to pander to our fears of failure by dwelling on the occasions when we're in need of repair. What you'll get here is intended as perspective, a framework in which to put the information encountered elsewhere. Our plumbing should be no leaden subject.

* * *

Without further preambulations, let me introduce the present protagonists and their assigned roles.

### The Task of a Circulation

Imagine a vast collection of ordinary suburban houses—quite a vast collection since we intend them as analogs of our 100,000,000,000,000 (100 trillion)[1] cells. Each has a certain functional autonomy, being equipped with the full facilities for storing, preparing, and eating food; for dressing and sleeping; for (as no biologist can forget) conceiving; and so forth. The autonomy, however, has its limits, transcended by the need for delivery of water, food, and energy, and for disposal of refuse and sewage. The biological analogs of these inputs and outputs are what a circulatory system manages—clearly crucial and just as clearly the most pedestrian of matters. Again I emphasize that for neither the houses nor the cells are they dramatic matters of active concern. In both cases requiring attention is the sort of pathological situation one prefers to avoid. For either, functions such as communication are more obtrusive—for a house both the wired and wireless sorts of communication, for a cell both neural and endocrine signals. Signals most often indicate changes, changes commonly demand responses, and we've learned (in several senses) to pay attention. Nonetheless, while perhaps more obvious and insistent, these communicative systems are only intermittently critical; their failure is less certainly and immediately fatal.

A circulatory system, then, moves material around within an animal. A carrier, blood, goes around and around, while other items make less monotonously repetitive circuits. Just what items are moved around varies a bit, both from time to time and from organism to organism. The system turns out to be more multifunctional than at first it appears. For one thing, the contrast I made with communicative systems



involves no single, sharp distinction—hormones are commonly bloodborne, and they are nothing more than messages that regulate and synchronize the activities of otherwise fairly autonomous cells. For another, heat is transferred through movement of blood—it's a byproduct of all of our metabolic chemistry and is eventually dumped off upon our surroundings. While heat is produced throughout a body, it must be lost across a surface. Thus it needs transporting from core to periphery; or, at least under some circumstances, one's core will get intolerably warm. Under other conditions we find it useful to heat our appendages with what we make in the middle: cold fingers and toes are as likely to reflect poor circulation as to indicate insufficient heat production. Circulatory systems are even used to transmit force. The obvious case is erectile tissue: without heart and bloodstream we'd have no way to pump up our kind of penis—muscles have no role in the job. A less obvious but more widespread use of the hydraulic force of a pressurized bloodstream is in pushing blood though the filtration stage of kidneys.

By far the most demanding circulatory task for creatures like us is the transport of dissolved gases. In particular, oxygen is carried from the lungs elsewhere, and carbon dioxide, the main product of using that oxygen, is returned to the lungs. Of the two, oxygen transport is probably the trickier, simply because less oxygen normally dissolves in watery liquids. (Oxygenated rather than carbonated beer would be a lot less bubbly.) All the numerous tasks beside transporting oxygen and carbon dioxide could be done with a simpler and more sluggish system. I defend this assertion that gas transport is the most demanding function with a typical bit of biologist's logic—through comparison with a circulatory system that proves completely adequate for organisms that don't use it to transport dissolved gases. As it happens, insects have a separate system of pipes that carry oxygen and carbon dioxide to and from individual cells in (mainly) gaseous form. They do have hearts and some blood vessels, but their circulatory systems work at rather low pressures and flow speeds. To anticipate any argument that insects are primitive or inactive let me point out that many of them fly, and flying is about the most energy-intensive activity known either in nature or in human-designed transportation systems.

Among animals, we birds and mammals are unusual (but not quite unique) in maintaining rather warm and fairly constant internal temperatures. By insisting on having hot innards, we're committed to a rapid pace of life. We eat copiously and often,[2] and we release heat by combining stored fat and carbohydrate with oxygen. Our internal fires burn intensely, and not just as analogy or metaphor. When the fat's in the fire it uses the same amount of oxygen and releases the same amount of energy as when it's burned under much more controlled conditions within our cells. A sedentary person consumes about 70 kilocalories[3] an hour, which translates into a heat production of 80 watts. By contrast, a sedentary alligator of the same weight but with a body at ambient temperature consumes only about 17 kilocalories an hour, corresponding to 20 watts, about four times less. Our cells need proportionately more oxygen and produce more carbon dioxide than do those of the alligator; our circulatory systems have to bring the first to the cells from our lungs and take the second back to the lungs. Still, as we'll see, without circulatory systems even alligators are quite out of the question.

Alligators and insects are certainly not everyone's favorite creatures. But notice the heuristic utility of the perspective they permit, even if one's concern is entirely with humans. I've used the comparison with insects to argue that gas transport is the most demanding circulatory function and with alligators to suggest that the demand is especially great because we're warm-blooded animals. Thus I justify what might otherwise seem a disproportionate emphasis on a single function in a peculiar subset of vertebrates in all that will follow.

