{a} \\
A &= \sqrt{a}
\end{aligned}
$$

(b)

$$\begin{aligned}
\phi(k) &= \sqrt{\frac{a}{2\pi}} \int_{-\infty}^{\infty} e^{-a|x|-ikx}\,dx \\
&= \sqrt{\frac{a}{2\pi}} \int_{-\infty}^{\infty} e^{-a|x|}[\cos(kx) - i\sin(kx)]\,dx \\
&= \sqrt{\frac{a}{2\pi}} \int_{-\infty}^{\infty} e^{-a|x|}\cos(kx)\,dx \\
&= \sqrt{\frac{a}{2\pi}} 2\int_{0}^{\infty} e^{-ax}\cos(kx)\,dx \\
&= \sqrt{\frac{a}{2\pi}} \frac{2a}{a^2+k^2}
\end{aligned}$$

(c)

$$\Psi(x,t) = \frac{a^{3/2}}{\pi} \int_{-\infty}^{\infty} \frac{1}{a^2+k^2} e^{i\left(kx - \frac{\hbar k^2}{2m}t\right)}\,dk$$

## 2.21

(a)

$$\begin{aligned}
\Psi(x,0) &= Ae^{-ax^2} \\
1 &= A^2 \int_{-\infty}^{\infty} e^{-2ax^2}\,dx \\
&= \sqrt{\frac{\pi}{2a}} A^2 \\
A &= \left(\frac{2a}{\pi}\right)^{1/4}
\end{aligned}$$

(b)

$$\begin{aligned}
\phi(k) &= \frac{1}{\sqrt{2\pi}} \left(\frac{2a}{\pi}\right)^{1/4} \int_{-\infty}^{\infty} e^{-(ax^2+ikx)}\,dx \\
&= \frac{1}{(2\pi a)^{1/4}} e^{-k^2/4a} \\
\Psi(x,t) &= \frac{1}{\sqrt{2\pi}} \frac{1}{(2\pi a)^{1/4}} \int_{-\infty}^{\infty} e^{-\frac{k^2}{4a} + i\left(kx - \frac{\hbar k^2}{2m}t\right)}\,dk \\
\Psi(x,t) &= \left(\frac{2a}{\pi}\right)^{1/4} \frac{1}{\gamma} e^{-ax^2/\gamma^2}
\end{aligned}$$

(c)

$$
\begin{aligned}
|\Psi(x,t)|^2 &= \Psi^*\Psi \\
&= \left(\frac{2a}{\pi}\right)^{1/2} \frac{1}{\gamma^*} e^{-ax^2/(\gamma^*)^2} \frac{1}{\gamma} e^{-ax^2/\gamma^2} \\
&= \left(\frac{2a}{\pi}\right)^{1/2} \frac{1}{\sqrt{1-2i\hbar at/m}} e^{-ax^2/(1-2i\hbar at/m)} \\
&\quad \frac{1}{\sqrt{1+2i\hbar at/m}} e^{-ax^2/(1+2i\hbar at/m)} \\
&= \left(\frac{2a}{\pi}\right)^{1/2} \frac{1}{\sqrt{1+(2\hbar at/m)^2}} e^{-2ax^2/[1+(2a\hbar t/m)^2]} \\
&= \sqrt{\frac{2}{\pi}} w e^{-2w^2x^2}
\end{aligned}
$$

As $t$ increases $|\Psi|^2$ flattens out and broadens.

(d)

$$
\begin{aligned}
\langle x \rangle &= \int_{-\infty}^{\infty} \Psi^* x \Psi \, dx \\
&= 0 \\
\langle p \rangle &= m \frac{d\langle x \rangle}{dt} \\
&= 0 \\
\langle x^2 \rangle &= \int_{-\infty}^{\infty} \Psi^* x^2 \Psi \, dx \\
&= \sqrt{\frac{2}{\pi}} w \int_{-\infty}^{\infty} x^2 e^{-2w^2x^2} \, dx \\
&= \frac{1}{4w^2}
\end{aligned}
$$

## 2.22

(a) $-25$

(b) 1

(c) 0

## 2.26

$$
\begin{aligned}
F(k) &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \delta(x) e^{-ikx}\, dx \\
&= \frac{1}{\sqrt{2\pi}} \\
f(x) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{ikx}\, dk
\end{aligned}
$$

## 2.29

$$
\begin{aligned}
\psi(x) &= \begin{cases} Fe^{-\kappa x} & x > a \\ C\sin(lx) & 0 < x < a \\ -\psi(-x) & x < 0 \end{cases} \\
Fe^{-\kappa a} &= C\sin(la) \\
-\kappa F e^{-\kappa a} &= lC\cos(la) \\
-\frac{1}{\kappa} &= \frac{1}{l}\tan(la) \\
\tan z &= -\frac{l}{\kappa} \\
&= -\frac{la}{\kappa a} \\
&= -\frac{z}{\sqrt{z_0^2 - z^2}}
\end{aligned}
$$

For large $z_0$ the intersections occur just below $z_n = n\pi$ so

$$
\begin{aligned}
z &= la \\
n\pi &\approx \frac{\sqrt{2m(E+V_0)}}{\hbar} a \\
E + V_0 &\approx \frac{n^2\pi^2\hbar^2}{2ma^2}.
\end{aligned}
$$

As $z_0$ decreases there are fewer and fewer bound states. When $z_0 < \pi/2$ there are no odd bound states.

## 2.30

$$
\begin{aligned}
\psi(x) &= \begin{cases} Fe^{-\kappa x} & x > a \\ D\cos(lx) & 0 < x < a \\ \psi(-x) & x < 0 \end{cases} \\
1 &= \int_{-\infty}^{\infty} |\psi|^2 \, dx \\
&= 2\left(|D|^2 \int_0^a \cos^2(lx)\, dx + |F|^2 \int_a^\infty e^{-2\kappa x}\, dx\right) \\
&= 2\left[|D|^2 \frac{2al + \sin(2al)}{4l} + \frac{|F|^2}{2\kappa} e^{-2\kappa a}\right] \\
&= |D|^2 \left[a + \frac{\sin(2al)}{2l} + \frac{\cos^2(al)}{\kappa}\right] \\
&= |D|^2 \left[a + \frac{2\sin(al)\cos(al)}{2l} + \frac{\cos^3(al)}{l\sin(al)}\right] \\
&= |D|^2 \left\{a + \frac{\cos(al)}{l\sin(al)}[\sin^2(al) + \cos^2(al)]\right\} \\
&= |D|^2 \left[a + \frac{\cos(al)}{l\sin(al)}\right] \\
&= |D|^2 \left[a + \frac{1}{l\tan(al)}\right] \\
&= |D|^2 \left[a + \frac{1}{\kappa}\right] \\
D &= \frac{1}{\sqrt{a + 1/\kappa}}
\end{aligned}
$$

$$
\begin{aligned}
1 &= \left\{\frac{1}{a + 1/\kappa}\left[a + \frac{\sin(2al)}{2l}\right] + |F|^2 \frac{e^{-2\kappa a}}{\kappa}\right\} \\
\frac{(Fe^{-\kappa a})^2}{\kappa} &= 1 - \frac{1}{a + 1/\kappa}\left[a + \frac{\sin(2al)}{2l}\right] \\
(Fe^{-\kappa a})^2 &= \kappa - \frac{\kappa}{a + 1/\kappa}\left[a + \frac{\sin(2al)}{2l}\right] \\
&= \frac{\kappa a + 1 - \kappa a - \kappa\sin(al)\cos(al)/l}{a + 1/\kappa} \\
&= \frac{1 - \sin^2(al)}{a + 1/\kappa} \\
F &= \frac{e^{\kappa a}\cos(al)}{\sqrt{a + 1/\kappa}}
\end{aligned}
$$

## 2.31

$$
\begin{aligned}
1 &= 2aV_0 \\
V_0 &= \frac{1}{2a} \\
z_0 &= \frac{a}{\hbar}\sqrt{2mV_0} \\
&= \frac{a}{\hbar}\sqrt{\frac{m}{a}} \\
&= \frac{\sqrt{am}}{\hbar} \\
\lim_{a\to 0} z_0 &= 0
\end{aligned}
$$

## 2.34

(a)

$$
\begin{aligned}
V(x) &= \begin{cases} 0 & x \le 0 \\ V_0 & x > 0 \end{cases} \\
-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} &= E\psi \\
\frac{d^2\psi}{dx^2} &= -\frac{2mE}{\hbar^2}\psi \\
&= -k^2\psi \\
k &= \frac{\sqrt{2mE}}{\hbar} \\
\psi &= Ae^{ikx} + Be^{-ikx} \\
-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} + V_0\psi &= E\psi \\
\frac{d^2\psi}{dx^2} &= -\frac{2m(E-V_0)}{\hbar^2}\psi \\
&= \kappa^2\psi \\
\kappa &= \frac{\sqrt{2m(V_0-E)}}{\hbar} \\
\psi &= Fe^{-\kappa x} \\
A + B &= F \\
ik(A-B) &= -\kappa F \\
F &= -i\frac{k}{\kappa}(A-B) \\
A + B &= -i\frac{k}{\kappa}(A-B) \\
\left(1 - i\frac{k}{\kappa}\right) B &= -\left(1 + i\frac{k}{\kappa}\right) A \\
B &= -\frac{1+ik/\kappa}{1-ik/\kappa}A \\
R &= \frac{|B|^2}{|A|^2} \\
&= \left(-\frac{1+ik/\kappa}{1-ik/\kappa}\right)\left(-\frac{1-ik/\kappa}{1+ik/\kappa}\right) \\
&= 1
\end{aligned}
$$

(b)

$$
\begin{aligned}
\psi(x) &= \begin{cases} Ae^{ikx} + Be^{-ikx} & x < 0 \\ Fe^{ilx} & x > 0 \end{cases} \\
k &= \frac{\sqrt{2mE}}{\hbar} \\
l &= \frac{\sqrt{2m(E - V_0)}}{\hbar} \\
A + B &= F \\
ik(A - B) &= ilF \\
F &= \frac{k}{l}(A - B) \\
A + B &= \frac{k}{l}(A - B) \\
\left(\frac{k}{l} + 1\right) B &= \left(\frac{k}{l} - 1\right) A \\
B &= \frac{k/l - 1}{k/l + 1} A \\
R &= \frac{|B|^2}{|A|^2} \\
&= \left(\frac{k/l - 1}{k/l + 1}\right)^2 \\
&= \left(\frac{k - l}{k + l}\right)^2 \\
&= \frac{(k - l)^4}{(k^2 - l^2)^2} \\
k^2 - l^2 &= \frac{2mE}{\hbar^2} - \frac{2m(E - V_0)}{\hbar^2} \\
&= \frac{2m}{\hbar^2} V_0 \\
k - l &= \frac{\sqrt{2m}}{\hbar}(\sqrt{E} - \sqrt{E - V_0}) \\
R &= \frac{(\sqrt{E} - \sqrt{E - V_0})^4}{V_0^2}
\end{aligned}
$$

(d)

$$
\begin{aligned}
B &= F - A \\
F &= \frac{k}{l}(A - F + A) \\
\left(1 + \frac{k}{l}\right) F &= \frac{2k}{l} A \\
F &= \frac{2k}{k+l} A \\
\frac{l}{k} &= \sqrt{\frac{E - V_0}{E}} \\
T &= \left|\frac{F}{A}\right|^2 \frac{l}{k} \\
&= \left(\frac{2k}{k+l}\right)^2 \frac{l}{k} \\
&= \frac{4kl}{(k+l)^2} \\
&= \frac{4kl(k-l)^2}{(k^2-l^2)^2} \\
&= \frac{4\sqrt{E}\sqrt{E-V_0}(\sqrt{E}-\sqrt{E-V_0})^2}{V_0^2} \\
T + R &= \frac{4kl}{(k+l)^2} + \frac{(k-l)^2}{(k+l)^2} \\
&= \frac{4kl + k^2 - 2kl + l^2}{(k+l)^2} \\
&= \frac{k^2 + 2kl + l^2}{(k+l)^2} \\
&= \frac{(k+l)^2}{(k+l)^2} \\
&= 1
\end{aligned}
$$

### 2.35

(a)

$$
\begin{aligned}
V(x) &= \begin{cases} 0 & x < 0 \\ -V_0 & x > 0 \end{cases} \\
-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} &= E\psi \\
\frac{d^2\psi}{dx^2} &= -\frac{2mE}{\hbar^2}\psi \\
&= -k^2\psi \\
k &= \frac{\sqrt{2mE}}{\hbar} \\
\psi &= Ae^{ikx} + Be^{-ikx} \\
-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} - V_0\psi &= E\psi \\
\frac{d^2\psi}{dx^2} &= -\frac{2m}{\hbar^2}(E+V_0)\psi \\
&= -l^2\psi \\
l &= \frac{\sqrt{2m(E+V_0)}}{\hbar} \\
\psi &= Fe^{ilx} \\
A + B &= F \\
ik(A-B) &= ilF \\
k(A-B) &= l(A+B) \\
(k+l)B &= (k-l)A \\
B &= \frac{k-l}{k+l}A \\
R &= \left|\frac{B}{A}\right|^2 \\
&= \left(\frac{k-l}{k+l}\right)^2 \\
&= \left(\frac{\sqrt{E}-\sqrt{E+V_0}}{\sqrt{E}+\sqrt{E+V_0}}\right)^2 \\
&= \frac{1}{9}
\end{aligned}
$$

(c)

$$
T = 1 - R = \frac{8}{9}
$$

## 2.36

$$
\begin{aligned}
V(x) &= \begin{cases} 0 & |x| < a \\ \infty & |x| > a \end{cases} \\
-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} &= E\psi \\
\frac{d^2\psi}{dx^2} &= -\frac{2mE}{\hbar^2}\psi \\
&= -k^2\psi \\
k &= \frac{\sqrt{2mE}}{\hbar} \\
\psi &= A\sin kx + B\cos kx \\
0 &= -A\sin ka + B\cos ka \\
0 &= A\sin ka + B\cos ka \\
B\cos ka &= 0 \\
k &= \frac{n\pi}{2a},\; n = 1, 3, 5, \ldots \\
E &= \frac{n^2\pi^2\hbar^2}{2m(2a)^2} \\
\psi &= B\cos\left(\frac{n\pi}{2a}x\right),\; n = 1, 3, 5, \ldots \\
1 &= |B|^2 \int_{-a}^{a} \cos^2\left(\frac{n\pi}{2a}x\right)\, dx \\
B &= \frac{1}{\sqrt{a}} \\
\psi &= \frac{1}{\sqrt{a}}\cos\left(\frac{n\pi}{2a}x\right),\; n = 1, 3, 5, \ldots \\
A\sin ka &= 0 \\
k &= \frac{n\pi}{2a},\; n = 2, 4, 6, \ldots \\
E &= \frac{n^2\pi^2\hbar^2}{2m(2a)^2} \\
\psi &= A\sin\left(\frac{n\pi}{2a}x\right),\; n = 2, 4, 6, \ldots \\
1 &= |A| \int_{-a}^{a} \sin^2\left(\frac{n\pi}{2a}x\right)\, dx \\
A &= \frac{1}{\sqrt{a}} \\
\psi &= \frac{1}{\sqrt{a}}\sin\left(\frac{n\pi}{2a}x\right),\; n = 2, 4, 6, \ldots
\end{aligned}
$$

