

Exercises

Review Questions

1. Why is the quantum-mechanical model of the atom important for understanding chemistry?
2. What is light? How fast does it travel in a vacuum?
3. Define the wavelength and amplitude of a wave.
4. Define the frequency of electromagnetic radiation. How is frequency related to wavelength?
5. What determines the color of light? Describe the difference between red light and blue light.
6. What determines the color of a colored object? Explain why grass appears green.
7. Give an approximate range of wavelengths for each type of electromagnetic radiation and summarize the characteristics and/or the uses of each.
 - a. gamma rays
 - b. X-rays
 - c. ultraviolet radiation
 - d. visible light
 - e. infrared radiation
 - f. microwave radiation
 - g. radio waves
8. Explain the wave behavior known as interference. Explain the difference between constructive and destructive interference.
9. Explain the wave behavior known as diffraction. Draw the diffraction pattern that occurs when light travels through two slits comparable in size and separation to the light's wavelength.
10. Describe the photoelectric effect. How did experimental observations of this phenomenon differ from the predictions of classical electromagnetic theory?
11. How did the photoelectric effect lead Einstein to propose that light is quantized?
12. What is a photon? How is the energy of a photon related to its wavelength? Its frequency?
13. What is an emission spectrum? How does an emission spectrum of a gas in a discharge tube differ from a white light spectrum?
14. Describe the Bohr model for the atom. How did the Bohr model account for the emission spectra of atoms?
15. Explain electron diffraction.
16. What is the de Broglie wavelength of an electron? What determines the value of the de Broglie wavelength for an electron?
17. What are complementary properties? How does electron diffraction demonstrate the complementarity of the wave nature and particle nature of the electron?
18. Explain Heisenberg's uncertainty principle. What paradox is at least partially solved by the uncertainty principle?
19. What is a trajectory? What kind of information do you need to predict the trajectory of a particle?
20. Why does the uncertainty principle make it impossible to predict a trajectory for the electron?
21. Newton's laws of motion are *deterministic*. Explain this statement.
22. An electron behaves in ways that are at least partially indeterminate. Explain this statement.
23. What is a probability distribution map?
24. For each solution to the Schrödinger equation, which quantity can be precisely specified: the electron's energy or its position? Explain.
25. What is a quantum-mechanical orbital?
26. What is the Schrödinger equation? What is a wave function? How is a wave function related to an orbital?
27. What are the possible values of the principal quantum number n ? What does the principal quantum number determine?
28. What are the possible values of the angular momentum quantum number l ? What does the angular

momentum quantum number determine?

29. What are the possible values of the magnetic quantum number m_l ? What does the magnetic quantum number determine?
30. List all the orbitals in each principal level. Specify the three quantum numbers for each orbital.
 - a. $n = 1$
 - b. $n = 2$
 - c. $n = 3$
 - d. $n = 4$
31. Explain the difference between a plot showing the probability density for an orbital and one showing the radial distribution function.
32. Sketch the general shapes of the s , p , and d orbitals.
33. List the four different sublevels. Given that only a maximum of two electrons can occupy an orbital, determine the maximum number of electrons that can exist in each sublevel.
34. Why are atoms usually portrayed as spheres when most orbitals are not spherically shaped?

Problems by Topic

Note: Answers to all odd-numbered Problems can be found in [Appendix III](#). Exercises in the Problems by Topic section are paired, with each odd-numbered problem followed by a similar even-numbered problem. Exercises in the Cumulative Problems section are also paired but more loosely. Because of their nature, Challenge Problems and Conceptual Problems are unpaired.