## Simple Circuitry

At this point, we should take a look at a specific circulatory system, perhaps starting with a picture of our own, but a formidable problem immediately arises—we can't draw a decently informative illustration of our circulatory system on an ordinary printed page. For one thing, the system is three-dimensional; worse yet, it's made of parts awkwardly diverse in size. If capillaries, 8 micrometers (a three-thousandth of an inch) in diameter, are shown, then the heart (less than 5 inches high and slightly more than 3 inches wide) won't fit on the page. So it takes considerable imagination to visualize the thing. In fact, there's a more



general problem. We biologists are all too prone, I think, to submerge ourselves and everyone else in anatomical and terminological detail. It's better if we defer that plunge at least briefly. Beginning with an overall view of function will greatly reduce the burden imposed by a lot of names and places.

For now, describing function can be helped considerably by using analogies and by beginning with less complex biological cases. So we'll go back to our suburban houses, now using them to draw parallels between household heating systems and the oxygen distribution systems of animals. In particular, we'll focus on those systems in which heat is produced centrally and then distributed as hot air or hot water to the various rooms. The components of such a system are, first, a set of pipes for transporting the hot air or water. There must also be some pump for either circulating medium. Finally, two different kinds of exchangers are needed. In one, heat is acquired by the medium—we call it a furnace; in the other heat is transferred to the living quarters—it may be a set of radiators or just a trivial mixing arrangement for hot air coming out of some ports. So—pipes, pump, and two kinds of exchangers. These are precisely, and for just the same reasons, the indispensable components of circulatory systems. All others are really just fillips and flourishes. At this point we might draw a picture of a heating system on one side of a page and at least a crude one of a circulatory system on the other, but the very different appearance and location of the parts of each would get in the way of recognizing any underlying similarity in their interconnections. A better way is to borrow the engineering practice of using purely functional diagrams. The hot air heating system (Figure 1.1a) needs a full set of distributional ducts, but it manages to work without much in the way of return pipes. A house has a fixed volume, and air is pretty nearly incompressible at any speeds of flow with which we might comfortably coexist. So blow air from furnace to periphery, and the air will return to the furnace of its own accord. A little help may be needed—my house has a few return ducts from the more remote bedrooms, and it ought to have another to keep the living room (on the other end) properly heated. (And animals arranged this way come equipped with a quite a few odd ducts and auxiliary pumps to handle their various anatomical tortuosities.)

The circulatory system of a snail or spider (Figure 1.1b) is arranged

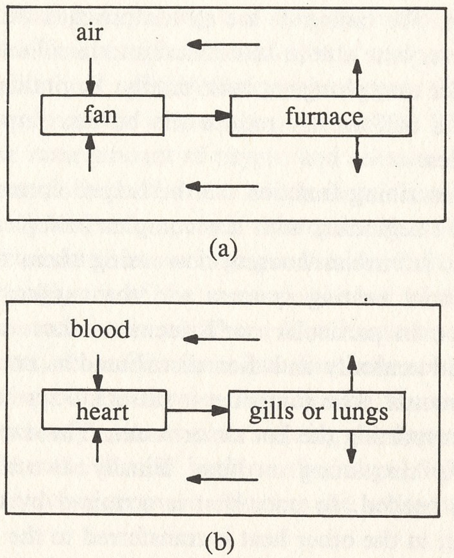


*Figure 1.1.* Analogous arrangements—(a) a hot air heating system, and (b) the "open" circulatory system of a spider or snail.

Spiders ⟷ [illegible]
air

in much the same way as the hot air heating system. Blood is pumped by a heart; it exchanges dissolved gases with the environment through a set of gills (most snails) or sheet-like lungs (most spiders); and it moves heartward again without benefit of very specific piping. In this heartward oozing through the rest of the body, the second exchange takes place, the one by which tissues are provided with dissolved oxygen and dump their dissolved carbon dioxide. In the biology textbooks of my youth such a system, termed an *open* circulatory system, was derided as primitive on account of its lack of discrete return pipes. That's probably an unnecessary and inappropriate bit of vertebrate or mammalian hubris. Spiders, lobsters, and the rest of the great phylum of arthropods (which includes the insects, a distinct group from the spiders) have inextensible outer shells rather than our more flexible skin. Furthermore, water and all bloods are even less easily compressed than air. If blood is pumped to the front, it simply has to find its way rearward since it can go nowhere else. Discrete pipes to carry blood rearward would be just so much needless baggage, wasting space better



invested in equipment closer to proper reproductive imperatives—in short, to guts and gonads. Similarly, pumping blood outward to the tips of legs must, if no leaks develop, force it back inward automatically.