## 2.37

$$
\begin{aligned}
\Psi(x,0) &= A\sin^3\left(\frac{\pi}{a}x\right) \\
&= A\left[\frac{3}{4}\sin\left(\frac{\pi}{a}x\right) - \frac{1}{4}\sin\left(\frac{3\pi}{a}x\right)\right] \\
&= A\sqrt{\frac{a}{2}}\left[\frac{3}{4}\psi_1(x) - \frac{1}{4}\psi_3(x)\right] \\
1 &= |A|^2\frac{a}{2}\int_0^a \left[\frac{3}{4}\psi_1(x) - \frac{1}{4}\psi_3(x)\right]^2 \, dx \\
&= |A|^2\frac{a}{2}\int_0^a \left[\frac{9}{16}\psi_1(x)^2 - \frac{3}{8}\psi_1(x)\psi_3(x) + \frac{1}{16}\psi_3(x)^2\right] dx \\
&= \frac{5}{16}a|A|^2 \\
A &= \frac{4}{\sqrt{5a}} \\
\Psi(x,0) &= \frac{1}{\sqrt{10}}[3\psi_1(x) - \psi_3(x)] \\
\Psi(x,t) &= \frac{1}{\sqrt{10}}[3\psi_1(x)e^{-iE_1t/\hbar} - \psi_3(x)e^{-iE_3t/\hbar}] \\
\langle x\rangle &= \int_0^a \Psi^* x\Psi \, dx \\
&= \frac{1}{10}\int_0^a x\left(9\psi_1^2 + \psi_3^2 - 3\psi_1\psi_3 e^{-i(E_3-E_1)t/\hbar} - 3\psi_1\psi_3 e^{-i(E_1-E_3)t/\hbar}\right) dx \\
&= \frac{1}{10}\int_0^a x\left[9\psi_1^2 + \psi_3^2 - 6\psi_1\psi_3\cos\left(\frac{E_3-E_1}{\hbar}t\right)\right] dx \\
&= \frac{1}{10}\left[9\left\langle x\right\rangle_1 + \left\langle x\right\rangle_3 - 6\cos\left(\frac{E_3-E_1}{\hbar}t\right)\int_0^a x\psi_1\psi_3 \, dx\right] \\
&= \frac{1}{10}\left[\frac{9}{2}a + \frac{1}{2}a\right] \\
&= \frac{a}{2} \\
P(E_1) &= \frac{9}{10} \\
P(E_3) &= \frac{1}{10} \\
\langle E\rangle &= E_1P(E_1) + E_3P(E_3) \\
&= \frac{9\pi^2\hbar^2}{20ma^2} + \frac{9\pi^2\hbar^2}{20ma^2} \\
&= \frac{9\pi^2\hbar^2}{10ma^2}
\end{aligned}
$$

**2.38**

(a)

$$\begin{aligned}
\Psi(x,t) &= \sum_{n=1}^{\infty} c_n \psi_n(x) e^{-iE_n t/\hbar} \\
\Psi(x,0) &= \sum_{n=1}^{\infty} c_n \psi_n(x) \\
E_n T &= \frac{n^2\pi^2\hbar^2}{2ma^2}\frac{4ma^2}{\pi\hbar} \\
&= 2\pi n^2 \hbar \\
\Psi(x,T) &= \sum_{n=1}^{\infty} c_n \psi_n(x) e^{-iE_n T/\hbar} \\
&= \sum_{n=1}^{\infty} c_n \psi_n(x) e^{-2\pi i n^2} \\
&= \sum_{n=1}^{\infty} c_n \psi_n(x) \\
&= \Psi(x,0)
\end{aligned}$$

(b)

$$\begin{aligned}
E &= \frac{1}{2}mv^2 \\
v &= \sqrt{\frac{2E}{m}} \\
T &= \frac{2a}{v} \\
&= a\sqrt{\frac{2m}{E}}
\end{aligned}$$

(c)

$$\begin{aligned}
\frac{4ma^2}{\pi\hbar} &= a\sqrt{\frac{2m}{E}} \\
\frac{16m^2a^2}{\pi^2\hbar^2} &= \frac{2m}{E} \\
E &= \frac{\pi^2\hbar^2}{8ma^2} \\
&= \frac{E_1}{4}
\end{aligned}$$

## 2.39

(a)

$$\Psi(x,0) = \begin{cases} \frac{2\sqrt{3}}{a\sqrt{a}}x & 0 \le x \le a/2 \\ \frac{2\sqrt{3}}{a\sqrt{a}}(a-x) & a/2 \le x \le a \end{cases}$$

$$\frac{d}{dx}\Psi(x,0) = \frac{2\sqrt{3}}{a\sqrt{a}}\left[1 - 2\theta\left(x - \frac{a}{2}\right)\right]$$

(b)

$$\frac{d^2}{dx^2}\Psi(x,0) = -\frac{4\sqrt{3}}{a\sqrt{a}}\delta\left(x - \frac{a}{2}\right)$$

(c)

$$\begin{aligned}
\hat{H}\Psi(x,0) &= \left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V(x)\right]\Psi(x,0) \\
&= \frac{\hbar^2}{2m}\frac{4\sqrt{3}}{a\sqrt{a}}\delta\left(x - \frac{a}{2}\right) + V(x)\Psi(x,0) \\
\langle H\rangle &= \int \Psi(x,0)^* \hat{H}\Psi(x,0)\,dx \\
&= \int_0^a \Psi(x,0)^* \left[\frac{\hbar^2}{2m}\frac{4\sqrt{3}}{a\sqrt{a}}\delta\left(x - \frac{a}{2}\right) + V(x)\Psi(x,0)\right] dx \\
&= \Psi\left(\frac{a}{2},0\right)^* \frac{\hbar^2}{2m}\frac{4\sqrt{3}}{a\sqrt{a}} + \int_0^a \Psi(x,0)^* V(x)\Psi(x,0)\,dx \\
&= \frac{6\hbar^2}{ma^2}
\end{aligned}$$

## 2.40

(a)

$$
\begin{aligned}
V(x) &= \frac{1}{2}m\omega^2x^2 \\
\xi &= \sqrt{\frac{m\omega}{\hbar}}x \\
\psi_n(x) &= \left(\frac{m\omega}{\pi\hbar}\right)^{1/4}\frac{1}{\sqrt{2^n n!}}H_n(\xi)e^{-\xi^2/2} \\
\Psi(x,0) &= A\left(1-2\sqrt{\frac{m\omega}{\hbar}}x\right)^2 e^{-\frac{m\omega}{2\hbar}x^2} \\
&= A\left(1-4\sqrt{\frac{m\omega}{\hbar}}x+\frac{4m\omega}{\hbar}x^2\right)e^{-\frac{m\omega}{2\hbar}x^2} \\
&= A\left(\frac{\pi\hbar}{m\omega}\right)^{1/4}\left[3\psi_0(x)-2\sqrt{2}\psi_1(x)+2\sqrt{2}\psi_2(x)\right] \\
1 &= A^2\sqrt{\frac{\pi\hbar}{m\omega}}\int_{-\infty}^{\infty}(3\psi_0-2\sqrt{2}\psi_1+2\sqrt{2}\psi_2)^2\,dx \\
&= A^2\sqrt{\frac{\pi\hbar}{m\omega}}\int_{-\infty}^{\infty}(9\psi_0^2-12\sqrt{2}\psi_0\psi_1+12\sqrt{2}\psi_0\psi_2+8\psi_1^2-16\psi_1\psi_2+8\psi_2^2)\,dx \\
&= 25A^2\sqrt{\frac{\pi\hbar}{m\omega}} \\
A &= \frac{1}{5}\left(\frac{m\omega}{\pi\hbar}\right)^{1/4} \\
\Psi(x,0) &= \frac{3}{5}\psi_0(x)-\frac{2\sqrt{2}}{5}\psi_1(x)+\frac{2\sqrt{2}}{5}\psi_2(x)
\end{aligned}
$$

(b)

$$
\begin{aligned}
E_0 &= \frac{\hbar\omega}{2} \\
P(E_0) &= \frac{9}{25} \\
E_1 &= \frac{3\hbar\omega}{2} \\
P(E_1) &= \frac{8}{25} \\
E_2 &= \frac{5\hbar\omega}{2} \\
P(E_2) &= \frac{8}{25} \\
\langle E \rangle &= \frac{\hbar\omega}{2}\frac{9}{25} + \frac{3\hbar\omega}{2}\frac{8}{25} + \frac{5\hbar\omega}{2}\frac{8}{25} \\
&= \frac{73}{50}\hbar\omega
\end{aligned}
$$

(c)

$$\begin{aligned}
\xi &= \sqrt{\frac{m\omega}{\hbar}}x \\
\psi_n(x) &= \left(\frac{m\omega}{\pi\hbar}\right)^{1/4} \frac{1}{\sqrt{2^n n!}} H_n(\xi) e^{-\xi^2/2} \\
\Psi(x,T) &= B\left(1 + 2\sqrt{\frac{m\omega}{\hbar}}x\right)^2 e^{-\frac{m\omega}{2\hbar}x^2} \\
&= B\left(1 + 4\sqrt{\frac{m\omega}{\hbar}}x + 4\frac{m\omega}{\hbar}x^2\right) e^{-\frac{m\omega}{2\hbar}x^2} \\
&= B\left(\frac{\pi\hbar}{m\omega}\right)^{1/4}\left[3\psi_0(x) + 2\sqrt{2}\psi_1(x) + 2\sqrt{2}\psi_2(x)\right] \\
1 &= |B|^2\sqrt{\frac{\pi\hbar}{m\omega}}\int_{-\infty}^{\infty}[3\psi_0 + 2\sqrt{2}\psi_1 + 2\sqrt{2}\psi_2]^2\,dx \\
&= |B|^2\sqrt{\frac{\pi\hbar}{m\omega}}\int_{-\infty}^{\infty}[9\psi_0^2 + 12\sqrt{2}\psi_0\psi_1 + 12\sqrt{2}\psi_0\psi_2 + 8\psi_1^2 + 16\psi_1\psi_2 + 8\psi_2^2]\,dx \\
&= 25|B|^2\sqrt{\frac{\pi\hbar}{m\omega}} \\
B &= \frac{1}{5}\left(\frac{m\omega}{\pi\hbar}\right)^{1/4} \\
\Psi(x,T) &= \frac{3}{5}\psi_0(x) + \frac{2\sqrt{2}}{5}\psi_1(x) + \frac{2\sqrt{2}}{5}\psi_2(x) \\
\Psi(x,t) &= \frac{3}{5}\psi_0(x)e^{-i\omega t/2} - \frac{2\sqrt{2}}{5}\psi_1(x)e^{-3i\omega t/2} + \frac{2\sqrt{2}}{5}\psi_2(x)e^{-5i\omega t/2} \\
&= e^{-i\omega t/2}\left[\frac{3}{5}\psi_0(x) - \frac{2\sqrt{2}}{5}\psi_1(x)e^{-i\omega t} + \frac{2\sqrt{2}}{5}e^{-2i\omega t}\right] \\
e^{-i\omega T} &= -1 \\
e^{-2i\omega T} &= 1 \\
T &= \frac{\pi}{\omega}
\end{aligned}$$

## 2.41

The argument for calculating the allowed energies and wavefunctions is the same, except there is a boundary condition $\psi(0) = 0$. This leaves only $\psi_n(x)$ for odd $n$.

## 2.43

$$
\begin{aligned}
k &= \frac{\sqrt{2mE}}{\hbar} \\
\psi(x) &= \begin{cases} -A\sin kx + B\cos kx & -a < x \leq 0 \\ A\sin kx + B\cos kx & 0 \leq x < a \end{cases} \\
\Delta\left(\frac{d\psi}{dx}\right) &= 2Ak \\
\Delta\left(\frac{d\psi}{dx}\right) &= \frac{2m\alpha}{\hbar^2}\psi(0) \\
2Ak &= \frac{2m\alpha}{\hbar^2}B \\
B &= \frac{\hbar^2 k}{m\alpha}A \\
\psi(x) &= A\left(\sin kx + \frac{\hbar^2 k}{m\alpha}\cos kx\right) \\
0 &= A\sin ka + \frac{\hbar^2 k}{m\alpha}A\cos ka \\
\tan ka &= -\frac{\hbar^2 k}{m\alpha} \\
ka &\approx \frac{n\pi}{2},\, n = 1, 3, 5, \ldots \\
E &\approx \frac{n^2\pi^2\hbar^2}{2m(2a)^2},\, n = 1, 3, 5, \ldots \\
\psi(x) &= \begin{cases} A\sin kx - B\cos kx & -a < x \leq 0 \\ A\sin kx + B\cos kx & 0 \leq x < a \end{cases} \\
-B &= B \\
B &= 0 \\
\psi(x) &= A\sin kx \\
0 &= A\sin ka \\
ka &= \frac{n\pi}{2},\, n = 2, 4, 6, \ldots \\
\psi(x) &= A\sin\left(\frac{n\pi}{2a}x\right) \\
E &= \frac{n^2\pi^2\hbar^2}{2m(2a)^2},\, n = 2, 4, 6, \ldots
\end{aligned}
$$

## 2.44

$$
\begin{aligned}
-\frac{\hbar^2}{2m}\frac{d^2\psi_1}{dx^2}\psi_2 + V\psi_1\psi_2 &= E\psi_1\psi_2 \\
-\frac{\hbar^2}{2m}\frac{d^2\psi_2}{dx^2}\psi_1 + V\psi_1\psi_2 &= E\psi_1\psi_2 \\
\psi_2\frac{d^2\psi_1}{dx^2} - \psi_1\frac{d^2\psi_2}{dx^2} &= 0 \\
\frac{d}{dx}\left(\psi_2\frac{d\psi_1}{dx} - \psi_1\frac{d\psi_2}{dx}\right) &= 0 \\
\psi_2\frac{d\psi_1}{dx} - \psi_1\frac{d\psi_2}{dx} &= c \\
c &= 0 \\
\psi_2\frac{d\psi_1}{dx} &= \psi_1\frac{d\psi_2}{dx} \\
\frac{1}{\psi_1}\frac{d\psi_1}{dx} &= \frac{1}{\psi_2}\frac{d\psi_2}{dx} \\
\ln\psi_1 &= \ln\psi_2 + c \\
\psi_1 &= A\psi_2
\end{aligned}
$$

