

# Introduction to Quantum Mechanics by David J. Griffiths Problems

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## 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)

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

(b)

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

## 1.4

(a)

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

(c)  $x = a$

(d)

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

(e)

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

## 1.5

(a)

$$\Psi(x, t) = Ae^{-\lambda|x|}e^{-i\omega t}$$

$$\Psi(x, 0) = Ae^{-\lambda|x|}$$

$$\begin{aligned} 1 &= A^2 \int_{-\infty}^{\infty} e^{-2\lambda|x|} dx \\ &= 2A^2 \int_0^{\infty} e^{-2\lambda x} dx \\ &= 2A^2 \left[ -\frac{1}{2\lambda} e^{-2\lambda x} \right]_0^{\infty} \\ &= \frac{A^2}{\lambda} \\ A &= \sqrt{\lambda} \end{aligned}$$

(b)

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

(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

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

$$\begin{aligned}
 \langle Q(x, p) \rangle &= \int \left( e^{-iV_0 t/\hbar} \Psi \right)^* [Q(x, -i\hbar \partial/\partial x)] e^{-iV_0 t/\hbar} \Psi dx \\
 &= \int e^{iV_0 t/\hbar} \Psi^* [Q(x, -i\hbar \partial/\partial x)] e^{-iV_0 t/\hbar} \Psi dx \\
 &= \int \Psi^* [Q(x, -i\hbar \partial/\partial x)] \Psi dx
 \end{aligned}$$

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)

$$\begin{aligned}
\langle x \rangle &= A^2 \int_{-\infty}^{\infty} e^{-2a(mx^2/\hbar)} x \, dx \\
&= 0 \\
\langle x^2 \rangle &= A^2 \int_{-\infty}^{\infty} e^{-2a(mx^2/\hbar)} x^2 \, dx \\
&= 2A^2 \int_0^{\infty} e^{-2a(mx^2/\hbar)} x^2 \, dx \\
&= \frac{\hbar}{4am} \\
\langle p \rangle &= \int_{-\infty}^{\infty} \Psi^* \left[ -i\hbar \frac{\partial}{\partial x} \right] \Psi \, dx \\
&= -i\hbar \int_{-\infty}^{\infty} A e^{-a[(mx^2/\hbar)-it]} \left( -\frac{2amx}{\hbar} A e^{-a[(mx^2/\hbar)+it]} \right) dx \\
&= 2iA^2 am \int_{-\infty}^{\infty} x e^{-2amx^2/\hbar} \, dx \\
&= 0 \\
\langle p^2 \rangle &= \int_{-\infty}^{\infty} \Psi^* \left[ -\hbar^2 \frac{\partial^2}{\partial x^2} \right] \Psi \, dx \\
&= -\hbar^2 \int_{-\infty}^{\infty} A e^{-a[(mx^2/\hbar)-it]} \left[ -\frac{2am}{\hbar} \left( 1 - \frac{2amx^2}{\hbar} \right) A e^{-a[(mx^2/\hbar)+it]} \right] dx \\
&= 2A^2 am\hbar \int_{-\infty}^{\infty} e^{-2amx^2/\hbar} \left( 1 - \frac{2amx^2}{\hbar} \right) dx \\
&= am\hbar
\end{aligned}$$

(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)

$$P(0) = 0$$

$$\begin{aligned} P(1) &= \frac{2}{25} \\ &= 0.08 \end{aligned}$$

$$\begin{aligned} P(2) &= \frac{3}{25} \\ &= 0.12 \end{aligned}$$

$$\begin{aligned} P(3) &= \frac{1}{5} \\ &= 0.2 \end{aligned}$$

$$\begin{aligned} P(4) &= \frac{3}{25} \\ &= 0.12 \end{aligned}$$

$$\begin{aligned} P(5) &= \frac{3}{25} \\ &= 0.2 \end{aligned}$$

$$\begin{aligned} P(6) &= \frac{3}{25} \\ &= 0.2 \end{aligned}$$

$$\begin{aligned} P(7) &= \frac{1}{25} \\ &= 0.04 \end{aligned}$$

$$\begin{aligned} P(8) &= \frac{2}{25} \\ &= 0.08 \end{aligned}$$

$$\begin{aligned} P(9) &= \frac{3}{25} \\ &= 0.12 \end{aligned}$$

(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)

