12 Solids

This chapter opens with a depiction of carbon nanotubes that have the greatest tensile strength of any material known, able to resist 100 times more strain than typical structural steel. The second photo is of John Hubisz, among the first friends I made attending AAPT meetings. John's profile begins this chapter. For the third photo I knew I had one for this book when I snapped the one of the stone arches. For the fourth photo, my physics-teaching nephew, Garth Orr, I'm happy to say is following in his Great Uncle Paul's footsteps. He's loving his conceptual physics teaching duties big time. One reason he loves his teaching is because his students love him. Why? Because they know that he loves them. A love of physics, plus a love of sharing it, makes for a successful teaching career!

The treatment of the crystalline nature of solids and bonding are very brief in this chapter. More emphasis is on elasticity, tension and compression, and the application to arches. Students should find the section on "Scaling" of particular interest. A fascinating source of additional scaling examples is George Barnes' fascinating oldie-but-goodie article, "Physics and Size in Biological Systems"—April 1989 issue of *The Physics Teacher*.

Scaling is becoming enormously important as more devices are being miniaturized. Researchers are finding that when something shrinks enough, whether it is an electronic circuit, motor, film of lubricant, or an individual metal or ceramic crystal, it stops acting like a miniature version of its larger self and starts behaving in new and different ways. Palladium metal, for example, which is normally composed of grains about 1000 nanometers in size, is found to be five times as strong when formed from 5 nanometer grains.

Take note of beverage containers that are partially spherical in shape. Some are like two spheres, one atop the other. Compared with a cylinder, any of these shapes that bulge have less surface area for a given volume. That's less waste.

Chromium has long been used to show off a shiny metal surface. But working with chromium has been environmentally harmful. New research suggests a greener alternative: a nano-crystalline nickel-tungsten alloy that tops chrome's features.

Practicing Physics:
• Scaling • Scaling Circles

Problem Solving Book:
Problems, yes

Laboratory Manual:
• Totally Stressed Out *Hooke's Law (Experiment*)
• Spring to Another World *Spring-Mass Simulation* (Tech Lab)

Next-Time Questions:
• Infant Growth • Material Strength • Wet Gravel

Hewitt-Drew-It! Screencasts: •*Solids* •*Quartz-Gold Problem* •*Scaling 1* •*Scaling 2* •*Scaling 3*

This chapter may be skipped with no particular consequence to following chapters. If this chapter is skipped and Chapter 13 is assigned, density should be introduced at that time.

SUGGESTED LECTURE PRESENTATION

Crystal Structure
Begin by calling attention to the micrograph held by John Hubisz in the chapter opener photo. The micrograph is evidence not only for the crystalline nature of the platinum needle, but also evidence for the wave nature of atoms is seen in the resulting diffraction pattern. It is easy to imagine the micrograph as a ripple tank photo made by grains of sand sprinkled in an orderly mosaic pattern upon the surface of water.

Density
Measure the dimensions of a large wooden cube in cm and find its mass with a pan balance. Define density = mass/volume. (Use the same cube when you discuss flotation in the next chapter.) Some of your students will unfortunately conceptualize density as massiveness or bulkiness rather than massiveness *per* bulkiness, even when they give a verbal definition properly. This can be helped with the following:

> CHECK QUESTIONS: Which has the greater density, a cupful of water or a lakeful of water? A kilogram of lead or a kilogram of feathers? A single uranium atom or the world?

I jokingly relate breaking a candy bar in two and giving the smaller piece to my friend who looks disturbed. "I gave you the same density of candy bar as I have."

Contrast the density of matter and density of atomic nuclei that comprise so tiny a fraction of space within matter. From about 2 gm/cm^3 to 2×10^{14} gm/cm^3. And in a further crushed state, the interior of neutron stars, about 10^{16} gm/cm^3.

Elasticity:

> DEMONSTRATION: Drop glass, steel, rubber, and spheres of various materials onto an anvil and compare the elasticities.

> DEMONSTRATION: Hang weights from a spring and illustrate Hooke's law. Set a pair of identical springs up as in Think and Solve 33, and ask the class to predict the elongation before suspending the load.