## 2.45

(a)

$$
\begin{aligned}
-\frac{\hbar^2}{2m}\frac{d^2\psi_n}{dx^2}\psi_m + V(x)\psi_n\psi_m &= E_n\psi_n\psi_m \\
-\frac{\hbar^2}{2m}\frac{d^2\psi_m}{dx^2}\psi_n + V(x)\psi_n\psi_m &= E_m\psi_n\psi_m \\
\frac{d^2\psi_m}{dx^2}\psi_n - \frac{d^2\psi_n}{dx^2}\psi_m &= \frac{2m}{\hbar^2}(E_n - E_m)\psi_n\psi_m \\
\frac{d}{dx}\left(\frac{d\psi_m}{dx}\psi_n - \frac{d\psi_n}{dx}\psi_m\right) &= \frac{2m}{\hbar^2}(E_n - E_m)\psi_n\psi_m
\end{aligned}
$$

(b)

$$
\begin{aligned}
\int_{x_1}^{x_2}\frac{d}{dx}(\psi_m'\psi_n - \psi_n'\psi_m)\,dx &= \frac{2m}{\hbar^2}(E_n - E_m)\int_{x_1}^{x_2}\psi_n\psi_m\,dx \\
\psi_m'(x_2)\psi_n(x_2) - \psi_m'(x_1)\psi_n(x_1) &= \frac{2m}{\hbar^2}(E_n - E_m)\int_{x_1}^{x_2}\psi_n\psi_m\,dx
\end{aligned}
$$

## 2.53

(a)

$$
\frac{1}{1-i\beta}\begin{pmatrix} i\beta & 1 \\ 1 & i\beta \end{pmatrix}
$$

(b)

$$\frac{e^{-2ika}}{\cos(2la) - i\frac{(k^2+l^2)}{2kl}\sin(2la)} \begin{pmatrix} i\frac{\sin(2la)}{2kl}(l^2-k^2) & 1 \\ 1 & i\frac{\sin(2la)}{2kl}(l^2-k^2) \end{pmatrix}$$

# 3 Formalism

## 3.1

(a)

$$\begin{aligned}
\left|\int_a^b (f^* + g^*)(f+g)\,dx\right| &= \left|\int_a^b (f^*f + f^*g + g^*f + g^*g)\,dx\right| \\
&\leq \int_a^b |f|^2\,dx + \left|\int_a^b f^*g\,dx\right| + \left|\int_a^b g^*f\,dx\right| + \int_a^b |g|^2\,dx \\
&\leq \int_a^b |f|^2\,dx + 2\sqrt{\int_a^b |f|^2\,dx \int_a^b |g|^2\,dx} + \int_a^b |g|^2\,dx
\end{aligned}$$

The set of all normalised functions isn't a vector space because e.g. multiplying a function by a constant also multiplies its integral by that constant meaning it's no longer a member of the vector space.

(b)

$$\begin{aligned}
\langle\beta|\alpha\rangle &= \int_a^b \beta^*\alpha\,dx \\
&= \left(\int_a^b \alpha^*\beta\,dx\right)^* \\
&= \langle\alpha|\beta\rangle^* \\
\langle a|a\rangle &= \int_a^b |a|^2\,dx \\
&\geq 0
\end{aligned}$$

If $\langle\alpha|\alpha\rangle = 0$ that implies $|\alpha|^2 = 0$ everywhere in the interval and thus $|\alpha\rangle = |0\rangle$.

$$\begin{aligned}
\langle\alpha|\left(b\,|\beta\rangle + c\,|\gamma\rangle\right) &= \int_{x_1}^{x_2} \alpha^*(b\beta)\,dx + \int_{x_1}^{x_2} \alpha^*(c\gamma)\,dx \\
&= b\int_{x_1}^{x_2} \alpha^*\beta\,dx + c\int_{x_1}^{x_2} \alpha^*\gamma\,dx \\
&= b\,\langle\alpha|\beta\rangle + c\,\langle\alpha|\gamma\rangle
\end{aligned}$$

## 3.2

(a)

$$\int_0^1 x^{2\nu}\,dx = \frac{1}{2\nu+1}\left[x^{2\nu+1}\right]_0^1$$

The integral is defined for $\nu > -1/2$. For the case $\nu = -1/2$

$$\int_0^1 x^{-1}\,dx = [\ln x]_0^1 = \ln 1 - \ln 0 = 0 - \infty.$$

So $f(x) = x^\nu$ is in Hilbert space for $\nu > -1/2$.

(b)

$$\begin{aligned}\int_0^1 x\,dx &= \frac{1}{2}\\ \int_0^1 x^3\,dx &= \frac{1}{4}\\ \int_0^1 x^{-1}\,dx &= [\ln x]_0^1\\ &= 0 - \infty\end{aligned}$$

$f(x)$ and $xf(x)$ are in Hilbert space, but not $(d/dx)f(x)$.

## 3.4

(a)

$$\begin{aligned}\langle f|(\hat{Q}+\hat{R})f\rangle &= \langle f|\hat{Q}f\rangle + \langle f|\hat{R}f\rangle\\ &= \langle \hat{Q}f|f\rangle + \langle \hat{R}f|f\rangle\\ &= \langle (\hat{Q}+\hat{R})f|f\rangle\end{aligned}$$

(b)

$$\begin{aligned}\langle f|\alpha\hat{Q}g\rangle &= \alpha\,\langle f|\hat{Q}g\rangle\\ &= \alpha\,\langle \hat{Q}f|g\rangle\\ \langle \alpha\hat{Q}f|g\rangle &= \alpha^*\,\langle \hat{Q}f|g\rangle\\ \alpha &= \alpha^*\end{aligned}$$

$\alpha$ is real.

(c)

$$\begin{aligned}\langle f|\hat{Q}\hat{R}g\rangle &= \langle \hat{Q}f|\hat{R}g\rangle \\ &= \langle \hat{R}\hat{Q}f|g\rangle\end{aligned}$$

The product of the operators is hermitian when $\hat{Q}\hat{R} = \hat{R}\hat{Q}$ i.e. $[\hat{Q}, \hat{R}] = 0$.

(d)

$$\begin{aligned}\langle \Psi|\hat{x}\Psi\rangle &= \int \Psi^* \hat{x}\Psi \, dx \\ &= \int \Psi^* \hat{x}^* \Psi \, dx \\ &= \int (\hat{x}\Psi)^* \Psi \, dx \\ &= \langle \hat{x}\Psi|\Psi\rangle \\ \langle \Psi|\hat{H}\Psi\rangle &= \int \Psi^* \hat{H}\Psi \, dx \\ &= \int \Psi^* \left[-\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + V(x)\right] \Psi \, dx \\ &= -\frac{\hbar^2}{2m} \int \Psi^* \frac{d^2\Psi}{dx^2} \, dx + \int \Psi^* V(x)\Psi \, dx \\ &= -\frac{\hbar^2}{2m} \left[ \Psi^* \frac{d\Psi}{dx}\bigg|_{-\infty}^{\infty} - \int \frac{d\Psi^*}{dx}\frac{d\Psi}{dx} \, dx \right] + \langle V(x)\Psi|\Psi\rangle \\ &= \frac{\hbar^2}{2m} \left[ \frac{d\Psi^*}{dx}\Psi\bigg|_{-\infty}^{\infty} - \int \frac{d^2\Psi^*}{dx}\Psi \, dx \right] + \langle V(x)\Psi|\Psi\rangle \\ &= -\frac{\hbar^2}{2m} \int \frac{d^2}{dx^2}\Psi^*\Psi \, dx + \langle V(x)\Psi|\Psi\rangle \\ &= \left\langle -\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\Psi \,\middle|\, \Psi \right\rangle + \langle V(x)\Psi|\Psi\rangle \\ &= \langle \hat{H}\Psi|\Psi\rangle\end{aligned}$$

## 3.5

(a)

$$\begin{aligned}x^\dagger &= x \\ i^\dagger &= -i \\ \left(\frac{d}{dx}\right)^\dagger &= -\frac{d}{dx}\end{aligned}$$

(b)

$$\begin{aligned}
\langle f|\hat{Q}\hat{R}g\rangle &= \int f^\dagger \hat{Q}\hat{R}g\,dx \\
&= \int (\hat{Q}^\dagger f)^\dagger \hat{R}g\,dx \\
&= \int (\hat{R}^\dagger \hat{Q}^\dagger f)^\dagger g\,dx \\
&= \langle \hat{R}^\dagger \hat{Q}^\dagger f|g\rangle
\end{aligned}$$

(c)

$$\begin{aligned}
\hat{a}_+ &= \frac{1}{\sqrt{2\hbar m\omega}}(-i\hat{p}+m\omega x) \\
\langle f|\hat{a}g\rangle &= \left\langle f \,\middle|\, \frac{1}{\sqrt{2\hbar m\omega}}(-i\hat{p}+m\omega x)g \right\rangle \\
&= \frac{1}{\sqrt{2\hbar m\omega}}\,\langle f|(-i\hat{p}+m\omega x)g\rangle \\
&= \frac{1}{\sqrt{2\hbar m\omega}}(\langle f|-i\hat{p}g\rangle + \langle f|m\omega x g\rangle) \\
&= \frac{1}{\sqrt{2\hbar m\omega}}(\langle f|-i\hat{p}g\rangle + \langle m\omega x f|g\rangle) \\
&= \frac{1}{\sqrt{2\hbar m\omega}}(\langle i\hat{p}f|g\rangle + \langle m\omega x f|g\rangle) \\
&= \left\langle \frac{1}{\sqrt{2\hbar m\omega}}(i\hat{p}+m\omega x)f \,\middle|\, g \right\rangle \\
&= \langle \hat{a}_- f|g\rangle
\end{aligned}$$

## 3.6

$$\begin{aligned}
\langle f|\hat{Q}g\rangle &= \int_0^{2\pi} f^* \frac{d^2 g}{d\phi^2}\,d\phi \\
&= f^* \frac{dg}{d\phi}\bigg|_0^{2\pi} - \int_0^{2\pi} \left(\frac{df}{d\phi}\right)^* \frac{dg}{d\phi}\,d\phi \\
&= -\left(\frac{df}{d\phi}\right)^* g\bigg|_0^{2\pi} + \int_0^{2\pi} \left(\frac{d^2 f}{d\phi}\right)^* g\,d\phi \\
&= \langle \hat{Q}f|g\rangle
\end{aligned}$$

Yes, the operator is hermitian.

$$
\begin{aligned}
\hat{Q}f &= qf \\
\frac{d^2 f}{d\phi^2} &= qf \\
\frac{d^2 f}{d\phi^2} - qf &= 0 \\
f &= Ae^{\sqrt{q}\phi} + Be^{-\sqrt{q}\phi} \\
f(\phi + 2\pi) &= Ae^{\sqrt{q}(\phi+2\pi)} + Be^{\sqrt{q}(\phi+2\pi)} \\
&= Ae^{\sqrt{q}\phi}e^{2\pi\sqrt{q}} + Be^{\sqrt{q}\phi}e^{2\pi\sqrt{q}} \\
2\pi\sqrt{q} &= 1 \\
q &= -n^2,\ n = 0, 1, 2, \ldots
\end{aligned}
$$

The eigenfunctions are $f = Ae^{\pm\sqrt{q}\phi}$ and the eigenvalues are $q = 0, 1, 2, \ldots$ The spectrum is degenerate as there are two eigenfunctions associated with each eigenvalue $q > 0$.

## 3.7

(a)

$$
\begin{aligned}
h &= af + bg \\
\hat{Q}h &= \hat{Q}(af + bg) \\
&= \hat{Q}(af) + \hat{Q}(bg) \\
&= a\hat{Q}f + b\hat{Q}g \\
&= aqf + bqg \\
&= q(af + bg) \\
&= qh
\end{aligned}
$$

(b)

$$
\begin{aligned}
\frac{d^2}{dx^2}e^x &= e^x \\
\frac{d^2}{dx^2}e^{-x} &= e^{-x} \\
f &= e^x + e^{-x} \\
g &= e^x - e^{-x}
\end{aligned}
$$

## 3.8

(a)

$$
\begin{aligned}
\hat{Q} &= i\frac{d}{d\phi} \\
\hat{Q}f &= qf \\
i\frac{df}{d\phi} &= qf \\
\frac{df}{d\phi} + iqf &= 0 \\
f &= Ae^{-iq\phi} \\
e^{-2\pi iq} &= 1 \\
q &= 0, \pm 1, \pm 2, \ldots \\
\int_0^{2\pi} Ae^{-iq\phi}Be^{-iq'\phi}\,d\phi &= AB\int_0^{2\pi} e^{-i(q+q')\phi}\,d\phi \\
&= 0
\end{aligned}
$$

(b)

$$
\begin{aligned}
\hat{Q} &= \frac{d^2}{d\phi^2} \\
\hat{Q}f &= qf \\
\frac{d^2f}{d\phi^2} - qf &= 0 \\
f &= Ae^{\pm\sqrt{q}\phi} \\
q &= -n^2,\ n = 0, 1, 2, \ldots \\
\int_0^{2\pi} Ae^{\pm\sqrt{q}\phi}Be^{\pm\sqrt{q'}\phi}\,d\phi &= AB\int_0^{2\pi} e^{\pm in\phi}e^{\pm in'\phi}\,d\phi \\
&= AB\int_0^{2\pi} e^{i(\pm n \pm n')\phi}\,d\phi \\
&= AB\left[\frac{1}{i(\pm n \pm n')}e^{i(\pm n \pm n')\phi}\right]_0^{2\pi} \\
&= AB\frac{1}{i(\pm n \pm n')}[e^{i(\pm n \pm n')2\pi} - 1] \\
&= 0
\end{aligned}
$$