Electromagnetic Radiation

35. The distance from the sun to Earth is 1.496×10^8 km. How long does it take light to travel from the sun to Earth?
36. The nearest star to our sun is Proxima Centauri, at a distance of 4.3 light-years from the sun. A light-year is the distance that light travels in one year (365 days). How far away, in km, is Proxima Centauri from the sun?
37. List these types of electromagnetic radiation in order of (i) increasing wavelength and (ii) increasing energy per photon:
 - a. radio waves
 - b. microwaves
 - c. infrared radiation
 - d. ultraviolet radiation
38. List these types of electromagnetic radiation in order of (i) increasing frequency and (ii) decreasing energy per photon:
 - a. gamma rays
 - b. radio waves
 - c. microwaves
 - d. visible light
39. Calculate the frequency of each wavelength of electromagnetic radiation:
 - a. 632.8 nm (wavelength of red light from helium–neon laser)
 - b. 503 nm (wavelength of maximum solar radiation)
 - c. 0.052 nm (wavelength contained in medical X-rays)
40. Calculate the wavelength of each frequency of electromagnetic radiation:
 - a. 100.2 MHz (typical frequency for FM radio broadcasting)
 - b. 1070 kHz (typical frequency for AM radio broadcasting) (assume four significant figures)
 - c. 835.6 MHz (common frequency used for cell phone communication)
41. Calculate the energy of a photon of electromagnetic radiation at each of the wavelengths indicated in [Problem 39](#).
42. Calculate the energy of a photon of electromagnetic radiation at each of the frequencies indicated in [Problem 40](#).
43. A laser pulse with wavelength 532 nm contains 3.85 mJ of energy. How many photons are in the laser pulse?
44. A heat lamp produces 32.8 watts of power at a wavelength of $6.5 \mu\text{m}$. How many photons are emitted per second? (1 watt = 1 J/s)
45. Determine the energy of 1 mol of photons for each kind of light. (Assume three significant figures.)
 - a. 600 nm (red light)
 - b. 450 nm (blue light)
 - c. 1.55 μm (infrared light)

- a. infrared radiation (1500 nm)
- b. visible light (500 nm)
- c. ultraviolet radiation (150 nm)

46. How much energy is contained in 1 mol of each?
- a. X-ray photons with a wavelength of 0.135 nm
 - b. γ -ray photons with a wavelength of 2.15×10^{-5} nm

The Wave Nature of Matter and the Uncertainty Principle

47. Sketch the interference pattern that results from the diffraction of electrons passing through two closely spaced slits.
48. What happens to the interference pattern described in **Problem 47** if the rate of electrons going through the slits is decreased to one electron per hour? What happens to the pattern if we try to determine which slit the electron goes through by using a laser placed directly behind the slits?
49. The resolution limit of a microscope is roughly equal to the wavelength of light used in producing the image. Electron microscopes use an electron beam (in place of photons) to produce much higher resolution images, about 0.20 nm in modern instruments. Assuming that the resolution of an electron microscope is equal to the de Broglie wavelength of the electrons used, to what speed must the electrons be accelerated to obtain a resolution of 0.20 nm?
50. The smallest atoms can themselves exhibit quantum-mechanical behavior. Calculate the de Broglie wavelength (in pm) of a hydrogen atom traveling 475 m/s.
51. What is the de Broglie wavelength of an electron traveling at 1.35×10^5 m/s?
52. A proton in a linear accelerator has a de Broglie wavelength of 122 pm. What is the speed of the proton?
53. Calculate the de Broglie wavelength of a 143-g baseball traveling at 95 mph. Why is the wave nature of matter not important for a baseball?
54. A 0.22-caliber handgun fires a 27-g bullet at a velocity of 765 m/s. Calculate the de Broglie wavelength of the bullet. Is the wave nature of matter significant for bullets?
55. An electron has an uncertainty in its position of 552 pm. What is the uncertainty in its velocity? (Hint: $\Delta x = 552 \times 10^{-12}$ m; use **Equation 2.5** to calculate Δv .)
56. An electron traveling at 1.35×10^5 m/s has an uncertainty in its velocity of 1.88×10^5 m/s. What is the uncertainty in its position?

Orbitals and Quantum Numbers

57. Which electron is, on average, closer to the nucleus: an electron in a 2s orbital or an electron in a 3s orbital?
58. Which electron is, on average, further from the nucleus: an electron in a 3p orbital or an electron in a 4p orbital?
59. What are the possible values of l for each given value of n ?
- a. 1
 - b. 2
 - c. 3
 - d. 4
60. What are the possible values of m_l for each given value of l ?
- a. 0
 - b. 1
 - c. 2
 - d. 3
61. Which set of quantum numbers *cannot* occur together to specify an orbital?
- a. $n = 2, l = 1, m_l = -1$
 - b. $n = 3, l = 2, m_l = 0$
 - c. $n = 3, l = 3, m_l = 2$
 - d. $n = 4, l = 3, m_l = 0$
62. Which combinations of n and l represent real orbitals, and which do not exist?
- a. 1s
 - b. 2p
 - c. 4s
 - d. 2d