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

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

(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

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

1.16

(a)

$$\begin{aligned}
1 &= \int_{-a}^a A^2 (a^2 - x^2)^2 \, dx \\
&= A^2 \int_0^a (a^2 - x^2)^2 \, dx \\
&= \frac{16}{15} A^2 a^5 \\
A &= \sqrt{\frac{15}{16a^5}}
\end{aligned}$$

(b)

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

(c)

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

(d)

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

(e)

$$\begin{aligned}\langle p^2 \rangle &= \int_{-a}^a \Psi^* \left( -\hbar^2 \frac{\partial^2}{\partial x^2} \right) \Psi dx \\ &= -\hbar^2 \int_{-a}^a A(a^2 - x^2)(-2A) dx \\ &= 4A^2 \hbar^2 \int_0^a (a^2 - x^2) dx \\ &= 4A^2 \hbar^2 \left[ a^2 x - \frac{1}{3} x^3 \right]_0^a \\ &= 4A^2 \hbar^2 \left( a^3 - \frac{1}{3} a^3 \right) \\ &= \frac{8}{3} A^2 a^3 \hbar^2 \\ &= \frac{8}{3} \frac{15}{16a^5} a^3 \hbar^2 \\ &= \frac{5}{2} \frac{\hbar^2}{a^2}\end{aligned}$$

(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)

$$\begin{aligned}\sigma_x \sigma_p &= \sqrt{\frac{5}{14}} \hbar \\ &\geq \frac{1}{2} \hbar\end{aligned}$$

**1.18**

(a)

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

(b)

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

## 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

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

## 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

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

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

## 2.7

(a)

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

(b)

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

(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)

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

## 2.11

(a)

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



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

(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)

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

## 2.12

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

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

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

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

$$\begin{aligned}
\langle T \rangle &= \left\langle \frac{p^2}{2m} \right\rangle \\
&= \frac{1}{2} \hbar \omega \left( n + \frac{1}{2} \right)
\end{aligned}$$

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

## 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)

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

(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

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

$$= 0.157$$

2.15

$$a_{j+2} = \frac{-2(n-j)}{(j+1)(j+2)} a_j$$

$$a_3 = -\frac{4}{3} a_1$$

$$a_5 = \frac{4}{15} a_1$$

$$H_5(\xi) = a_1 \left( \xi - \frac{4}{3} \xi^3 + \frac{4}{15} \xi^5 \right)$$

$$= \frac{1}{120} a_1 (120\xi - 160\xi^3 + 32\xi^5)$$

$$= 32\xi^5 - 160\xi^3 + 120\xi$$

$$a_2 = -6a_0$$

$$a_4 = \frac{-8}{12} a_2$$

$$= 4a_0$$

$$a_6 = \frac{-4}{30} a_4$$

$$= -\frac{8}{15} a_0$$

$$H_6(\xi) = a_0 \left( 1 - 6\xi^2 + 4\xi^4 - \frac{8}{15} \xi^6 \right)$$

$$= \frac{1}{120} a_0 (120 - 720\xi^2 + 480\xi^4 - 64\xi^6)$$

$$= 64\xi^6 - 480\xi^4 + 720\xi^2 - 120$$

## 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)

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

(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)

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

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

(d)

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

## 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

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

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**

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

## 2.34

(a)

