

Introduction to Quantum Mechanics by David J. Griffiths Problems

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Contents

I	Theory	2
1	The Wave Function	2
1.1	2
1.2	3
1.3	4
1.4	5
1.5	6
1.6	7
1.8	7
1.9	8
1.10	10
1.14	.....	11
1.15	.....	12
1.16	.....	12
1.18	.....	14
2	Time-Independent Schrödinger Equation	14
2.1	.....	14
2.2	.....	15
2.3	.....	15
2.4	.....	16
2.5	.....	17
2.6	.....	18
2.7	.....	19
2.8	.....	21
2.9	.....	21
2.10	.....	22
2.11	.....	23
2.12	.....	26

2.13	27
2.14	29
2.15	29
2.17	30
2.18	30
2.20	30
2.21	31
2.22	32
2.26	33
2.29	33
2.30	34
2.31	35
2.34	36
2.35	39

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)

$$\Delta j_{14} = -7$$

$$\Delta j_{15} = -6$$

$$\Delta j_{16} = -5$$

$$\Delta j_{22} = 1$$

$$\Delta j_{24} = 3$$

$$\Delta j_{25} = 4$$

$$\begin{aligned}\sigma^2 &= \sum (\Delta j)^2 P(j) \\ &= \frac{130}{7} \\ &\approx 18.571\end{aligned}$$

(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)

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

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 , Γ 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 ψ and its second derivative always have the same sign, ψ 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)

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