63. Sketch the 1s and 2p orbitals. How do the 2s and 3p orbitals differ from the 1s and 2p orbitals?

63. Sketch the $2s$ and $2p$ orbitals. How do the $2s$ and $2p$ orbitals differ from the $1s$ and $1p$ orbitals?

64. Sketch the $3d$ orbitals. How do the $4d$ orbitals differ from the $3d$ orbitals?

Atomic Spectroscopy

65. An electron in a hydrogen atom is excited with electrical energy to an excited state with $n = 2$. The atom then emits a photon. What is the value of n for the electron following the emission?
66. Determine whether each transition in the hydrogen atom corresponds to absorption or emission of energy.
- $n = 3 \rightarrow n = 1$
 - $n = 2 \rightarrow n = 4$
 - $n = 4 \rightarrow n = 3$
67. According to the quantum-mechanical model for the hydrogen atom, which electron transition produces light with the longer wavelength: $2p \rightarrow 1s$ or $3p \rightarrow 1s$?
68. According to the quantum-mechanical model for the hydrogen atom, which electron transition produces light with the longer wavelength: $4p \rightarrow 2s$ or $4p \rightarrow 3p$?
69. Calculate the wavelength of the light emitted when an electron in a hydrogen atom makes each transition and indicate the region of the electromagnetic spectrum (infrared, visible, ultraviolet, etc.) where the light is found.
- $n = 2 \rightarrow n = 1$
 - $n = 3 \rightarrow n = 1$
 - $n = 4 \rightarrow n = 2$
 - $n = 5 \rightarrow n = 2$
70. Calculate the frequency of the light emitted when an electron in a hydrogen atom makes each transition:
- $n = 4 \rightarrow n = 3$
 - $n = 5 \rightarrow n = 1$
 - $n = 5 \rightarrow n = 4$
 - $n = 6 \rightarrow n = 5$
71. An electron in the $n = 7$ level of the hydrogen atom relaxes to a lower energy level, emitting light of 397 nm. What is the value of n for the level to which the electron relaxed?
72. An electron in a hydrogen atom relaxes to the $n = 4$ level, emitting light of 114 THz. What is the value of n for the level in which the electron originated?

Cumulative Problems

73. Ultraviolet radiation and radiation of shorter wavelengths can damage biological molecules because they carry enough energy to break bonds within the molecules. A typical carbon-carbon bond requires 348 kJ/mol to break. What is the longest wavelength of radiation with enough energy to break carbon-carbon bonds?
74. The human eye contains a molecule called 11-*cis*-retinal that changes shape when struck with light of sufficient energy. The change in shape triggers a series of events that results in an electrical signal being sent to the brain. The minimum energy required to change the conformation of 11-*cis*-retinal within the eye is about 164 kJ/mol. Calculate the longest wavelength visible to the human eye.
75. An argon ion laser puts out 5.0 W of continuous power at a wavelength of 532 nm. The diameter of the laser beam is 5.5 mm. If the laser is pointed toward a pinhole with a diameter of 1.2 mm, how many photons will travel through the pinhole per second? Assume that the light intensity is equally distributed throughout the entire cross-sectional area of the beam. (1 W = 1 J/s) *Hint:* Use the formula for the area of a circle ($A = \pi r^2$) to find the cross-sectional area of the beam and of the pinhole and determine what fraction of the power gets through the pinhole.
76. A green leaf has a surface area of 2.50 cm^2 . If solar radiation is 1000 W/m^2 , how many photons strike the leaf every second? Assume three significant figures and an average wavelength of 504 nm for solar radiation.
77. In a technique used for surface analysis called auger electron spectroscopy (AES), electrons are accelerated toward a metal surface. These electrons cause the emissions of secondary electrons—called auger electrons—from the metal surface. The kinetic energy of the auger electrons depends on the composition of the surface. The presence of oxygen atoms on the surface results in auger electrons with a kinetic energy of approximately 506 eV. What is the de Broglie wavelength of one of these electrons?

$$\left[\text{KE} = \frac{1}{2}mv^2; 1 \text{ electron volt (eV)} = 1.602 \times 10^{-19} \text{ J} \right]$$