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

(b)

$$\psi(x) = \begin{cases} Ae^{ikx} + Be^{-ikx} & x < 0 \\ Fe^{ilx} & x > 0 \end{cases}$$

$$k = \frac{\sqrt{2mE}}{\hbar}$$

$$l = \frac{\sqrt{2m(E - V_0)}}{\hbar}$$

$$A + B = F$$

$$ik(A - B) = ilF$$

$$F = \frac{k}{l}(A - B)$$

$$A + B = \frac{k}{l}(A - B)$$

$$\left(\frac{k}{l} + 1\right)B = \left(\frac{k}{l} - 1\right)A$$

$$B = \frac{k/l - 1}{k/l + 1}A$$

$$R = \frac{|B|^2}{|A|^2}$$

$$= \left(\frac{k/l - 1}{k/l + 1}\right)^2$$

$$= \left(\frac{k - l}{k + l}\right)^2$$

$$= \frac{(k - l)^4}{(k^2 - l^2)^2}$$

$$k^2 - l^2 = \frac{2mE}{\hbar^2} - \frac{2m(E - V_0)}{\hbar^2}$$

$$= \frac{2m}{\hbar^2}V_0$$

$$k - l = \frac{\sqrt{2m}}{\hbar}(\sqrt{E} - \sqrt{E - V_0})$$

$$R = \frac{(\sqrt{E} - \sqrt{E - V_0})^4}{V_0^2}$$

(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

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

### 2.37

$$\begin{aligned}
\Psi(x, 0) &= A \sin^3 \left( \frac{\pi}{a} x \right) \\
&= A \left[ \frac{3}{4} \sin \left( \frac{\pi}{a} x \right) - \frac{1}{4} \sin \left( \frac{3\pi}{a} x \right) \right] \\
&= A \sqrt{\frac{a}{2}} \left[ \frac{3}{4} \psi_1(x) - \frac{1}{4} \psi_3(x) \right] \\
1 &= |A|^2 \frac{a}{2} \int_0^a \left[ \frac{3}{4} \psi_1(x) - \frac{1}{4} \psi_3(x) \right]^2 dx \\
&= |A|^2 \frac{a}{2} \int_0^a \left[ \frac{9}{16} \psi_1(x)^2 - \frac{3}{8} \psi_1(x) \psi_3(x) + \frac{1}{16} \psi_3(x)^2 \right] dx \\
&= \frac{5}{16} a |A|^2 \\
A &= \frac{4}{\sqrt{5a}} \\
\Psi(x, 0) &= \frac{1}{\sqrt{10}} [3\psi_1(x) - \psi_3(x)] \\
\Psi(x, t) &= \frac{1}{\sqrt{10}} [3\psi_1(x) e^{-iE_1 t/\hbar} - \psi_3(x) e^{-iE_3 t/\hbar}] \\
\langle x \rangle &= \int_0^a \Psi^* x \Psi dx \\
&= \frac{1}{10} \int_0^a x \left( 9\psi_1^2 + \psi_3^2 - 3\psi_1\psi_3 e^{-i(E_3-E_1)t/\hbar} - 3\psi_1\psi_3 e^{-i(E_1-E_3)t/\hbar} \right) dx \\
&= \frac{1}{10} \int_0^a x \left[ 9\psi_1^2 + \psi_3^2 - 6\psi_1\psi_3 \cos \left( \frac{E_3 - E_1}{\hbar} t \right) \right] dx \\
&= \frac{1}{10} \left[ 9 \langle x \rangle_1 + \langle x \rangle_3 - 6 \cos \left( \frac{E_3 - E_1}{\hbar} t \right) \int_0^a x \psi_1 \psi_3 dx \right] \\
&= \frac{1}{10} \left[ \frac{9}{2} a + \frac{1}{2} a \right] \\
&= \frac{a}{2} \\
P(E_1) &= \frac{9}{10} \\
P(E_3) &= \frac{1}{10} \\
\langle E \rangle &= E_1 P(E_1) + E_3 P(E_3) \\
&= \frac{9\pi^2 \hbar^2}{20ma^2} + \frac{9\pi^2 \hbar^2}{20ma^2} \\
&= \frac{9\pi^2 \hbar^2}{10ma^2}
\end{aligned}$$

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)

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

(c)

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

### 2.39

(a)

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

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

(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)

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

(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)

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

## 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

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



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  $|\alpha\rangle = |0\rangle$ .

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

### 3.2

(a)

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

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)

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

### 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)

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

### 3.6

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

Yes, the operator is hermitian.