Tension, Compression, and Arches
Bend a meterstick held at both ends and ask which side is being stretched and which side is being compressed. Stretching is tension, and compressing is compression. If one side is being stretched and the other compressed, there must be a "crossover" place—where neither stretching nor compression occurs. This is the neutral layer.

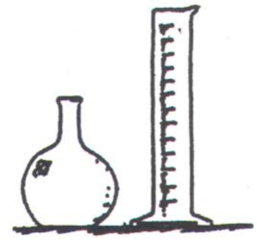
Compare a cantilever and a simple beam. Then discuss the shape of an I-beam and Think and Explain 56 at the end of the chapter.

Discuss the strength of arches. Before the time of concrete, stone bridges and the like were self-supporting by virtue of the way they pressed against one another—in an arch shape. Wooden scaffolding allowed their construction, and when the keystone was inserted, the structures stood when the scaffolding was removed. The same practice is used today.

Discuss the **catenary**, as shown by my grandson Manuel in Figure 12.14. From my understanding, the catenary idea likely originated with Robert Hooke, who discussed it with the famed architect, Christopher Wren. Wren wisely used this idea when he designed the dome to St. Paul's Cathedral in London. Unlike former structures, the dome needs no buttressing. Indeed, a free standing catenary could be made of blocks of slippery ice! How many earlier successful domes approximated the shapes of catenaries? Think and Explains 60 and 61 at the end of the chapter involve catenaries.

Area-Volume

Introduce the relationship between area and volume as Chelcie Liu does by showing the following: Have a 500-ml spherical flask filled with colored water sitting on your lecture table. Produce a tall cylindrical flask, also of 500 ml (unknown to your students), and ask for speculations as to how high the water level will be when water is poured into it from the spherical flask. You can ask for a show of hands for those who think that the water will reach more than half the height, and those who think it will fill to less than half the height, and for those who guess it will fill to exactly half the height. Your students will be amazed when they see that the seemingly smaller spherical flask has the same volume as the tall cylinder. To explain, call attention to the fact that the *area* of the spherical flask is considerably smaller than the surface area of the cylinder. We see a greater area and we unconsciously think that the volume should be greater as well. Be sure to do this. It is more impressive than it may first seem.



Scaling

Now for the most interesting part of your lecture. Have at least 8 large cubes on your lecture table as you explain Figures 12.16 and 12.17. For more about the relationships among the size, area, and volume of objects, read the essays cited in the first footnote of this chapter.

> CHECK QUESTIONS: Which has more surface area, an elephant or a mouse? 2000 kilograms of elephant or 2000 kilograms of mice? (Distinguish carefully between these different questions.)
>
> CHECK QUESTION: Cite two reasons why small cars are more affected by wind.
>
> CHECK QUESTION: Why do cooks preparing Chinese food chop food in such small pieces to stir-fry quickly in a wok?
>
> CHECK QUESTION: In terms of surface area to volume, why should parents take extra care that a baby is warm enough in a cold environment? [Baby has proportionally more radiating surface.]
>
> CHECK QUESTION: Why are elevated reservoirs usually spherical in shape? [Minimum building material for the same volume.]
>
> CHECK QUESTION: What does the somewhat spherical shape in beverage containers have to do with ecology? [Less material, less waste.]

Your lecture can continue by posing exercises from the chapter end material and having your class volunteer answers. The examples posed in the chapter backmatter will perk class interest. (The answer to Think and Solve 34 may need more explanation. How much more surface area is there for a body with twice the volume? Consider a cube; twice the volume means each side is the cube root of two, 1.26 times the side of the smaller cube. Its area is then $1.26 \times 1.26 = 1.588$ times greater than the smaller cube.

Interestingly, this means that a twice-as-heavy person at the beach, say 200 lbs, needs about 1.6 times as much suntan lotion as a 100-lb person.