## 3.9

(a) Infinite square well

(b) Delta function barrier

(c) Delta function well

## 3.11

$$\begin{aligned}
\Psi_0(x,t) &= \left(\frac{m\omega}{\pi\hbar}\right)^{1/4} e^{-m\omega x^2/2\hbar} e^{-i\omega t/2} \\
\Phi_0(p,t) &= \frac{1}{\sqrt{2\pi\hbar}} \int_{-\infty}^{\infty} e^{-ipx/\hbar} \left(\frac{m\omega}{\pi\hbar}\right)^{1/4} e^{-m\omega x^2/2\hbar} e^{-i\omega t/2}\, dx \\
&= \frac{1}{\sqrt{2\pi\hbar}} \left(\frac{m\omega}{\pi\hbar}\right)^{1/4} e^{-i\omega t/2} \int_{-\infty}^{\infty} e^{-ipx/\hbar} e^{-m\omega x^2/2\hbar}\, dx \\
&= \frac{1}{\sqrt{2\pi\hbar}} \left(\frac{m\omega}{\pi\hbar}\right)^{1/4} e^{-i\omega t/2} \sqrt{\frac{2\pi\hbar}{m\omega}} e^{-p^2/2\hbar m\omega} \\
&= \frac{1}{(\pi\hbar m\omega)^{1/4}} e^{-p^2/2\hbar m\omega} e^{-i\omega t/2} \\
\frac{p^2}{2m} &= \frac{\hbar\omega}{2} \\
p &= \pm\sqrt{\hbar m\omega} \\
1 - \int_{-\sqrt{\hbar m\omega}}^{\sqrt{\hbar m\omega}} |\Phi_0|^2\, dp &= 1 - \frac{1}{(\pi\hbar m\omega)^{1/4}} \int_{-\sqrt{\hbar m\omega}}^{\sqrt{\hbar m\omega}} e^{-p^2/\hbar m\omega}\, dp \\
&= 1 - \frac{1}{(\pi\hbar m\omega)^{1/2}} \sqrt{\pi\hbar m\omega}\, \mathrm{erf}\, 1 \\
&= 0.16
\end{aligned}$$

## 3.12

$$\begin{aligned}
\Psi(x,t) &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \phi(k) e^{i\left(kx - \frac{\hbar k^2}{2m} t\right)}\, dk \\
\Phi(p,t) &= \frac{1}{\sqrt{2\pi\hbar}} \int_{-\infty}^{\infty} e^{-ipx/\hbar} \left(\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \phi(k) e^{i\left(kx - \frac{\hbar k^2}{2m} t\right)}\, dk\right) dx \\
&= \frac{1}{2\pi\sqrt{\hbar}} \int_{-\infty}^{\infty} \phi(k) e^{-i\frac{\hbar k^2}{2m} t} \left(\int_{-\infty}^{\infty} e^{i(k-p/\hbar)x}\, dx\right) dk \\
&= \frac{1}{2\pi\sqrt{\hbar}} \int_{-\infty}^{\infty} \phi(k) e^{-i\frac{\hbar k^2}{2m} t} 2\pi\delta(k - p/\hbar)\, dk \\
&= \frac{1}{\sqrt{\hbar}} \int_{-\infty}^{\infty} \delta(k - p/\hbar)\phi(k) e^{-i\frac{\hbar k^2}{2m} t}\, dk \\
&= \frac{1}{\sqrt{\hbar}} \phi(p/\hbar) e^{-i\frac{p^2}{2\hbar m} t} \\
|\Phi(p,t)|^2 &= \frac{1}{\hbar} |\phi(p/\hbar)|^2
\end{aligned}$$

### 3.14

(a)

$$
\begin{aligned}
[\hat{A}+\hat{B},\hat{C}] &= (\hat{A}+\hat{B})\hat{C}-\hat{C}(\hat{A}+\hat{B}) \\
&= \hat{A}\hat{C}+\hat{B}\hat{C}-\hat{C}\hat{A}-\hat{C}\hat{B} \\
&= \hat{A}\hat{C}-\hat{C}\hat{A}+\hat{B}\hat{C}-\hat{C}\hat{B} \\
&= [\hat{A},\hat{C}]+[\hat{B},\hat{C}] \\
\hat{A}[\hat{B},\hat{C}]+[\hat{A},\hat{C}]\hat{B} &= \hat{A}\hat{B}\hat{C}-\hat{A}\hat{C}\hat{B}+\hat{A}\hat{C}\hat{B}-\hat{C}\hat{A}\hat{B} \\
&= \hat{A}\hat{B}\hat{C}-\hat{C}\hat{A}\hat{B} \\
&= [\hat{A}\hat{B},\hat{C}]
\end{aligned}
$$

(b)

$$
\begin{aligned}
[x^n,\hat{p}] &= \left[x^n,-i\hbar\frac{d}{dx}\right] \\
&= x^n\left(-i\hbar\frac{d}{dx}\right)-\left(-i\hbar\frac{d}{dx}\right)x^n \\
&= x^n\left(-i\hbar\frac{d}{dx}\right)(1)+i\hbar n x^{n-1} \\
&= i\hbar n x^{n-1}
\end{aligned}
$$

(c)

$$
\begin{aligned}
[f(x),\hat{p}]g(x) &= f(x)\left(-i\hbar\frac{d}{dx}\right)g(x)-\left(-i\hbar\frac{d}{dx}\right)[f(x)g(x)] \\
&= -i\hbar f(x)\frac{dg}{dx}+i\hbar\left[\frac{df}{dx}g(x)+f(x)\frac{dg}{dx}\right] \\
&= i\hbar\frac{df}{dx}g(x) \\
[f(x),\hat{p}] &= i\hbar\frac{df}{dx}
\end{aligned}
$$

(d)

$$
\begin{aligned}
[\hat{H}, \hat{a}_-]g &= \hat{H}\hat{a}_- g - \hat{a}_-\hat{H}g \\
&= \hbar\omega\left(\hat{a}_-\hat{a}_+ - \frac{1}{2}\right)\hat{a}_- g - \hat{a}_-\hbar\omega\left(\hat{a}_-\hat{a}_+ - \frac{1}{2}\right)g \\
&= \hbar\omega\hat{a}_-\hat{a}_+\hat{a}_- g - \frac{1}{2}\hbar\omega\hat{a}_- g - \hbar\omega\hat{a}_-^2\hat{a}_+ g + \frac{1}{2}\hbar\omega\hat{a}_- g \\
&= \hbar\omega\hat{a}_-\hat{a}_+\hat{a}_- g - \hbar\omega\hat{a}_-^2\hat{a}_+ g \\
&= \hbar\omega\hat{a}_-(\hat{a}_+\hat{a}_- - \hat{a}_-\hat{a}_+)g \\
&= -\hbar\omega\hat{a}_- g \\
[\hat{H}, \hat{a}_-] &= -\hbar\omega\hat{a}_- \\
[\hat{H}, \hat{a}_+]g &= \hat{H}\hat{a}_+ g - \hat{a}_+\hat{H}g \\
&= \hbar\omega\left(\hat{a}_-\hat{a}_+ - \frac{1}{2}\right)\hat{a}_+ g - \hat{a}_+\hbar\omega\left(\hat{a}_-\hat{a}_+ - \frac{1}{2}\right)g \\
&= \hbar\omega\hat{a}_-\hat{a}_+^2 g - \frac{1}{2}\hbar\omega\hat{a}_+ g - \hbar\omega\hat{a}_+\hat{a}_-\hat{a}_+ g + \frac{1}{2}\hbar\omega\hat{a}_+ g \\
&= \hbar\omega\hat{a}_-\hat{a}_+^2 g - \hbar\omega\hat{a}_+\hat{a}_-\hat{a}_+ g \\
&= \hbar\omega(\hat{a}_-\hat{a}_+ - \hat{a}_+\hat{a}_-)\hat{a}_+ g \\
&= \hbar\omega\hat{a}_+ g \\
[\hat{H}, \hat{a}_+] &= \hbar\omega\hat{a}_+
\end{aligned}
$$

## 3.15

$$
\begin{aligned}
\left[x, \frac{p^2}{2m}+V\right] g &= x\left(\frac{p^2}{2m}+V\right) g-\left(\frac{p^2}{2m}+V\right) x g \\
&= x \frac{p^2}{2m} g+x V g-\frac{p^2}{2m} x g-V x g \\
&= \frac{1}{2m}\left(x p^2 g-p^2 x g\right) \\
&= \frac{1}{2m}\left[-\hbar^2 x \frac{d^2 g}{d x^2}+\hbar^2 \frac{d}{d x}\left(g+x \frac{d g}{d x}\right)\right] \\
&= \frac{1}{2m}\left[-\hbar^2 x \frac{d^2 g}{d x^2}+\hbar^2\left(\frac{d g}{d x}+\frac{d g}{d x}+x \frac{d^2 g}{d x^2}\right)\right] \\
&= \frac{\hbar^2}{m} \frac{d g}{d x} \\
\left[x, \frac{p^2}{2m}+V\right] &= \frac{\hbar^2}{m} \frac{d}{d x} \\
&= -\frac{\hbar}{i m}\langle p\rangle \\
\sigma_x^2 \sigma_H^2 &\geq\left(\frac{1}{2i}\left\langle\left[x, \frac{p^2}{2m}+V\right]\right\rangle\right)^2 \\
&= \frac{\hbar^2}{4m^2}|\langle p\rangle|^2 \\
\sigma_x \sigma_H &\geq \frac{\hbar}{2m}|\langle p\rangle|
\end{aligned}
$$

This doesn't tell us much because for stationary states $\sigma_H=0$ and $\langle p\rangle=0$ so this says $0 \geq 0$.

## 3.17

$$
\begin{aligned}
\left(-i \hbar \frac{d}{d x}-\langle p\rangle\right) \Psi &= i a(x-\langle x\rangle) \Psi \\
-i \hbar \frac{d \Psi}{d x}-\langle p\rangle \Psi &= i a(x-\langle x\rangle) \Psi \\
\frac{d \Psi}{d x}+\frac{\langle p\rangle+i a(x-\langle x\rangle)}{i \hbar} \Psi &= 0 \\
\frac{d \Psi}{d x}+\left[\frac{a}{\hbar}(x-\langle x\rangle)-i \frac{\langle p\rangle}{\hbar}\right] \Psi &= 0 \\
\frac{d \Psi}{d x}+\frac{a}{\hbar} x \Psi-\frac{a}{\hbar}\langle x\rangle \Psi-i \frac{\langle p\rangle}{\hbar} \Psi &= 0 \\
\Psi &= A e^{-a x^2 / 2 \hbar} e^{a\langle x\rangle x / \hbar} e^{i\langle p\rangle x / \hbar} \\
&= B e^{-a(x-\langle x\rangle)^2 / 2 \hbar} e^{i\langle p\rangle x / \hbar}
\end{aligned}
$$

### 3.18

(a)

$$\begin{aligned} Q &= 1 \\ \hat{Q} &= 1 \\ [\hat{H}, \hat{Q}] &= 0 \\ \frac{d}{dt}\langle Q \rangle &= 0 \end{aligned}$$

(b)

$$\begin{aligned} Q &= H \\ \hat{Q} &= \hat{H} \\ [\hat{H}, \hat{Q}] &= [\hat{H}, \hat{H}] \\ &= 0 \\ \frac{d}{dt}\langle H \rangle &= 0 \end{aligned}$$

(c)

$$\begin{aligned} Q &= x \\ \hat{Q} &= x \\ [\hat{H}, \hat{Q}] &= [\hat{H}, x] \\ &= -i\frac{\hbar}{m}\hat{p} \\ \frac{d}{dt}\langle x \rangle &= \frac{i}{\hbar}\left\langle -i\frac{\hbar}{m}p \right\rangle \\ &= \frac{\langle p \rangle}{m} \end{aligned}$$

(d)

$$\begin{aligned} Q &= p \\ \hat{Q} &= \hat{p} \\ [\hat{H}, \hat{Q}] &= [\hat{H}, \hat{p}] \\ &= i\hbar\frac{\partial V}{\partial x} \\ \frac{d}{dt}\langle p \rangle &= \frac{i}{\hbar}\left\langle i\hbar\frac{\partial V}{\partial x} \right\rangle \\ &= -\left\langle \frac{\partial V}{\partial x} \right\rangle \end{aligned}$$

## 3.19

(a)

$$\begin{aligned}\frac{d^2}{dt^2}\langle x\rangle &= \frac{d}{dx}\left(\frac{\langle p\rangle}{m}\right)\\ &= -\frac{1}{m}\left\langle\frac{\partial V}{\partial x}\right\rangle\\ &= 0\end{aligned}$$

(b)

$$\begin{aligned}\frac{d^2}{dt^2}\langle x\rangle &= \frac{d}{dx}\left(\frac{\langle p\rangle}{m}\right)\\ &= -\frac{1}{m}\left\langle\frac{\partial V}{\partial x}\right\rangle\\ &= -\omega^2\langle x\rangle\\ \frac{d^2}{dt^2}\langle x\rangle + \omega^2\langle x\rangle &= 0\\ \langle x\rangle &= A\sin\omega t + B\cos\omega t\end{aligned}$$