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

The eigenfunctions are  $f = Ae^{\pm\sqrt{q}\phi}$  and the eigenvalues are  $q = 0, 1, 2, \dots$ . 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)

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

(b)

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

### 3.9

(a) Infinite square well

(b) Delta function barrier

(c) Delta function well

### 3.11

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

### 3.12

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



### 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)

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

### 3.15

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

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

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

### 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

$$\begin{aligned}\Psi &= \frac{1}{\sqrt{2}}(\psi_1 e^{-iE_1 t/\hbar} + \psi_2 e^{-iE_2 t/\hbar}) \\ \hat{H}\Psi &= \frac{1}{\sqrt{2}}(E_1 \psi_1 e^{-iE_1 t/\hbar} + E_2 \psi_2 e^{-iE_2 t/\hbar}) \\ \hat{H}^2\Psi &= \frac{1}{\sqrt{2}}(E_1^2 \psi_1 e^{-iE_1 t/\hbar} + E_2^2 \psi_2 e^{-iE_2 t/\hbar}) \\ \langle H^2 \rangle &= \langle \Psi | \hat{H}^2 | \Psi \rangle \\ &= \frac{1}{2} \int_0^a (\psi_1^* e^{iE_1 t/\hbar} + \psi_2^* e^{iE_2 t/\hbar})(E_1^2 \psi_1 e^{-iE_1 t/\hbar} + E_2^2 \psi_2 e^{-iE_2 t/\hbar}) dx \\ &= \frac{1}{2} \int_0^a (E_1^2 |\psi_1|^2 + E_2^2 \psi_1^* \psi_2^* e^{i(E_1 - E_2)t/\hbar} + E_1^2 \psi_2^* \psi_1 e^{i(E_2 - E_1)t/\hbar} \\ &\quad + E_2^2 |\psi_2|^2) dx \\ &= \frac{1}{2}(E_1^2 + E_2^2) \\ \langle H \rangle &= \frac{1}{2}(E_1 + E_2) \\ \sigma_H^2 &= \langle H^2 \rangle - \langle H \rangle^2 \\ &= \frac{1}{2}(E_1^2 + E_2^2) - \frac{1}{4}(E_1 + E_2)^2 \\ &= \frac{1}{4}(E_2 - E_1)^2\end{aligned}$$

$$\begin{aligned}
\omega &= \frac{\pi^2 \hbar}{2ma^2} \\
\langle x \rangle &= \frac{a}{2} \left[ 1 - \frac{32}{9\pi^2} \cos(3\omega t) \right] \\
\langle x^2 \rangle &= \frac{1}{2} \int_0^a (\psi_1^* e^{iE_1 t/\hbar} + \psi_2^* e^{iE_2 t/\hbar}) x^2 (\psi_1 e^{-iE_1 t/\hbar} + \psi_2 e^{-iE_2 t/\hbar}) dx \\
&= \frac{1}{2} \int_0^a x^2 (|\psi_1|^2 + \psi_1^* \psi_2 e^{i(E_1 - E_2)t/\hbar} + \psi_2^* \psi_1 e^{i(E_2 - E_1)t/\hbar} + |\psi_2|^2) dx \\
&= \frac{1}{a} \int_0^a x^2 \left[ \sin^2\left(\frac{\pi}{a}x\right) + \sin^2\left(\frac{2\pi}{a}x\right) \right. \\
&\quad \left. + 2 \sin\left(\frac{\pi}{a}x\right) \sin\left(\frac{2\pi}{a}x\right) \cos(3\omega t) \right] dx \\
&= \frac{a^2}{144\pi^2} [-45 + 48\pi^2 - 256 \cos(3\omega t)] \\
\sigma_x^2 &= \langle x^2 \rangle - \langle x \rangle^2 \\
&= \frac{a^2}{4} \left[ \frac{1}{3} - \frac{5}{4\pi^2} - \left( \frac{32}{9\pi^2} \right)^2 \cos^2(3\omega t) \right] \\
\frac{d\langle x \rangle}{dt} &= \frac{16a\omega}{3\pi^2} \sin(3\omega t) \\
&= \frac{8\hbar}{3ma} \sin(3\omega t)
\end{aligned}$$

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