78. An X-ray photon of wavelength 0.989 nm strikes a surface. The emitted electron has a kinetic energy of 969 eV. What is the binding energy of the electron in kJ/mol? *Hint:* The kinetic energy of the electron is equal to the energy of the photon ($h\nu$) minus the binding energy of the electron (ϕ): $KE = h\nu - \phi$.

$$[1 \text{ electron volt (eV)} = 1.602 \times 10^{-19} \text{ J}]$$

79. Ionization involves completely removing an electron from an atom. How much energy is required to ionize a hydrogen atom in its ground (or lowest energy) state? What wavelength of light contains enough energy in a single photon to ionize a hydrogen atom?
80. The energy required to ionize sodium is 496 kJ/mol. What minimum frequency of light is required to ionize sodium?
81. Suppose that in an alternate universe, the possible values of l are the integer values from 0 to n (instead of 0 to $n - 1$). Assuming no other differences between this imaginary universe and ours, how many orbitals would exist in each level?
- $n = 1$
 - $n = 2$
 - $n = 3$
82. Suppose that, in an alternate universe, the possible values of m_l are the integer values including 0 ranging from $-l - 1$ to $l + 1$ (instead of simply $-l$ to l). How many orbitals exist in each sublevel?
- s sublevel
 - p sublevel
 - d sublevel
83. An atomic emission spectrum of hydrogen shows three wavelengths: 1875 nm, 1282 nm, and 1093 nm. Assign these wavelengths to transitions in the hydrogen atom.
84. An atomic emission spectrum of hydrogen shows three wavelengths: 121.5 nm, 102.6 nm, and 97.23 nm. Assign these wavelengths to transitions in the hydrogen atom.
85. The binding energy of electrons in a metal is 193 kJ/mol. Find the threshold frequency of the metal.
86. In order for a thermonuclear fusion reaction of two deuterons (${}^2_1\text{H}^+$) to take place, the deuterons must collide with each deuteron traveling at 1×10^6 m/s. Find the wavelength of such a deuteron.
87. The speed of sound in air is 344 m/s at room temperature. The lowest frequency of a large organ pipe is 30 s^{-1} and the highest frequency of a piccolo is $1.5 \times 10^4 \text{ s}^{-1}$. Determine the difference in wavelength between these two sounds.
88. The distance from Earth to the sun is 1.5×10^8 km. Find the number of crests in a light wave of frequency $1.0 \times 10^{14} \text{ s}^{-1}$ traveling from the sun to the Earth.
89. The iodine molecule can be photodissociated (broken apart with light) into iodine atoms in the gas phase with light of wavelengths shorter than about 792 nm. A glass tube contains 1.80×10^{17} iodine molecules. What minimum amount of light energy must be absorbed by the iodine in the tube to dissociate 15.0% of the molecules?
90. An ampule of naphthalene in hexane contains 5.00×10^{-4} mol naphthalene. The naphthalene is excited with a flash of light and then emits 15.5 J of energy at an average wavelength of 349 nm. What percentage of the naphthalene molecules emitted a photon?
91. A laser produces 20.0 mW of red light. In 1.00 hr, the laser emits 2.29×10^{20} photons. What is the wavelength of the laser?
92. A particular laser consumes 150.0 watts of electrical power and produces a stream of 1.33×10^{19} 1064-nm photons per second. What is the percent efficiency of the laser in converting electrical power to light?

Challenge Problems

93. An electron confined to a one-dimensional box has energy levels given by the equation

$$E_n = n^2 h^2 / 8 m L^2$$

where n is a quantum number with possible values of 1, 2, 3, ..., m is the mass of the particle, and L is the length of the box.

- Calculate the energies of the $n = 1$, $n = 2$, and $n = 3$ levels for an electron in a box with a length of 155 pm.
- Calculate the wavelength of light required to make a transition from $n = 1 \rightarrow n = 2$ and from

$n = 2 \rightarrow n = 3$. In what region of the electromagnetic spectrum do these wavelengths lie?

94. The energy of a vibrating molecule is quantized much like the energy of an electron in the hydrogen atom. The energy levels of a vibrating molecule are given by the equation

$$E_n = \left(n + \frac{1}{2} \right) h\nu$$

where n is a quantum number with possible values of 1, 2, ..., and ν is the frequency of vibration. The vibration frequency of HCl is approximately $8.85 \times 10^{13} \text{ s}^{-1}$. What minimum energy is required to excite a vibration in HCl? What wavelength of light is required to excite this vibration?