## 3.20

$$\begin{aligned}\Psi &= \frac{1}{\sqrt{2}}(\psi_1 e^{-iE_1t/\hbar} + \psi_2 e^{-iE_2t/\hbar})\\ \hat{H}\Psi &= \frac{1}{\sqrt{2}}(E_1\psi_1 e^{-iE_1t/\hbar} + E_2\psi_2 e^{-iE_2t/\hbar})\\ \hat{H}^2\Psi &= \frac{1}{\sqrt{2}}(E_1^2\psi_1 e^{-iE_1t/\hbar} + E_2^2\psi_2 e^{-iE_2t/\hbar})\\ \langle H^2\rangle &= \langle\Psi|\hat{H}^2\Psi\rangle\\ &= \frac{1}{2}\int_0^a (\psi_1^* e^{iE_1t/\hbar} + \psi_2^* e^{iE_2t/\hbar})(E_1^2\psi_1 e^{-iE_1t/\hbar} + E_2^2\psi_2 e^{-iE_2t/\hbar})\,dx\\ &= \frac{1}{2}\int_0^a (E_1^2|\psi_1|^2 + E_2^2\psi_1^*\psi_2^* e^{i(E_1-E_2)t/\hbar} + E_1^2\psi_2^*\psi_1 e^{i(E_2-E_1)t/\hbar}\\ &\qquad + E_2^2|\psi_2|^2)\,dx\\ &= \frac{1}{2}(E_1^2 + E_2^2)\\ \langle H\rangle &= \frac{1}{2}(E_1 + E_2)\\ \sigma_H^2 &= \langle H^2\rangle - \langle H\rangle^2\\ &= \frac{1}{2}(E_1^2 + E_2^2) - \frac{1}{4}(E_1 + E_2)^2\\ &= \frac{1}{4}(E_2 - E_1)^2\end{aligned}$$

$$
\begin{aligned}
\omega &= \frac{\pi^2\hbar}{2ma^2} \\
\langle x \rangle &= \frac{a}{2}\left[1 - \frac{32}{9\pi^2}\cos(3\omega t)\right] \\
\langle x^2 \rangle &= \frac{1}{2}\int_0^a (\psi_1^* e^{iE_1t/\hbar} + \psi_2^* e^{iE_2t/\hbar}) x^2 (\psi_1 e^{-iE_1t/\hbar} + \psi_2 e^{-iE_2t/\hbar})\, dx \\
&= \frac{1}{2}\int_0^a x^2 (|\psi_1|^2 + \psi_1^*\psi_2 e^{i(E_1-E_2)t/\hbar} + \psi_2^*\psi_1 e^{i(E_2-E_1)t/\hbar} + |\psi_2|^2)\, dx \\
&= \frac{1}{a}\int_0^a x^2 \left[\sin^2\left(\frac{\pi}{a}x\right) + \sin^2\left(\frac{2\pi}{a}x\right)\right. \\
&\qquad \left. + 2\sin\left(\frac{\pi}{a}x\right)\sin\left(\frac{2\pi}{a}x\right)\cos(3\omega t)\right]\, dx \\
&= \frac{a^2}{144\pi^2}[-45 + 48\pi^2 - 256\cos(3\omega t)] \\
\sigma_x^2 &= \langle x^2 \rangle - \langle x \rangle^2 \\
&= \frac{a^2}{4}\left[\frac{1}{3} - \frac{5}{4\pi^2} - \left(\frac{32}{9\pi^2}\right)^2 \cos^2(3\omega t)\right] \\
\frac{d\langle x \rangle}{dt} &= \frac{16a\omega}{3\pi^2}\sin(3\omega t) \\
&= \frac{8\hbar}{3ma}\sin(3\omega t)
\end{aligned}
$$

$$
\begin{aligned}
\sigma_H^2\sigma_x^2 &\geq \left(\frac{\hbar}{2}\right)^2 \left|\frac{d\langle x \rangle}{dt}\right|^2 \\
\frac{1}{4}\left(\frac{3\pi^2\hbar^2}{2ma^2}\right)^2 \frac{a^2}{4}\left[\frac{1}{3} - \frac{5}{4\pi^2} - \left(\frac{32}{9\pi^2}\right)^2\cos^2(3\omega t)\right] &\geq \left(\frac{\hbar}{2}\right)^2 \left[\frac{8\hbar}{3ma}\sin(3\omega t)\right]^2 \\
\left(\frac{3}{4}\right)^2\left[\frac{1}{3} - \frac{5}{4\pi^2} - \left(\frac{32}{9\pi^2}\right)^2\cos^2(3\omega t)\right] &\geq \left(\frac{8}{3\pi^2}\right)^2 \sin^2(3\omega t) \\
\frac{1}{3} - \frac{5}{4\pi^2} &\geq \left(\frac{32}{9\pi^2}\right)^2
\end{aligned}
$$

## 3.23

$$\begin{aligned}\hat{P}^2 |\beta\rangle &= \hat{P}(\hat{P} |\beta\rangle) \\ &= \hat{P}(\langle\alpha|\beta\rangle |\alpha\rangle) \\ &= \langle\alpha|\beta\rangle \hat{P} |\alpha\rangle \\ &= \langle\alpha|\beta\rangle (\langle\alpha|\alpha\rangle |\alpha\rangle) \\ &= \langle\alpha|\beta\rangle |\alpha\rangle \\ &= \hat{P} |\beta\rangle\end{aligned}$$

So, $\hat{P}^2 = \hat{P}$.

$$\begin{aligned}\hat{P} |\beta\rangle &= \lambda |\beta\rangle \\ \langle\alpha|\beta\rangle |\alpha\rangle &= \lambda |\beta\rangle\end{aligned}$$

If $|\beta\rangle$ is a constant multiple of $|\alpha\rangle$, then

$$\begin{aligned}\langle\alpha|c\alpha\rangle |\alpha\rangle &= \lambda c |\alpha\rangle \\ c \langle\alpha|\alpha\rangle |\alpha\rangle &= \lambda c |\alpha\rangle \\ c |\alpha\rangle &= \lambda c |\alpha\rangle\end{aligned}$$

thus $\lambda = 1$.
If $|\beta\rangle$ is orthogonal to $|\alpha\rangle$, then

$$\begin{aligned}\langle\alpha|\beta\rangle |\alpha\rangle &= \lambda |\beta\rangle \\ 0 &= \lambda |\beta\rangle\end{aligned}$$

thus $\lambda = 0$.

## 3.24

$$\begin{aligned}\hat{Q} &= \hat{Q}^\dagger \\ Q_{mn} &= \langle e_m|\hat{Q}|e_n\rangle \\ Q_{nm} &= \langle e_n|\hat{Q}|e_m\rangle \\ Q_{nm}^* &= \langle e_n|\hat{Q}|e_m\rangle^* \\ &= \langle e_m|\hat{Q}^\dagger|e_n\rangle \\ &= \langle e_m|\hat{Q}|e_n\rangle \\ &= Q_{mn}\end{aligned}$$

## 3.25

$$\hat{H}\,|\alpha\rangle = \lambda\,|\alpha\rangle$$
$$\epsilon[(\langle 1|\alpha\rangle + \langle 2|\alpha\rangle)\,|1\rangle + (\langle 1|\alpha\rangle - \langle 2|\alpha\rangle)\,|2\rangle] = \lambda(\langle 1|\alpha\rangle\,|1\rangle + \langle 2|\alpha\rangle\,|2\rangle)$$

From this we get two equations

$$\epsilon(\langle 1|\alpha\rangle + \langle 2|\alpha\rangle) = \lambda\,\langle 1|\alpha\rangle$$
$$\epsilon(\langle 1|\alpha\rangle) - \langle 2|\alpha\rangle) = \lambda\,\langle 2|\alpha\rangle$$

If we let $|\alpha\rangle = \begin{pmatrix} a \\ b \end{pmatrix}$ then this becomes

$$\epsilon(a+b) = \lambda a$$
$$\epsilon(a-b) = \lambda b$$

or in matrix form

$$\epsilon \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix} = \lambda \begin{pmatrix} a \\ b \end{pmatrix}.$$

The eigenvalues of this matrix are $\lambda = \pm\sqrt{2}\epsilon$ and the eigenvectors are $|1\rangle + (\sqrt{2} \pm 1)\,|2\rangle$.

## 3.26

(a)

$$\langle\alpha| = -i\,\langle 1| - 2\,\langle 2| + i\,\langle 3|$$
$$\langle\beta| = -i\,\langle 1| + 2\,\langle 3|$$

(b)

$$\begin{aligned}
\langle\alpha|\beta\rangle &= (-i\,\langle 1| - 2\,\langle 2| + i\,\langle 3|)(i\,|1\rangle + 2\,|3\rangle) \\
&= \langle 1|1\rangle - 2i\,\langle 1|3\rangle - 2i\,\langle 2|1\rangle - 4\,\langle 2|3\rangle - \langle 3|1\rangle + 2i\,\langle 3|3\rangle \\
&= 1 + 2i \\
\langle\beta|\alpha\rangle &= (-i\,\langle 1| + 2\,\langle 3|)(i\,|1\rangle - 2\,|2\rangle - i\,|3\rangle) \\
&= \langle 1|1\rangle + 2i\,\langle 1|2\rangle - \langle 1|3\rangle + 2i\,\langle 3|1\rangle - 4\,\langle 3|2\rangle - 2i\,\langle 3|3\rangle \\
&= 1 - 2i \\
&= \langle\alpha|\beta\rangle^*
\end{aligned}$$

(c)

$$
\begin{aligned}
\hat{A} &= |\alpha\rangle \langle\beta| \\
\hat{A}|1\rangle &= |\alpha\rangle \langle\beta|1\rangle \\
&= |\alpha\rangle \langle 1|\beta\rangle^* \\
&= -i\,|\alpha\rangle \\
&= |1\rangle + 2i\,|2\rangle - |3\rangle \\
A_{11} &= \langle 1|\hat{A}|1\rangle \\
&= 1 \\
A_{21} &= 2i \\
A_{31} &= -1 \\
\hat{A}|2\rangle &= |\alpha\rangle \langle\beta|2\rangle \\
&= |\alpha\rangle \langle 2|\beta\rangle^* \\
&= 0 \\
A_{12} &= 0 \\
A_{22} &= 0 \\
A_{32} &= 0 \\
\hat{A}|3\rangle &= |\alpha\rangle \langle\beta|3\rangle \\
&= |\alpha\rangle \langle 3|\beta\rangle^* \\
&= 2\,|\alpha\rangle \\
&= 2i\,|1\rangle - 4\,|2\rangle - 2i\,|3\rangle \\
A_{13} &= 2i \\
A_{23} &= -4 \\
A_{33} &= -2i \\
A &= \begin{pmatrix} 1 & 0 & 2i \\ 2i & 0 & -4 \\ -1 & 0 & -2i \end{pmatrix}
\end{aligned}
$$

It's not hermitian.

## 3.27

(a)

$$\begin{aligned}
\hat{Q}\left|\alpha\right\rangle &= \hat{Q}\sum_{n=1}^{\infty}\left\langle e_n|\alpha\right\rangle\left|e_n\right\rangle \\
&= \hat{Q}\left(\sum_{n=1}^{\infty}\left|e_n\right\rangle\left\langle e_n\right|\right)\left|\alpha\right\rangle \\
&= \left(\sum_{n=1}^{\infty}\hat{Q}\left|e_n\right\rangle\left\langle e_n\right|\right)\left|\alpha\right\rangle \\
&= \left(\sum_{n=1}^{\infty}q_n\left|e_n\right\rangle\left\langle e_n\right|\right)\left|\alpha\right\rangle \\
\hat{Q} &= \sum_{n=1}^{\infty}q_n\left|e_n\right\rangle\left\langle e_n\right|
\end{aligned}$$

(b)

$$\begin{aligned}
\hat{Q} &= \sum_{n=1}^{\infty}q_n\left|e_n\right\rangle\left\langle e_n\right| \\
\hat{Q}^2 &= \left(\sum_{n=1}^{\infty}q_n\left|e_n\right\rangle\left\langle e_n\right|\right)\left(\sum_{l=1}^{\infty}q_l\left|e_l\right\rangle\left\langle e_l\right|\right) \\
&= \sum_{n=1}^{\infty}\sum_{l=0}^{\infty}q_nq_l\left|e_n\right\rangle\left\langle e_n|e_l\right\rangle\left\langle e_l\right| \\
&= \sum_{n=1}^{\infty}q_n^2\left|e_n\right\rangle\left\langle e_n\right| \\
e^{\hat{Q}} &= \sum_{n=1}^{\infty}e^{q_n}\left|e_n\right\rangle\left\langle e_n\right| \\
&= \sum_{n=1}^{\infty}\left(\sum_{k=0}^{\infty}\frac{q_n^k}{k!}\right)\left|e_n\right\rangle\left\langle e_n\right| \\
&= \sum_{k=0}^{\infty}\frac{1}{k!}\left(\sum_{n=1}^{\infty}q_n^k\left|e_n\right\rangle\left\langle e_n\right|\right) \\
&= \sum_{k=0}^{\infty}\frac{1}{k!}\hat{Q}^k \\
&= 1+\hat{Q}+\frac{1}{2}\hat{Q}^2+\frac{1}{3!}\hat{Q}^3+\cdots
\end{aligned}$$

## 3.28

(a)

$$\begin{aligned}
\sin \hat{D} &= \hat{D} - \frac{D^3}{3!} + \frac{\hat{D}^5}{5!} - \frac{\hat{D}^7}{7!} + \cdots \\
(\sin \hat{D})x^5 &= 5x^4 - 10x^2 + 1
\end{aligned}$$

(b)

$$\begin{aligned}
\frac{1}{1-\hat{D}/2} &= 1 + \frac{\hat{D}}{2} + \left(\frac{\hat{D}}{2}\right)^2 + \left(\frac{\hat{D}}{2}\right)^3 + \cdots \\
&= 1 + \frac{\hat{D}}{2} + \frac{\hat{D}^2}{4} + \frac{\hat{D}^3}{8} + \cdots \\
\frac{1}{1-\hat{D}/2}\cos x &= \cos x - \frac{1}{2}\sin x - \frac{1}{4}\cos x + \frac{1}{8}\sin x + \cdots \\
&= \left(-\frac{1}{2} + \frac{1}{8} - \frac{1}{32} + \cdots\right)\sin x + \left(1 - \frac{1}{4} + \frac{1}{16} - \cdots\right)\cos x \\
&= -\frac{2}{5}\sin x + \frac{4}{5}\cos x
\end{aligned}$$

## 3.30

$$\begin{aligned}
c_n(t) &= \langle n | S(t) \rangle \\
&= \left\langle n \,\middle|\, \int dx\, |x\rangle \langle x| \,\middle|\, S(t) \right\rangle \\
&= \int \langle n|x\rangle \langle x|S(t)\rangle \; dx \\
&= \int \langle x|n\rangle^* \, \Psi(x,t)\, dx \\
&= \int \psi_n(x)^* \Psi(x,t)\, dx
\end{aligned}$$