Regarding Figure 12.18, note that the eartip-to-eartip span is almost the height of the elephant. The dense packing of veins and arteries in the elephant's ears finds a difference in five degrees in blood entering and leaving the ears. A second type of African elephant that resides in cooler forested regions has smaller ears. Perhaps Indian elephants evolved in cooler climates. Anther consequence of scaling: elephants can't jump!

Answers and Solutions for Chapter 12

Reading Check Questions

1. Atoms are orderly in a crystalline substance, and random in non-crystalline substances.
2. Micrographs (chapter-opener photo) and X-ray diffraction patterns show the crystal nature of certain solids. Macroscopic evidence of crystals are the 3-dimensional shape of materials such as quartz, and even brass doorknobs that have been etched by the perspiration of hands.
3. A squeezed loaf of bread has reduced volume, the same mass, and increased density.
4. Both densites are one and the same.
5. Close packing of atoms in iridium accounts for its great density.
6. Water has a mass density of 1 g/cm^3, and a weight density of 9.8 N/cm^3.
7. A spring when deformed returns to its initial shape when the deforming force is removed.
8. Putty when deformed, remains deformed when the deforming force is removed.
9. Hooke's law: $F \sim \Delta x$; applies to elastic materials.
10. The elastic limit is the point at which deformation remains after the deforming force is removed.
11. Stretch will be 3 times as much, 6 cm.
12. Tension is "stretching" of a substance when force is applied; compression is squeezing a substance when force is applied.
13. The neutral layer in a beam is the region of neither tension nor compression when supporting a load, and is in the middle portion of the beam.
14. I beams have material removed where strength is not needed, which makes the beam lighter for nearly the same strength.
15. Long horizontal slabs of stone fracture when carrying a load, so vertical columns reduce the lengths of the slabs.
16. For an arch, compression strengthens it.
17. Cement is not needed because compressive forces hold the arch together.
18. Vertical columns are not needed because the shape of the arched parts form an inverted catenary.
19. Strength depends on the cross-sectional area.
20. For the cube, volume is 1 cm^3; cross section is 1 cm^2; total surface area is 6 cm^2.
21. Surface area increases by four; volume increases by eight.
22. An elephant has more skin than a mouse, but less skin *per bodyweight* than a mouse.
23. A mouse daily requires more food per bodyweight than an elephant.
24. The saying is a consequence of a small ratio of surface to volume.
25. Small creatures have more surface area per bodyweight, and encounter greater air resistance per bodyweight, resulting in a slower fall than that of larger creatures.

Think and Do

26. Snowflakes melt quickly, so be alert!
27. Note the smaller area with close packing.
28. You should find you're slightly taller lying down. When standing compression of your spine occurs.
29. The chain will have the shape of the egg. This must be tried!

Think and Solve

30. Density = $\frac{\text{mass}}{\text{volume}} = \frac{5\text{ kg}}{V}$. Now the volume of a cylinder is its (round area) × (its height), ($\pi r^2 h$).

    So density = $\frac{5\text{ kg}}{\pi r^2 h} = \frac{5000\text{ g}}{(3.14)(3^2)(10)\text{cm}^3}$ = 17.7 g/cm^3.

31. A cubic meter of cork has a mass of 400 kg and a weight of about 4,000 N. Its weight in pounds is 400 kg × 2.2 lb/kg = 880 lb, much too heavy to lift.

32. 50 N is 5/3 times 30 N, so the spring will stretch 5/3 times as far, **10 cm**. Or from Hooke's law; $F = kx$, $x = F/k$ = 50 N/(30 N/6 cm) = 10 cm. (The spring constant k = 5 N/cm.)

33. When the springs are arranged as in (a), each spring supports half the weight, stretches half as far (2 cm), and reads 5 N. In position (b) each spring supports the full weight, each stretches 4 cm, and each reads 10 N. Both springs stretch 4 cm so the weight pulls the combination down a total distance of 8 cm.

34. (a) **Eight** smaller cubes (see Figure 12.16).