95. The wave functions for the 1s and 2s orbitals are as follows:

$$\begin{aligned} 1s \psi &= (1/\pi)^{1/2} \left(1/a_0^{3/2} \right) \exp(-r/a_0) \\ 2s \psi &= (1/32\pi)^{1/2} \left(1/a_0^{3/2} \right) (2 - r/a_0) \exp(-r/a_0) \end{aligned}$$

where a_0 is a constant ($a_0 = 53 \text{ pm}$) and r is the distance from the nucleus. Use a spreadsheet to make a plot of each of these wave functions for values of r ranging from 0 pm to 200 pm. Describe the differences in the plots and identify the node in the 2s wave function.

96. Before quantum mechanics was developed, Johannes Rydberg developed an equation that predicted the wavelengths (λ) in the atomic spectrum of hydrogen:

$$1/\lambda = R(1/m^2 - 1/n^2)$$

In this equation R is a constant and m and n are integers. Use the quantum-mechanical model for the hydrogen atom to derive the Rydberg equation.

97. Find the velocity of an electron emitted by a metal whose threshold frequency is $2.25 \times 10^{14} \text{ s}^{-1}$ when it is exposed to visible light of wavelength $5.00 \times 10^{-7} \text{ m}$.
98. Water is exposed to infrared radiation of wavelength $2.8 \times 10^{-4} \text{ cm}$. Assume that all the radiation is absorbed and converted to heat. How many photons are required for the sample to absorb 16.72 J of heat?
99. The 2005 Nobel Prize in Physics was given, in part, to scientists who had made ultrashort pulses of light. These pulses are important in making measurements involving very short time periods. One challenge in making such pulses is the uncertainty principle, which can be stated with respect to energy and time as $\Delta E \cdot \Delta t \geq h/4\pi$. What is the energy uncertainty (ΔE) associated with a short pulse of laser light that lasts for only 5.0 femtoseconds (fs)? Suppose the low-energy end of the pulse had a wavelength of 722 nm. What is the wavelength of the high-energy end of the pulse that is limited only by the uncertainty principle?
100. A metal with a threshold frequency of $6.71 \times 10^{14} \text{ s}^{-1}$ emits an electron with a velocity of $6.95 \times 10^5 \text{ m/s}$ when radiation of $1.01 \times 10^{15} \text{ s}^{-1}$ strikes the metal. Calculate the mass of the electron.
101. Find the longest wavelength of a wave that can travel around in a circular orbit of radius 1.8 m.
102. The amount of heat to melt ice is 0.333 kJ/g. Find the number of photons of wavelength $= 6.42 \times 10^{-6} \text{ m}$ that must be absorbed to melt $5.55 \times 10^{-2} \text{ mol}$ of ice.

Conceptual Problems

103. Explain the difference between the Bohr model for the hydrogen atom and the quantum-mechanical model. Is the Bohr model consistent with Heisenberg's uncertainty principle?
104. The light emitted from one of the following electronic transitions ($n = 4 \rightarrow n = 3$ or $n = 3 \rightarrow n = 2$) in the hydrogen atom causes the photoelectric effect in a particular metal while light from the other transition does not. Which transition causes the photoelectric effect and why?
105. Determine whether an interference pattern is observed on the other side of the slits in each experiment.
- An electron beam is aimed at two closely spaced slits. The beam is attenuated (made dimmer) to produce only 1 electron per minute.
 - An electron beam is aimed at two closely spaced slits. A light beam is placed at each slit to determine when an electron goes through the slit.
 - A high-intensity light beam is aimed at two closely spaced slits.
 - A gun is fired at a solid wall containing two closely spaced slits. (Will the bullets that pass through the slits form an interference pattern on the other side of the solid wall?)