## 3.31

$$
\begin{aligned}
|e_1\rangle &= 1 \\
\langle e_1|e_1\rangle &= \int_{-1}^{1} dx \\
&= 2 \\
|e_1'\rangle &= \frac{1}{\sqrt{2}} \\
|e_2\rangle &= x \\
\langle e_1'|e_2\rangle &= \int_{-1}^{1} \frac{1}{\sqrt{2}} x\, dx \\
&= \frac{1}{\sqrt{2}} \left[\frac{1}{2}x^2\right]_{-1}^{1} \\
&= 0 \\
\langle e_2|e_2\rangle &= \int_{-1}^{1} x^2\, dx \\
&= \left[\frac{1}{3}x^3\right]_{-1}^{1} \\
&= \frac{2}{3} \\
|e_2'\rangle &= \sqrt{\frac{3}{2}} x \\
|e_3\rangle &= x^2 \\
\langle e_1'|e_3\rangle &= \int_{-1}^{1} \frac{1}{\sqrt{2}} x^2\, dx \\
&= \frac{1}{\sqrt{2}} \left[\frac{1}{3}x^3\right]_{-1}^{1} \\
&= \frac{\sqrt{2}}{3} \\
\langle e_2'|e_3\rangle &= \int_{-1}^{1} \sqrt{\frac{3}{2}} x^3\, dx \\
&= 0 \\
|e_3'\rangle &= x^2 - \frac{\sqrt{2}}{3} |e_1'\rangle \\
&= x^2 - \frac{1}{3}
\end{aligned}
$$

$$
\begin{aligned}
\langle e_3'|e_3'\rangle &= \int_{-1}^{1} \left(x^2 - \frac{1}{3}\right)^2 \, dx \\
&= \int_{-1}^{1} \left(x^4 - \frac{2}{3}x^2 + \frac{1}{9}\right) \, dx \\
&= \left[\frac{1}{5}x^5 - \frac{2}{9}x^3 + \frac{1}{9}x\right]_{-1}^{1} \\
&= \frac{2}{5} - \frac{4}{9} + \frac{2}{9} \\
&= \frac{18}{45} - \frac{20}{45} + \frac{10}{45} \\
&= \frac{8}{45} \\
|e_3''\rangle &= \sqrt{\frac{45}{8}} \left(x^2 - \frac{1}{3}\right) \\
&= \sqrt{\frac{5}{2}} \left(\frac{3}{2}x^2 - \frac{1}{2}\right) \\
|e_4\rangle &= x^3 \\
\langle e_1'|e_4\rangle &= \int_{-1}^{1} \frac{1}{\sqrt{2}} x^3 \, dx \\
&= 0 \\
\langle e_2'|e_4\rangle &= \int_{-1}^{1} \sqrt{\frac{3}{2}} x^4 \, dx \\
&= \sqrt{\frac{3}{2}} \left[\frac{1}{5}x^5\right] \\
&= \frac{\sqrt{6}}{5} \\
\langle e_3''|e_4\rangle &= \int_{-1}^{1} \sqrt{\frac{5}{2}} \left(\frac{3}{2}x^2 - \frac{1}{2}\right) x^3 \, dx \\
&= \sqrt{\frac{5}{2}} \int_{-1}^{1} \left(\frac{3}{2}x^5 - \frac{1}{2}x^3\right) \, dx \\
&= 0 \\
|e_4'\rangle &= |e_4\rangle - \frac{\sqrt{6}}{5} |e_2'\rangle \\
&= x^3 - \frac{3}{5}x
\end{aligned}
$$

$$
\begin{aligned}
\langle e_4'|e_4'\rangle &= \int_{-1}^{1}\left(x^3-\frac{3}{5}x\right)^2\,dx \\
&= \int_{-1}^{1}\left(x^6-\frac{6}{5}x^4+\frac{9}{25}x^2\right)\,dx \\
&= \left[\frac{1}{7}x^7-\frac{6}{25}x^5+\frac{3}{25}x^3\right]_{-1}^{1} \\
&= \frac{2}{7}-\frac{12}{25}+\frac{6}{25} \\
&= \frac{50}{175}-\frac{84}{175}+\frac{42}{175} \\
&= \frac{8}{175} \\
|e_4''\rangle &= \sqrt{\frac{175}{8}}\left(x^3-\frac{3}{5}x\right) \\
&= \sqrt{\frac{7}{2}}\left(\frac{5}{2}x^3-\frac{3}{2}x\right)
\end{aligned}
$$

## 3.32

(a)

$$
\begin{aligned}
\langle\hat{Q}\rangle &= \langle\Psi|\hat{Q}|\Psi\rangle \\
&= \langle\Psi|\hat{Q}^\dagger|\Psi\rangle^* \\
&= -\langle\Psi|\hat{Q}|\Psi\rangle^* \\
&= -\langle\hat{Q}\rangle^*
\end{aligned}
$$

(b)

$$
\begin{aligned}
\hat{Q}\,|\psi\rangle &= \lambda\,|\psi\rangle \\
\langle\psi|\hat{Q}|\psi\rangle &= \langle\psi|\lambda|\psi\rangle \\
&= \lambda\,\langle\psi|\psi\rangle \\
\langle\psi|\hat{Q}|\psi\rangle^* &= \lambda^*\,\langle\psi|\psi\rangle^* \\
\langle\psi|\hat{Q}^\dagger|\psi\rangle &= \lambda^*\,\langle\psi|\psi\rangle \\
-\langle\psi|\hat{Q}|\psi\rangle &= \lambda^*\,\langle\psi|\psi\rangle \\
\langle\psi|\hat{Q}|\psi\rangle &= -\lambda^*\,\langle\psi|\psi\rangle \\
\hat{Q}\,|\psi\rangle &= -\lambda^*\,|\psi\rangle
\end{aligned}
$$

(c)

$$\begin{aligned}
\hat{Q}\,|f\rangle &= \lambda_1\,|f\rangle \\
\hat{Q}\,|g\rangle &= \lambda_2\,|g\rangle \\
\langle g|\hat{Q}|f\rangle &= \langle g|\lambda_1|f\rangle \\
&= \lambda_1\,\langle g|f\rangle \\
\langle f|\hat{Q}^\dagger|g\rangle &= \lambda_1^*\,\langle f|g\rangle \\
-\,\langle f|\hat{Q}|g\rangle &= \lambda_1^*\,\langle f|g\rangle \\
\langle f|\lambda_2|g\rangle &= -\lambda_1^*\,\langle f|g\rangle \\
\lambda_2\,\langle f|g\rangle &= -\lambda_1^*\,\langle f|g\rangle \\
\lambda_2 &= -\lambda_1^* \\
\lambda_2 &= \lambda_1 \\
\langle f|g\rangle &= 0
\end{aligned}$$

(d)

$$\begin{aligned}
[\hat{A},\hat{B}] &= \hat{A}\hat{B} - \hat{B}\hat{A} \\
[\hat{A},\hat{B}]^\dagger &= (\hat{A}\hat{B} - \hat{B}\hat{A})^\dagger \\
&= \hat{A}^\dagger\hat{B}^\dagger - \hat{B}^\dagger\hat{A}^\dagger \\
&= -(\hat{A}\hat{B} - \hat{B}\hat{A}) \\
&= -[\hat{A},\hat{B}] \\
[\hat{A},\hat{B}]^\dagger &= \hat{A}^\dagger\hat{B}^\dagger - \hat{B}^\dagger\hat{A}^\dagger \\
&= -(\hat{A}\hat{B} - \hat{B}\hat{A}) \\
&= -[\hat{A},\hat{B}]
\end{aligned}$$

(e)

$$\begin{aligned}
\hat{Q}\,|q_n\rangle &= \lambda_n\,|q_n\rangle \\
&= (x+iy)\,|q_n\rangle \\
&= x\,|q_n\rangle + iy\,|q_n\rangle \\
&= \hat{X}\,|q_n\rangle + \hat{Y}\,|q_n\rangle \\
&= (\hat{X}+\hat{Y})\,|q_n\rangle
\end{aligned}$$

## 3.33

(a) $\psi_1$

(b) $b_1$ and $b_2$ with $P(b_1) = \frac{9}{25}$ and $P(b_2) = \frac{16}{25}$.

(c)

$$\begin{aligned}
\phi_1 &= \frac{3}{5}\psi_1 + \frac{4}{5}\psi_2 \\
\phi_2 &= \frac{4}{5}\psi_1 - \frac{3}{5}\psi_2 \\
P(a_1) &= P(b_1)\left(\frac{3}{5}\right)^2 + P(b_2)\left(\frac{4}{5}\right)^2 \\
&= \left(\frac{9}{25}\right)^2 + \left(\frac{16}{25}\right)^2 \\
&= \frac{337}{625} \\
&\approx 53.9\%
\end{aligned}$$

## 3.34

(a)

$$\begin{aligned}
\Phi_n(p,t) &= \frac{1}{\sqrt{2\pi\hbar}}\int_0^a e^{-ipx/\hbar}\sqrt{\frac{2}{a}}\sin\left(\frac{n\pi}{a}x\right)e^{-iE_nt/\hbar}\,dx \\
&= \frac{1}{\sqrt{\pi\hbar a}}e^{-iE_nt/\hbar}\int_0^a e^{-ipx/\hbar}\sin\left(\frac{n\pi}{a}x\right)\,dx \\
&= \sqrt{\frac{a\pi}{\hbar}}\frac{ne^{-iE_nt/\hbar}}{(n\pi)^2-(ap/\hbar)^2}[1-(-1)^n e^{-ipa/\hbar}]
\end{aligned}$$

(b)

$$|\Phi_n(p,t)|^2 = \frac{a\pi}{\hbar}\frac{4n^2}{[(n\pi)^2-(ap/\hbar)^2]^2}\begin{cases}\cos^2\left(\frac{a}{2\hbar}p\right) & n \text{ odd} \\ \sin^2\left(\frac{a}{2\hbar}p\right) & n \text{ even}\end{cases}$$

## 3.35

$$\begin{aligned}
\Psi(x,0) &= \begin{cases} \frac{1}{\sqrt{2n\lambda}} e^{i2\pi x/\lambda} & -n\lambda < x < n\lambda \\ 0 & \text{otherwise} \end{cases} \\
\Phi(p,0) &= \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi\hbar}} e^{-ipx/\hbar} \Psi(x,0)\, dx \\
&= \frac{1}{2\sqrt{\pi\hbar n\lambda}} \int_{-n\lambda}^{n\lambda} e^{i(2\pi/\lambda - p/\hbar)x}\, dx \\
&= \frac{1}{2\sqrt{\pi\hbar n\lambda}} \frac{1}{i(2\pi/\lambda - p/\hbar)} \left[ e^{i(2\pi/\lambda - p/\hbar)x} \right]_{-n\lambda}^{n\lambda} \\
&= \frac{1}{2\sqrt{\pi\hbar n\lambda}} \frac{1}{i(2\pi/\lambda - p/\hbar)} e^{i(2\pi/\lambda - p/\hbar)n\lambda} - e^{-i(2\pi/\lambda - p/\hbar)n\lambda} \\
&= \frac{1}{\sqrt{\pi\hbar n\lambda}} \frac{1}{2\pi/\lambda - p/\hbar} \sin\left[ \left( \frac{2\pi}{\lambda} - \frac{p}{\hbar} \right) n\lambda \right] \\
&= \sqrt{\frac{\lambda\hbar}{n\pi}} \frac{1}{\lambda p - 2\pi\hbar} \sin\left( \frac{n\lambda}{\hbar} p \right) \\
w_x &= 2n\lambda \\
w_p &= \frac{2\pi\hbar}{n\lambda}
\end{aligned}$$

As $n \to \infty$, $w_x \to \infty$ and $w_p \to 0$.

$$\begin{aligned}
w_x w_p &= 2n\lambda \frac{2\pi\hbar}{n\lambda} \\
&= 4\pi\hbar \\
&\geq \frac{\hbar}{2}
\end{aligned}$$

## 3.36

(a)

$$\begin{aligned}
1 &= \int_{-\infty}^{\infty} \left( \frac{A}{x^2 + a^2} \right)^2 dx \\
&= |A|^2 \int_{-\infty}^{\infty} \frac{1}{(x^2 + a^2)^2}\, dx \\
&= \frac{\pi |A|^2}{2a^3} \\
A &= a\sqrt{\frac{2a}{\pi}}
\end{aligned}$$

(b)

$$
\begin{aligned}
\langle x \rangle &= \langle \Psi | x | \Psi \rangle \\
&= \int_{-\infty}^{\infty} \Psi^* x \Psi \, dx \\
&= \frac{a^3}{\pi} \int_{-\infty}^{\infty} \frac{2x}{(x^2 + a^2)^2} \, dx \\
u &= x^2 + a^2 \\
du &= 2x \, dx \\
\langle x \rangle &= \frac{a^3}{\pi} \int_{-\infty}^{\infty} \frac{1}{u^2} \\
&= \frac{a^3}{\pi} \left[ -\frac{1}{u} \right]_{-\infty}^{\infty} \\
&= 0 \\
\langle x^2 \rangle &= \langle \Psi | x^2 \Psi \rangle \\
&= \int_{-\infty}^{\infty} \Psi^* x^2 \Psi \, dx \\
&= \frac{2a^3}{\pi} \int_{-\infty}^{\infty} \frac{x^2}{(x^2 + a^2)^2} \, dx \\
&= a^2 \\
\sigma_x &= \sqrt{\langle x^2 \rangle - \langle x \rangle^2} \\
&= a
\end{aligned}
$$

(c)

$$
\begin{aligned}
\Phi(x, 0) &= \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi\hbar}} e^{-ipx/\hbar} a \sqrt{\frac{2a}{\pi}} \frac{1}{x^2 + a^2} \, dx \\
&= \frac{a\sqrt{a}}{\pi\sqrt{\hbar}} \int_{-\infty}^{\infty} e^{-ipx/\hbar} \frac{1}{x^2 + a^2} \, dx \\
&= \sqrt{\frac{a}{\hbar}} e^{-|p|a/\hbar}
\end{aligned}
$$

$$
\frac{a}{\hbar} \int_{-\infty}^{\infty} e^{-2|p|a/\hbar} \, dp = 1
$$

(d)

$$\begin{aligned}
\langle p \rangle &= \langle \Phi | p | \Phi \rangle \\
&= \int_{-\infty}^{\infty} \Phi^* p \Psi \, dp \\
&= \frac{a}{\hbar} \int_{-\infty}^{\infty} p e^{-2|p|a/\hbar} \, dp \\
&= 0 \\
\langle p^2 \rangle &= \frac{a}{\hbar} \int_{-\infty}^{\infty} p^2 e^{-2|p|a/\hbar} \, dp \\
&= \frac{\hbar^2}{2a^2} \\
\sigma_p &= \sqrt{\langle p^2 \rangle - \langle p \rangle^2} \\
&= \frac{\hbar}{\sqrt{2}a}
\end{aligned}$$

(e)

$$\begin{aligned}
\sigma_x \sigma_p &= \frac{\hbar}{\sqrt{2}} \\
&\geq \frac{\hbar}{2}
\end{aligned}$$

## 3.37

$$\begin{aligned}
[\hat{H}, xp] &= x[\hat{H}, p] + [\hat{H}, x]p \\
&= i\hbar x \frac{dV}{dx} - \frac{i\hbar p^2}{m} \\
\frac{d}{dt} \langle xp \rangle &= \frac{i}{\hbar} \langle [\hat{H}, xp] \rangle \\
&= \frac{i}{\hbar} \left\langle i\hbar x \frac{dV}{dx} - \frac{i\hbar p^2}{m} \right\rangle \\
&= \left\langle \frac{p^2}{m} \right\rangle - \left\langle x \frac{dV}{dx} \right\rangle \\
&= 2 \langle T \rangle - \left\langle x \frac{dV}{dx} \right\rangle
\end{aligned}$$