(b) Each face of the original cube has an area of 4 cm^2 and there are 6 faces, so the total area is 24 cm^2. Each of the smaller cubes has an area of 6 cm^2 and there are eight of them, so their total surface area is 48 cm^2, twice as great.
(c) The surface-to-volume ratio for the original cube is (24 cm^2)/(8 cm^3) = 3 cm^{-1}. For the set of smaller cubes, it is (48 cm^2)/(8 cm^3) = 6 cm^{-1}, twice as great. (Notice that the surface-to-volume ratio has the unit inverse cm.)

35. Twice the mass of gold has twice the volume = 2cm^3=L^3 $\Rightarrow L = \sqrt[3]{2}$ cm = 1.26 cm.

36. $\$700 \times 10^9 \times \frac{1\text{gram}}{\$28.40} = 2.46 \times 10^{10}\text{ gram} \times \frac{1\text{cm}^3}{19.3\text{ g}} = 1.28 \times 10^9\text{cm}^3 \times \left(\frac{1\text{ m}}{100\text{ cm}}\right)^3 =$
1.28×10^3 m^3.

Since this is a cube of volume $V = L^3$, each side $L = \sqrt[3]{V} = \sqrt[3]{1.28 \times 10^3\text{ m}^3} = \mathbf{10.8\text{ m}}$. (This turns out to be more than five times the total stored in Fort Knox, and about 10 times the world's annual gold production.)

Think and Rank

37. C, A, B.
38. a. C, B, A. b. C, B, A. c. C, B, A. d. C, B, A. e. A, B, C.

Think and Explain

39. Both the same, for 1000 mg = 1 g.

40. Disagree, for it is the arrangement of atoms and molecules that distinguishes a solid from a liquid.

41. The carbon and part of the oxygen that comprises much of the mass of a tree originates from CO_2 in the air.

42. Physical properties involve the order, bonding, and structure of atoms that make up a material, and on the presence of other atoms and their interactions in the material. The silicon in glass is amorphous, whereas in semiconductors it is crystalline. Silicon in sand, from which glass is made, is bound to oxygen as silicon dioxide, while that in semiconductor devices are elemental and extremely pure. Hence their physical properties differ.

43. Evidence for crystalline structure include the symmetric diffraction patterns given off by various materials, micrographs such as the one shown by Professor Hubisz in the chapter-opener photo, the 3-dimensional shape of materials such as quartz, and even brass doorknobs that have been etched by the perspiration of hands.
44. Density decreases as the volume of the balloon increases.

45. The densities are the same, for they are both samples of iron.

46. Density of water decreases when it becomes ice.

47. Its density increases.

48. Aluminum has more volume because it is less dense.

49. Water is denser, so a liter of water has more mass than a liter of ice. (Once a liter of water freezes, its volume is greater than 1 liter.)

50. For one thing, drop a steel ball on a steel anvil. It will bounce!

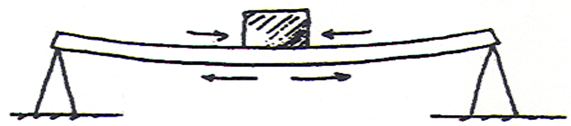
51. The top part of the spring supports the entire weight of the spring and stretches more than, say the middle, which only supports half the weight and stretches half as far. Parts of the spring toward the bottom support very little of the spring's weight and hardly stretch at all.

52. All parts of the spring would stretch more nearly the same because the lower part of the spring would be supporting nearly as much weight as the upper part is supporting.

53. The concave side is under compression; the convex side is under tension.

54. Case 1: Tension at the top and compression at the bottom.

Case 2: Compression at the top and tension at the bottom.



55. Concrete undergoes compression well, but not tension. So the steel rods should be in the part of the slab that is under tension, the top part.

56. A horizontal I-beam is stronger when the web is vertical because most of the material is where it is needed for the most strength, in the top and bottom flanges. When supporting a load, one flange will be under tension and the other flange under compression. But when the web is horizontal, only the edges of the flanges, much smaller than the flanges themselves, play these important roles.

57. The design to the left is better because the weight of water against the dam puts compression on the dam. Compression tends to jam the parts of the dam together, with added strength like the compression on an arch. The weight of water puts tension on the dam at the right, which tends to separate the parts of the dam.