106. Which transition in the hydrogen atom results in emitted light with the longest wavelength?

- a. $n = 4 \rightarrow n = 3$
- b. $n = 2 \rightarrow n = 1$
- c. $n = 3 \rightarrow n = 2$

Questions for Group Work

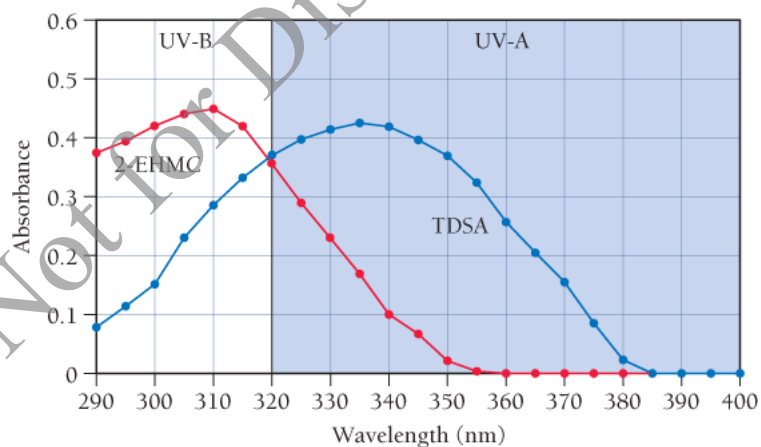
Active Classroom Learning

Discuss these questions with the group and record your consensus answer.

107. Discuss the nature of light with your group. Transcribe one complete sentence about the physical nature of light for each member of your group.
108. How are electrons like baseballs? How are they unlike baseballs?
109. What are all the possible values of m_l if $l = 0$ (an s orbital)? If $l = 1$ (a p orbital)? If $l = 2$ (a d orbital)? How many possible values of m_l would there be if $l = 20$? Write an equation to determine the number of possible values of m_l from the value of l .
110. Have each group member choose a set of quantum numbers for an electron in a hydrogen atom. Calculate the wavelength of light produced if an electron moves from your state to each of the states of the other group members. Make a table comparing all possible combinations, and list all wavelengths in order of increasing energy.
111. How many nodes are there in the $1s$, $2p$, and $3d$ orbitals? How many nodes are in a $4f$ orbital?

Data Interpretation and Analysis

112. Sunscreen contains compounds that absorb ultraviolet light. When sunscreen is applied to skin, it prevents ultraviolet light from reaching the skin. The graph that follows shows the absorbance of light as a function of wavelength for two different compounds (2-EHMC and TDSA) common in sunscreen. Absorbance is a measure of the amount of light absorbed by the compound—the higher the absorbance, the more light is absorbed. Study the graph and answer the questions.



<http://mycpss.com/critical-wavelength-broad-spectrum-uv-protection/>

- a. Calculate the energy of a photon at the maximum absorption of TDSA.
- b. Calculate the energy of a photon at the maximum absorption of 2-EHMC.
- c. Which compound absorbs more energy at its maximum absorption?
- d. Why do you think sunscreens commonly contain both of these compounds and not just one of them?
- e. Assuming that sunlight produces $3.066 \times 10^{22} \frac{\text{UV photons}}{\text{m}^2 \cdot \text{s}}$, and that the skin absorbs one-half of these photons (and reflects the other half), calculate the total UV energy absorbed over 0.42 m^2 of skin that is exposed to sunlight for one hour. Assume that the average wavelength of the UV photons is 330 nm .

Answers to Conceptual Connections

Cc 2.1

- a. infrared < visible < X-ray
- b. X-ray < visible < infrared

Cc 2.2 Observation A corresponds to 632 nm; observation B corresponds to 325 nm; and observation C corresponds to 455 nm. The shortest wavelength of light (highest energy per photon) corresponds to the photoelectrons with the greatest kinetic energy. The longest wavelength of light (lowest energy per photon) corresponds to the instance where no photoelectrons were observed.

Cc 2.3 Because of the baseball's large mass, its de Broglie wavelength is minuscule. (For a 150-g baseball, λ is on the order of 10^{-34} m.) This minuscule wavelength is insignificant compared to the size of the baseball itself, and therefore its effects are not observable.

Cc 2.4 (c) Since l can have a maximum value of $n - 1$, and since $n = 3$, then l can have a maximum value of 2.

Cc 2.5 (d) Since m_l can have the integer values (including 0) between $-l$ and $+l$, and since $l = 2$, the possible values of m_l are -2 , -1 , 0 , $+1$, and $+2$.

Cc 2.6 (c) The energy difference between $n = 3$ and $n = 2$ is greatest because the energy differences get closer together with increasing n . The greater energy difference results in an emitted photon of greater energy and therefore shorter wavelength.

Not for Distribution

Not for Distribution

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