The left hand side is 0 because expectation values are constant in stationary states.

$$
\begin{aligned}
V &= \frac{1}{2}m\omega^2 x^2 \\
\frac{dV}{dx} &= m\omega^2 x \\
x\frac{dV}{dx} &= m\omega^2 x \\
&= 2V \\
2\left\langle T \right\rangle &= \left\langle x\frac{dV}{dx} \right\rangle \\
&= \left\langle 2V \right\rangle \\
&= 2\left\langle V \right\rangle \\
\left\langle T \right\rangle &= \left\langle V \right\rangle
\end{aligned}
$$

**3.38**

$$
\begin{aligned}
\Psi(x,0) &= \frac{1}{\sqrt{2}}(\psi_1 + \psi_2) \\
\Psi(x,t) &= \frac{1}{\sqrt{2}}(\psi_1 e^{-iE_1 t/\hbar} + \psi_2 e^{-iE_2 t/\hbar}) \\
0 &= \int_{-\infty}^{\infty} \Psi(x,0)\Psi(x,t)\,dx \\
&= \frac{1}{2}\int_{-\infty}^{\infty} (\psi_1 + \psi_2)(\psi_1 e^{-iE_1 t/\hbar} + \psi_2 e^{-iE_2 t/\hbar})\,dx \\
&= \frac{1}{2}\int_{-\infty}^{\infty} (\psi_1^2 e^{-iE_1 t/\hbar} + \psi_1\psi_2 e^{-iE_2 t/\hbar} + \psi_1\psi_2 e^{-iE_1 t/\hbar} + \psi_2^2 e^{-iE_2 t/\hbar})\,dx \\
&= \frac{1}{2}(e^{-iE_1 t/\hbar} + e^{-iE_2 t/\hbar}) \\
&= e^{-iE_1 t/\hbar} + e^{-iE_2 t/\hbar} \\
e^{-iE_1 t/\hbar} &= -e^{-iE_2 t/\hbar} \\
&= e^{\pi i} e^{-iE_2 t/\hbar} \\
-\frac{iE_1 t}{\hbar} &= i\left(\pi - \frac{E_2 t}{\hbar}\right) \\
-\frac{E_1 t}{\hbar} &= \pi - \frac{E_2 t}{\hbar} \\
t &= \frac{\pi\hbar}{E_2 - E_1} \\
\Delta t &= \frac{t}{\pi} \\
&= \frac{\hbar}{E_2 - E_1} \\
\Delta E &= \frac{1}{2}(E_2 - E_1) \\
\Delta E \Delta t &= \frac{\hbar}{2}
\end{aligned}
$$

## 3.41

$$
\begin{aligned}
\Psi &= \frac{e^{i\theta_0}}{\sqrt{2}}\psi_0 e^{-i\omega t/2} + \frac{e^{i\theta_1}}{\sqrt{2}}\psi_1 e^{-3i\omega t/2} \\
\langle p\rangle &= \langle \Psi|p|\Psi\rangle \\
&= \frac{1}{2}\langle\psi_0|p|\psi_0\rangle + \frac{1}{2}e^{i(\theta_1-\theta_0)}e^{-i\omega t}\langle\psi_0|p|\psi_1\rangle \\
&\quad + \frac{1}{2}e^{i(\theta_0-\theta_1)}e^{i\omega t}\langle\psi_1|p|\psi_0\rangle + \frac{1}{2}\langle\psi_1|p|\psi_1\rangle \\
\langle\psi_0|p|\psi_0\rangle &= \frac{d}{dt}\langle\psi_0|x|\psi_0\rangle \\
&= 0 \\
\langle\psi_1|p|\psi_1\rangle &= \frac{d}{dt}\langle\psi_1|x|\psi_1\rangle \\
&= 0 \\
\langle p\rangle &= \frac{1}{2}e^{i(\theta_1-\theta_0-\omega t)}\langle\psi_0|p|\psi_1\rangle + \frac{1}{2}e^{-i(\theta_1-\theta_0-\omega t)}\langle\psi_1|p|\psi_0\rangle \\
\langle\psi_0|p|\psi_1\rangle &= -i\sqrt{\frac{\hbar m\omega}{2}} \\
\langle\psi_1|p|\psi_0\rangle &= i\sqrt{\frac{\hbar m\omega}{2}} \\
\langle p\rangle &= -\frac{1}{2}ie^{i(\theta_1-\theta_0-\omega t)}\sqrt{\frac{\hbar m\omega}{2}} + \frac{1}{2}ie^{-i(\theta_1-\theta_0-\omega t)}\sqrt{\frac{\hbar m\omega}{2}} \\
&= -\frac{1}{2}i\sqrt{\frac{\hbar m\omega}{2}}(e^{i(\theta_1-\theta_0-\omega t)} - e^{-i(\theta_1-\theta_0-\omega t)}) \\
&= \sqrt{\frac{\hbar m\omega}{2}}\sin(\theta_1-\theta_0-\omega t)
\end{aligned}
$$

The largest possible value of $\langle p\rangle$ is $\sqrt{\hbar m\omega/2}$. If it takes on this value at $t = 0$ then

$$\Psi(x,t) = \frac{1}{\sqrt{2}}e^{-i\omega t/2}(\psi_0 + i\psi_1 e^{-i\omega t}).$$

## 3.43

(a)

$$
\begin{aligned}
|z|^2 &= \mathrm{Re}(z)^2 + \mathrm{Im}(z)^2 \\
&= \left(\frac{z+z^*}{2}\right)^2 + \left(\frac{z-z^*}{2i}\right)^2 \\
\sigma_A^2\sigma_B^2 &\geq \left(\frac{\langle f|g\rangle + \langle g|f\rangle}{2}\right)^2 + \left(\frac{\langle f|g\rangle - \langle g|f\rangle}{2i}\right)^2 \\
&= \left(\frac{\langle \hat{A}\hat{B}\rangle + \langle \hat{B}\hat{A}\rangle - 2\langle A\rangle\langle B\rangle}{2}\right)^2 + \left(\frac{\langle [\hat{A},\hat{B}]\rangle}{2i}\right)^2 \\
&= \frac{1}{4}[\langle -i[\hat{A},\hat{B}]\rangle^2 + (\langle \hat{A}\hat{B}\rangle + \langle \hat{B}\hat{A}\rangle - 2\langle A\rangle\langle B\rangle)^2] \\
&= \frac{1}{4}(\langle C\rangle^2 + \langle D\rangle^2)
\end{aligned}
$$

(b)

$$
\begin{aligned}
B &= A \\
\hat{C} &= -i[\hat{A},\hat{B}] \\
&= 0 \\
\hat{D} &= 2(\hat{A}^2 - \langle A\rangle^2) \\
\langle D\rangle &= \langle \Psi|D|\Psi\rangle \\
&= \langle \Psi|2(\hat{A}^2 - \langle A\rangle^2)|\Psi\rangle \\
&= 2(\langle \Psi|\hat{A}^2|\Psi\rangle - \langle A\rangle^2) \\
&= 2(\langle A^2\rangle - \langle A\rangle^2) \\
&= 2\sigma_A^2 \\
\sigma_A^2\sigma_B^2 &= \frac{1}{4}(\langle C\rangle^2 + \langle D\rangle^2) \\
\sigma_A^4 &\geq \sigma_A^4
\end{aligned}
$$

## 3.44

(a) The eigenvalues of $\mathbf{H}$ are $a-b$, $a+b$, and $c$ and the associated eigenvectors are $\begin{pmatrix}-1\\0\\1\end{pmatrix}$, $\begin{pmatrix}1\\0\\1\end{pmatrix}$, and $\begin{pmatrix}0\\1\\0\end{pmatrix}$, respectively.

$$
|S(t)\rangle = \begin{pmatrix}0\\1\\0\end{pmatrix} e^{-ict/\hbar}
$$

(b)

$$
\begin{aligned}
\begin{pmatrix}1\\0\\0\end{pmatrix} &= \frac{1}{2}\left[\begin{pmatrix}1\\0\\1\end{pmatrix} - \begin{pmatrix}-1\\0\\1\end{pmatrix}\right] \\
|S(t)\rangle &= \frac{1}{2}\left[\begin{pmatrix}1\\0\\1\end{pmatrix} e^{-i(a+b)t/\hbar} - \begin{pmatrix}-1\\0\\1\end{pmatrix} e^{-i(a-b)t/\hbar}\right] \\
&= \frac{1}{2}e^{-iat/\hbar}\begin{pmatrix}e^{-ibt/\hbar} + e^{ibt/\hbar}\\0\\e^{-ibt/\hbar} - e^{ibt/\hbar}\end{pmatrix} \\
&= e^{-iat/\hbar}\begin{pmatrix}\cos(bt/\hbar)\\0\\-i\sin(bt/\hbar)\end{pmatrix}
\end{aligned}
$$

## 3.45

$$
\begin{aligned}
\langle n|\hat{x}|S(t)\rangle &= \left\langle n \middle| \hat{x} \sum_{n'=0}^{\infty} |n'\rangle \langle n'| \middle| S(t) \right\rangle \\
&= \sum_{n'=0}^{\infty} \langle n|\hat{x}|n'\rangle \langle n'|S(t)\rangle \\
&= \sqrt{\frac{\hbar}{2m\omega}} \sum_{n'=0}^{\infty} (\sqrt{n'}\delta_{n,n'-1} + \sqrt{n}\delta_{n',n-1})c_{n'}(t) \\
&= \sqrt{\frac{\hbar}{2m\omega}}[\sqrt{n+1}c_{n+1}(t) + \sqrt{n}c_{n-1}(t)]
\end{aligned}
$$

## 3.46

(a)

$$h_1 = \hbar\omega$$
$$h_2 = 2\hbar\omega$$
$$h_3 = 2\hbar\omega$$
$$|h_1\rangle = \begin{pmatrix}1\\0\\0\end{pmatrix}$$
$$|h_2\rangle = \begin{pmatrix}0\\1\\0\end{pmatrix}$$
$$|h_3\rangle = \begin{pmatrix}0\\0\\1\end{pmatrix}$$
$$a_1 = 2\lambda$$
$$a_2 = \lambda$$
$$a_3 = -\lambda$$
$$|a_1\rangle = \begin{pmatrix}0\\0\\1\end{pmatrix}$$
$$|a_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\\0\end{pmatrix}$$
$$|a_3\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}-1\\1\\0\end{pmatrix}$$
$$b_1 = 2\mu$$
$$b_2 = \mu$$
$$b_3 = -\mu$$
$$|b_1\rangle = \begin{pmatrix}1\\0\\0\end{pmatrix}$$
$$|b_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\1\\1\end{pmatrix}$$
$$|b_3\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\-1\\1\end{pmatrix}$$

(b)

$$
\begin{aligned}
\langle H\rangle &= \langle S(0)|H|S(0)\rangle \\
&= \begin{pmatrix} c_1^* & c_2^* & c_3^* \end{pmatrix} \hbar\omega \begin{pmatrix} 1 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 2 \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \\ c_3 \end{pmatrix} \\
&= \hbar\omega \begin{pmatrix} c_1^* & c_2^* & c_3^* \end{pmatrix} \begin{pmatrix} c_1 \\ 2c_2 \\ 2c_3 \end{pmatrix} \\
&= \hbar\omega(|c_1|^2 + 2|c_2|^2 + 2|c_3|^2) \\
\langle A\rangle &= \lambda(c_1^* c_2 + c_2^* c_1 + 2|c_3|^2) \\
\langle B\rangle &= \mu(2|c_1|^2 + c_2^* c_3 + c_3^* c_2)
\end{aligned}
$$

(c)

$$|S(t)\rangle = c_1 |h_1\rangle e^{-i\omega t} + c_2 |h_2\rangle e^{-2i\omega t} + c_3 |h_3\rangle e^{-2i\omega t}$$

You could measure $H$ as $\hbar\omega$ with probability $|c_1|^2$ or $2\hbar\omega$ with probability $|c_2|^2 + |c_3|^2$.

# 4 Quantum Mechanics in Three Dimensions

## 4.1

(a)

$$
\begin{aligned}
[r_i, r_j] &= 0 \\
[p_i, p_j] &= 0 \\
[x, p_x]f &= x\left(-i\hbar\frac{\partial}{\partial x}\right)f - \left(-i\hbar\frac{\partial}{\partial x}\right)(xf) \\
&= -i\hbar x\frac{\partial f}{\partial x} + i\hbar\left(f + x\frac{\partial f}{\partial x}\right) \\
&= i\hbar f \\
[p_x, x] &= \left(-i\hbar\frac{\partial}{\partial x}\right)(xf) - x\left(-i\hbar\frac{\partial}{\partial x}\right)f \\
&= -i\hbar\left(f + x\frac{\partial f}{\partial x}\right) + i\hbar x\frac{\partial f}{\partial x} \\
&= -i\hbar f \\
[x, p_y] &= x\left(-i\hbar\frac{\partial}{\partial y}\right)f - \left(-i\hbar\frac{\partial}{\partial y}\right)(xf) \\
&= -i\hbar x\frac{\partial f}{\partial y} + i\hbar x\frac{\partial f}{\partial y} \\
&= 0 \\
[r_i, p_j] &= i\hbar\delta_{ij} \\
[p_i, r_j] &= -i\hbar\delta_{ij}
\end{aligned}
$$