58. Like the dams in the preceding exercise, the ends should be concave as on the left. Then the pressure due to the wine inside produces compression on the ends that strengthens rather than weakens the barrel. If the ends are convex as on the right, the pressure due to the wine inside produces tension, which tends to separate the boards that make up the ends.

59. Scale a beam up to twice its linear dimensions, I-beam or otherwise, and it will be four times as thick. Along its cross-section then, it will be four times as strong. But it will be eight times as heavy. Four times the strength supporting eight times the weight results in a beam only half as strong as the original beam. The same holds true for a bridge that is scaled up by two. The larger bridge will be only half as strong as the smaller one. (Larger bridges have different designs than smaller bridges. How they differ is what architects and engineers get paid for!) Interestingly, how strength depends on size was one of Galileo's "two new sciences," published in 1638.

60. Catenaries make up the arches of the ends of an egg. Pressing them together strengthens the egg. Not so when pressing the sides, which do not constitute catenary shapes, and easily splay outward under pressure.

61. Since each link in a chain is pulled by its neighboring links, tension in the hanging chain is exactly along the chain—parallel to the chain at every point. If the arch takes the same shape, then compression all along the arch will similarly be exactly along the arch—parallel to the arch at every point. There will be no internal forces tending to bend the arch. This shape is a catenary, and is the shape of modern-day arches such as the one that graces the city of St. Louis.

62. No, the rods would not be necessary if the shape of the arch were an upside down version of a hanging chain. Why? Because compression of the stones in the semi-circular design press outward. Compression in the hanging chain design (catenary) is everywhere parallel to the arch, with no net sideways components.

63. The candymaker needs less taffy for the larger apples because the surface area is less per kilogram. (This is easily noticed by comparing the peelings of the same number of kilograms of small and large apples.)

64. Kindling will heat to a higher temperature in a shorter time than large sticks and logs. Its greater surface area per mass results in most of its mass being very near the surface, which quickly heats from all sides to its ignition temperature. The heat supplied to a log, on the other hand, is not so

concentrated as it conducts into the greater mass. Large sticks and logs are slower to reach the ignition temperature.

65. The answer to this question uses the same principle as the answer to the previous exercise. The greater surface area of the coal in the form of dust insures an enormously greater proportion of carbon atoms in the coal having exposure to the oxygen in the air. The result is very rapid combustion.

66. More heat is lost from the rambling house due to its greater surface area.

67. An apartment building has less area per dwelling unit exposed to the weather than a single-family unit of the same volume. The smaller area means less heat loss per unit. (It is interesting to see the nearly cubical shapes of apartment buildings in northern climates—a cube has the least surface area for a solid with rectangular sides.)

68. For a given volume, a sphere has less surface area than any other geometrical figure. A dome-shaped structure similarly has less surface area per volume than conventional block designs. Less surface exposed to the climate = less heat loss.

69. The ratio of area (square meters) to volume (cubic meters) decreases.

70. The surface area of crushed ice is greater which provides more melting surface to the surroundings.
71. Curling up presents less surface area to the surroundings.

72. Rusting is a surface phenomenon. For a given mass, iron rods present more surface area to the air than thicker piles.

73. More potato is exposed to the cooking oil when sliced thinly than in larger pieces. Thin fries will therefore cook faster than larger fries.

74. The wider, thinner burger has more surface area for the same volume. The greater the surface area, the greater will be the heat transfer from the stove to the meat.

75. Mittens have less surface than gloves. Anyone who has made mittens and gloves will tell you that much more material is required to make gloves. Hands in gloves will cool faster than hands in mittens. Fingers, toes, and ears have a disproportionately large surface area relative to other parts of the body and are therefore more prone to frostbite.

76. The greater amount of radiating area of a mouse means that it radiates a greater amount of energy, which in turn means the small creature needs a greater proportion of food daily.

77. The mouse has more surface area per bodyweight, which means greater air resistance per bodyweight, which means its terminal speed of fall is slower than the gorillas.

78. Small animals radiate more energy per bodyweight, so the flow of blood is correspondingly greater, and the heartbeat faster.

79. The inner surface of the lungs is not smooth, but is sponge-like. As a result, there is an enormous surface exposed to the air that is breathed. This is nature's way of compensating for the proportional decrease in surface area for large bodies. In this way, an adequate amount of oxygen vital to life is taken in.

80. Cells of all creatures have essentially the same upper limit in size dictated by the surface area per volume relationship. The nourishment of all cells takes place through the surface by the process called osmosis. As cells grow they require more nourishment, but the proportional increase in surface area falls behind the increase in mass. The cell overcomes this liability by dividing into two cells. The process is repeated and there is life that takes the form of whales, mice, and us.

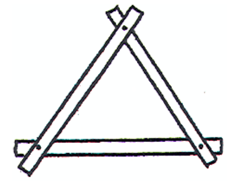
81. Large raindrops fall faster than smaller raindrops for the same reason that heavier parachutists fall faster than lighter parachutists. Both larger things have less surface area and therefore less air resistance relative to their weights.

Think and Discuss

82. Iron is denser than cork, but not necessarily heavier. A common cork from a wine bottle, for example, is heavier than an iron thumbtack—but it wouldn't be heavier if the volumes of each were the same.

83. Density has not only to do with the mass of the atoms that make up a material, but with the size of those atoms and their stacking arrangement. Iridium atoms are both smaller and they stack more closely than uranium atoms, which is why iridium metal is denser than uranium metal even though uranium's atoms are heavier.

84. A triangle is the most rigid of geometrical structures. Consider nailing four sticks together to form a rectangle, for example. It doesn't take much effort to distort the rectangle so that it collapses to form a parallelogram. But a triangle made by nailing three sticks together cannot collapse to form a tighter shape. When strength is important, triangles are used. That's why you see them in the construction of so many things.



85. A twice-as-thick rope has four times the cross-section and is therefore four times as strong. The length of the rope does not contribute to its strength. (Remember the old adage, a chain is only as strong as its weakest link—the strength of the chain has to do with the thickness of the links, not the length of the chain.)

86. Cupcakes have more surface area per amount of material than a cake, which means there is more area exposed to the heat that the oven will provide, which means cooking will be facilitated. This also means the cupcakes will be overcooked if they are cooked for the time specified for a cake. (Now you see why recipes call for a "shallow pan" or a "deep dish" when baking times are given.)

87. As an organism increases in size, surface area decreases relative to the increasing size. Therefore, a large organism such as a human being must have a many-folded intestinal tract so that the area will be large enough to digest the needed food.

88. Strength varies in approximate proportion to the cross-sectional area of arms and legs (proportional to the square of the linear dimensions). Weight varies in proportion to the volume of the body (proportional to the cube of the linear dimension). So—other things being equal—the ratio of strength to weight is greater for smaller persons.

89. A child, for a child has more surface area per volume, and therefore loses disproportionately more water to the air.

90. Scaling plays a significant role in the design of the hummingbird and the eagle. The wings of a hummingbird are smaller than those of the eagle relative to the size of the bird, but are larger relative to the mass of the bird. The hummingbird's swift maneuvers are possible because the small rotational inertia of the short wings permits rapid flapping that would be impossible for wings as large as those of an eagle. If a hummingbird were scaled up to the size of an eagle, its wings would be much shorter than those of an eagle, so it couldn't soar. Its customary rate of flapping would be insufficient to provide lift for its disproportionately greater weight. Such a giant hummingbird couldn't fly, and unless its legs were disproportionately thicker, it would have great difficulty walking. The great difference in the design of hummingbirds and eagles is a natural consequence of the area to volume ratio of scaling. Interesting!

91. The idea of scaling, that one quantity, such as area, changes in a different way than another quantity, such as volume, goes beyond geometry. Rules that work well for a system of one size may be disastrous when applied to a system of a different size. The rules for managing a small town well may not work at all for a large city. Other examples are left to you. This is an open-ended question that may provoke thought—or better, discussion.