(b)

$$
\begin{aligned}
[\hat{H}, x]f &= \left(-\frac{\hbar^2}{2m}\nabla^2 + V\right)(xf) - x\left(-\frac{\hbar^2}{2m}\nabla^2 + V\right)f \\
&= -\frac{\hbar^2}{2m}\left[\frac{\partial}{\partial x}\left(f + x\frac{\partial f}{\partial x}\right) + \frac{\partial}{\partial y}\left(x\frac{\partial f}{\partial y}\right) + \frac{\partial}{\partial x}\left(z\frac{\partial f}{\partial z}\right)\right] \\
&\quad + Vxf + \frac{\hbar^2}{2m}x\nabla^2 f - Vxf \\
&= -\frac{\hbar^2}{2m}\left(2\frac{\partial f}{\partial x} + x\nabla^2 f\right) + \frac{\hbar^2}{2m}x\nabla^2 f \\
&= -\frac{\hbar^2}{m}\frac{\partial f}{\partial x} \\
[\hat{H}, x] &= -\frac{\hbar^2}{m}\frac{\partial}{\partial x} \\
[\hat{H}, \mathbf{r}] &= -\frac{\hbar^2}{m}\nabla \\
\frac{d}{dt}\langle \mathbf{r} \rangle &= \frac{i}{\hbar}\langle [\hat{H}, \mathbf{r}] \rangle \\
&= \frac{1}{m}\langle -i\hbar\nabla \rangle \\
&= \frac{1}{m}\langle \mathbf{p} \rangle \\
[\hat{H}, \hat{p}_x]f &= \left(-\frac{\hbar^2}{2m}\nabla^2 + V\right)\left(-i\hbar\frac{\partial}{\partial x}\right)f - \left(-i\hbar\frac{\partial}{\partial x}\right)\left(-\frac{\hbar^2}{2m}\nabla^2 + V\right)f \\
&= -i\hbar\left(-\frac{\hbar^2}{2m}\nabla^2 + V\right)\frac{\partial f}{\partial x} + i\hbar\left(\frac{\partial}{\partial x}\right)\left(-\frac{\hbar^2}{2m}\nabla^2 f + Vf\right) \\
&= i\frac{\hbar^3}{2m}\nabla^2\frac{\partial f}{\partial x} - i\hbar V\frac{\partial f}{\partial x} - i\frac{\hbar^3}{2m}\nabla^2\frac{\partial f}{\partial x} + i\hbar\left(\frac{\partial V}{\partial x}f + V\frac{\partial f}{\partial x}\right) \\
&= i\hbar\frac{\partial V}{\partial x}f \\
[\hat{H}, \hat{p}_x] &= i\hbar\frac{\partial V}{\partial x} \\
[\hat{H}, \mathbf{p}] &= i\hbar\nabla V \\
\frac{d}{dt}\langle \mathbf{p} \rangle &= \frac{i}{\hbar}\langle [\hat{H}, \mathbf{p}] \rangle \\
&= \langle -\nabla V \rangle
\end{aligned}
$$

(c)

$$\begin{aligned}\sigma_{r_i}\sigma_{p_j} &\geq \frac{1}{2i}\langle[r_i, p_j]\rangle \\ &= \frac{1}{2i} i\hbar\delta_{ij} \\ &= \frac{\hbar}{2}\delta_{ij}\end{aligned}$$

## 4.2

(a)

$$\begin{aligned}\psi(\mathbf{r}) &= X(x)Y(y)Z(z) \\ -\frac{\hbar^2}{2m}\nabla^2\psi &= E\psi \\ -\frac{\hbar^2}{2m}\left(\frac{\partial^2 X}{\partial x^2}YZ + X\frac{\partial^2 Y}{\partial y^2}Z + XY\frac{\partial^2 Z}{\partial z^2}\right) &= EXYZ \\ \frac{X''}{X} + \frac{Y''}{Y} + \frac{Z''}{Z} &= -\frac{2m}{\hbar^2}E\end{aligned}$$

The terms on the left hand side are each functions of a different variable, so they must be constant. Starting with the $X$ term:

$$\begin{aligned}\frac{X''}{X} &= -\alpha \\ X'' + \alpha X &= 0\end{aligned}$$

If $\alpha < 0$

$$X = A_x e^{\sqrt{-\alpha x}} + B_x e^{-\sqrt{-\alpha x}}$$

If $\alpha = 0$

$$X = A_x x + B_x$$

If $\alpha > 0$

$$X = A_x \sin(\sqrt{\alpha}x) + B_x \cos(\sqrt{\alpha}x)$$

Boundary conditions require that $\alpha > 0$. $X(0) = 0$ so $B_x = 0$. $X(a) = 0$ so $\sqrt{\alpha} = n_x\pi/a \Rightarrow \alpha = n_x^2\pi^2/a^2$,

$$X = A_x \sin\left(\frac{n_x\pi}{a}x\right).$$

Repeating the above for $Y$ and $Z$ finds

$$\begin{aligned}
Y &= A_y \sin\left(\frac{n_y \pi}{a} y\right) \\
Z &= A_z \sin\left(\frac{n_z \pi}{a} z\right)
\end{aligned}$$

so

$$\psi(\mathbf{r}) = A_x A_y A_z \sin\left(\frac{n_x \pi}{a} x\right) \sin\left(\frac{n_y \pi}{a} y\right) \sin\left(\frac{n_z \pi}{a} z\right).$$

Assuming $A_x = A_y = A_z = A$ and normalising finds

$$\begin{aligned}
1 &= \int_0^a \int_0^a \int_0^a A^6 \sin^2\left(\frac{n_x \pi}{a} x\right) \sin^2\left(\frac{n_y \pi}{a} y\right) \sin^2\left(\frac{n_z \pi}{a} z\right)\, d^3\mathbf{r} \\
&= A^6 \frac{a^3}{8} \\
A^6 &= \frac{8}{a^3} \\
&= \left(\frac{2}{a}\right)^3 \\
A &= \sqrt{\frac{2}{a}}
\end{aligned}$$

so

$$\psi(\mathbf{r}) = \left(\frac{2}{a}\right)^{3/2} \sin\left(\frac{n_x \pi}{a} x\right) \sin\left(\frac{n_y \pi}{a} y\right) \sin\left(\frac{n_z \pi}{a} z\right).$$

Finally

$$\begin{aligned}
-\frac{2m}{\hbar^2} E &= -\alpha - \beta - \gamma \\
&= -\frac{\pi^2 n_x^2}{a^2} - \frac{\pi^2 n_y^2}{a^2} - \frac{\pi^2 n_z^2}{a^2} \\
E &= \frac{\pi^2 \hbar^2}{2ma^2}(n_x^2 + n_y^2 + n_z^2),\ n_x, n_y, n_z = 1, 2, 3, \ldots
\end{aligned}$$

(b)

$$
\begin{aligned}
E_1 &= 3\frac{\pi^2\hbar^2}{2ma^2},\, n = 1 \\
E_2 &= 6\frac{\pi^2\hbar^2}{2ma^2},\, n = 3 \\
E_3 &= 9\frac{\pi^2\hbar^2}{2ma^2},\, n = 3 \\
E_4 &= 11\frac{\pi^2\hbar^2}{2ma^2},\, n = 3 \\
E_5 &= 12\frac{\pi^2\hbar^2}{2ma^2},\, n = 1 \\
E_6 &= 14\frac{\pi^2\hbar^2}{2ma^2},\, n = 6
\end{aligned}
$$

(c)

$$
\begin{aligned}
E_{14} &= 27\frac{\pi^2\hbar^2}{2ma^2} \\
d &= 4
\end{aligned}
$$

## 4.3

(a)

$$\begin{aligned}
\phi(r,\theta,\phi) &= Ae^{-r/a} \\
\frac{\partial\psi}{\partial r} &= -\frac{A}{a}e^{-r/a} \\
\frac{\partial}{\partial r}\left(r^2\frac{\partial\psi}{\partial r}\right) &= \frac{\partial}{\partial r}\left(-\frac{A}{a}r^2e^{-r/a}\right) \\
&= -\frac{A}{a}\left(2re^{-r/a}-\frac{1}{a}r^2e^{-r/a}\right) \\
&= \frac{A}{a^2}r^2\left(1-\frac{2a}{r}\right)e^{-r/a} \\
\frac{\partial\psi}{\partial\theta} &= 0 \\
\frac{\partial^2\psi}{\partial\phi^2} &= 0 \\
-\frac{\hbar^2}{2m}\frac{A}{a^2}\left(1-\frac{2a}{r}\right)e^{-r/a}+V(r)Ae^{-r/a} &= EAe^{-r/a} \\
-\frac{\hbar^2}{2ma^2}\left(1-\frac{2a}{r}\right)+V(r) &= E \\
-\frac{\hbar^2}{2ma^2} &= E \\
V(r) &= -\frac{\hbar^2}{mar}
\end{aligned}$$

(b)

$$\begin{aligned}
\phi(r,\theta,\phi) &= Ae^{-r^2/a^2} \\
\frac{\partial\psi}{\partial r} &= -\frac{2}{a^2}rAe^{-r^2/a^2} \\
\frac{\partial}{\partial r}\left(r^2\frac{\partial\psi}{\partial r}\right) &= \frac{\partial}{\partial r}\left(-\frac{2}{a^2}r^3Ae^{-r^2/a^2}\right) \\
&= -\frac{2A}{a^2}\left(3r^2e^{-r^2/a^2}-\frac{2}{a^2}r^4e^{-r^2/a^2}\right) \\
&= \frac{2A}{a^2}r^2\left(\frac{2}{a^2}r^2-3\right)e^{-r^2/a^2}
\end{aligned}$$

$$
\begin{aligned}
-\frac{\hbar^2}{2m}\frac{2A}{a^2}\left(\frac{2}{a^2}r^2-3\right)e^{-r^2/a^2}+V(r)Ae^{-r^2/a^2} &= EAe^{-r^2/a^2} \\
-\frac{\hbar^2}{2m}\frac{2}{a^2}\left(\frac{2}{a^2}r^2-3\right)+V(r) &= E \\
\frac{\hbar^2}{2m}\frac{2}{a^2}3 &= E \\
\frac{3\hbar^2}{ma^2} &= E \\
\frac{3\hbar^2}{ma^2}+\frac{\hbar^2}{2m}\frac{2}{a^2}\left(\frac{2}{a^2}r^2-3\right) &= V(r) \\
\frac{2\hbar^2}{ma^4}r^2 &= V(r)
\end{aligned}
$$

## 4.4

$$
\begin{aligned}
Y_0^0 &= \frac{1}{2\sqrt{\pi}} \\
Y_2^1 &= \frac{1}{2}\sqrt{\frac{5}{6\pi}}e^{i\phi}P_2^1(\cos\theta) \\
&= \frac{1}{2}\sqrt{\frac{5}{6\pi}}e^{i\phi}(-1)^1(1-\cos^2\theta)^{1/2}\left(\frac{d}{dx}\right)P_2(\cos\theta) \\
&= -\frac{1}{2}\sqrt{\frac{5}{6\pi}}e^{i\phi}\sin\theta\left(\frac{d\theta}{dx}\frac{d}{d\theta}\right)\frac{1}{2}(3\cos^2\theta-1) \\
&= -\frac{1}{4}\sqrt{\frac{5}{6\pi}}e^{i\phi}\sin\theta\left(-\frac{1}{\sin\theta}\right)(-6\cos\theta\sin\theta) \\
&= -\frac{1}{2}\sqrt{\frac{15}{2\pi}}e^{i\phi}\sin\theta\cos\theta \\
\int |Y_0^0|^2\,d\Omega &= \frac{1}{4\pi}\int_0^\pi\int_0^{2\pi}\sin\theta\,d\theta\,d\phi \\
&= 1 \\
\int |Y_2^1|^2\,d\Omega &= \frac{15}{8\pi}\int_0^\pi\int_0^{2\pi}\sin^3\theta\cos^2\theta\,d\theta\,d\phi \\
&= 1 \\
\int (Y_0^0)^*Y_2^1\,d\Omega &= -\frac{1}{2\sqrt{\pi}}\frac{1}{2}\sqrt{\frac{15}{2\pi}}\int_0^\pi\int_0^{2\pi}e^{i\phi}\sin^2\theta\cos\theta\,d\theta\,d\phi \\
&= 0
\end{aligned}
$$

## 4.5

$$
\begin{aligned}
\Theta(\theta) &= A\ln\left(\tan\frac{\theta}{2}\right) \\
0 &= \sin\theta\frac{d}{d\theta}\left(\sin\theta\frac{d\Theta}{d\theta}\right) \\
&= \frac{1}{2}A\sin\theta\frac{d}{d\theta}\left(\sin\theta\csc\frac{\theta}{2}\sec\frac{\theta}{2}\right) \\
&= \frac{1}{2}A\sin\theta\left(\cos\theta\csc\frac{\theta}{2}\sec\frac{\theta}{2} - \frac{1}{2}\csc^2\frac{\theta}{2}\sin\theta + \frac{1}{2}\sec^2\frac{\theta}{2}\sin\theta\right) \\
&= 0
\end{aligned}
$$

It's not a valid physical solution because it blows up at $\theta = 0$ and $\theta = \pi$.

## 4.6

$$
\begin{aligned}
Y_\ell^{-m} &= \sqrt{\frac{(2\ell+1)}{4\pi}\frac{(\ell+m)!}{(\ell-m)!}}e^{-im\phi}P_\ell^{-m}(\cos\theta) \\
&= \sqrt{\frac{(2\ell+1)}{4\pi}\frac{(\ell+m)!}{(\ell-m)!}}e^{-im\phi}(-1)^m\frac{(\ell-m)!}{(\ell+m)!}P_\ell^{m}(\cos\theta) \\
&= (-1)^m\sqrt{\frac{(2\ell+1)}{4\pi}\frac{(\ell-m)!}{(\ell+m)!}}e^{-im\phi}P_\ell^{m}(\cos\theta) \\
&= (-1)^m(Y_\ell^m)^*
\end{aligned}
$$

## 4.7

$$
\begin{aligned}
Y_3^2(\theta,\phi) &= \sqrt{\frac{7}{480\pi}}e^{2i\phi}P_3^2(\cos\theta) \\
&= \frac{1}{4}\sqrt{\frac{105}{2\pi}}e^{2i\phi}\sin^2\theta\cos\theta \\
Y_\ell^\ell(\theta,\phi) &= \sqrt{\frac{2\ell+1}{4\pi(2\ell)!}}e^{i\ell\phi}P_\ell^\ell(\cos\theta) \\
P_\ell^\ell(x) &= (-1)^\ell(1-x^2)^{\ell/2}\left(\frac{d}{dx}\right)^\ell P_\ell(x) \\
&= (-1)^\ell(1-x^2)^{\ell/2}\left(\frac{d}{dx}\right)^\ell \left[\frac{1}{2^\ell\ell!}\left(\frac{d}{dx}\right)^\ell (x^2-1)^\ell\right] \\
&= (-1)^\ell\frac{1}{2^\ell\ell!}(1-x^2)^{\ell/2}\left(\frac{d}{dx}\right)^{2\ell}(x^2-1)^\ell \\
&= (-1)^\ell\frac{(2\ell)!}{2^\ell\ell!}(1-x^2)^{\ell/2} \\
Y_\ell^\ell(\theta,\phi) &= \sqrt{\frac{2\ell+1}{4\pi(2\ell)!}}e^{i\ell\phi}(-1)^\ell\frac{(2\ell)!}{2^\ell\ell!}(1-\cos^2\theta)^{\ell/2} \\
&= \frac{1}{\ell!}\sqrt{\frac{(2\ell+1)!}{4\pi}}\left(-\frac{1}{2}e^{i\phi}\sin\theta\right)^\ell
\end{aligned}
$$