By contrast, in a recirculating hot water system (a fine, if initially expensive way to heat a house), a pump pushes water first through the heat exchanger of the furnace and then through the heat exchangers more commonly referred to as radiators (Figure 1.2a). A return pipe from each radiator carries the somewhat cooler water back to the pump and furnace. Radiators are necessary, of course, because our houses are filled with air rather than water. The circulatory system of a fish (Figure 1.2b) is closely analogous. A heart pumps blood forward; blood then passes through the gills where it acquires oxygen and disposes of carbon dioxide. After that it goes by way of arteries to the other exchanger, the network of capillaries elsewhere in the body; it finally returns through veins to the heart again.

Fish ⟷ water

## The Bird-and-Mammal Scheme

What of ourselves, neither spiders nor fish, but proper mammals? We use a modification of the piscine scheme; and I mean modification in both of the biologist's senses—historical and functional. That is, our structures represent the end of a long history of modification of what some early fishes invented about 400 million years ago. Our mammalian version probably reached very much its present form by a still ancient 200 million years ago. At least that's the well-accepted inference, since our circulatory equipment operates in a way quite similar to that of modern fishes and most likely of ancient fishes as well. A little educated guessing is, of course, involved—circulatory systems don't leave nice, accommodating fossils as do bones. It would, however, be quite astonishing if ancient fish did things very much differently from their extant descendants. The evolutionary history isn't irrelevant. If you set out to design, de novo, a mammalian circulation, you might do better to arrange it a bit differently from what we in fact have. If you're limited to modifying pre-existing anatomy, then you're likely to end up with certain quirks and jury-rigged arrangements.

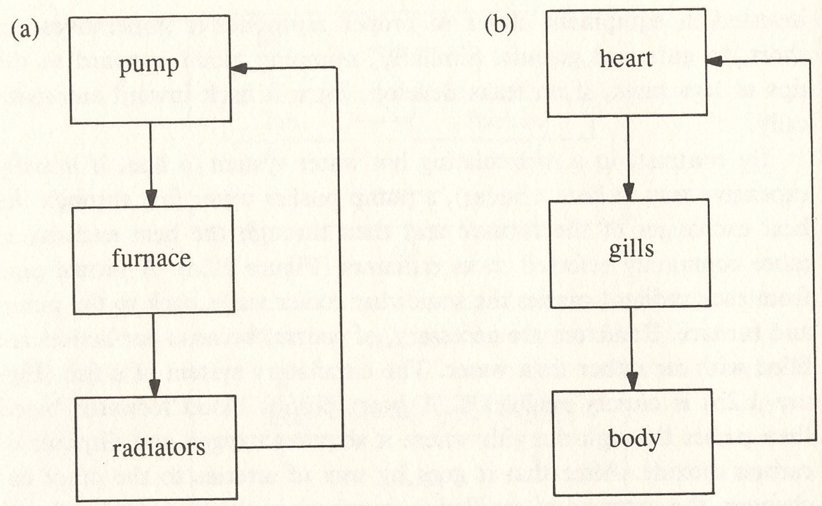


*Figure 1.2.* Another analogous pair—(a) the layout of a hot-water heating system, and (b) the arrangement of the circulatory system of a fish.

It's worth noting that, while descent with modification is evolution's way, existing structures are not uncommonly pressed into service for new functions. The main buoyancy devices of fish, swim bladders, come from the same antecedent structures as do our lungs. The tiny bones in our middle ears come from the same antecedents as some associated with the gills of fish, bones whose equivalents see service in the jaws of reptiles and amphibians.[4] By contrast, these circulatory systems we're talking about not only come from the same ancestral structures, but also retain the same essential function. Vertebrates have been pretty conservative, evolutionarily, and circulatory systems seem to have especially strong traditions. According to the best evidence, birds and mammals represent separate offshoots of the reptilian stock, lineages that branched from different reptilian forebears at different times. Birds and mammals nonetheless hit upon the same basic alterations of the reptilian circulation. Perhaps that isn't too surprising—the changes are simple, logical, and effective.

Figure 1.3 is a circuit diagram of the circulatory arrangements of mammals and birds. Two really major alterations are evident. Gills, suitable for extracting oxygen from water, have been replaced, func-



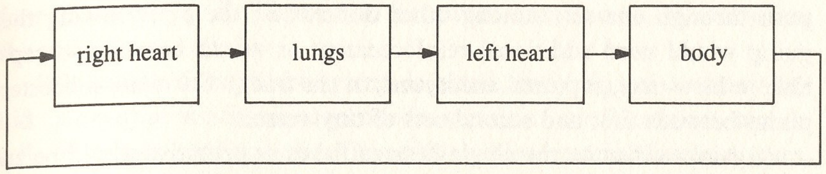


*Figure 1.3.* The path of the blood in birds and mammals.

tionally, by lungs that extract oxygen from air. Gills haven't, it turns out, been modified into lungs. Curiously, the components of the gills have been lost or put to other purposes, and lungs have developed separately as outpocketings of the esophagus—the outpocketings that in fish we noted serve as gas-filled swim bladders. The other alteration is the addition of a second heart. A fish pushes blood through two exchangers with one heart; a bird or mammal has an additional pump between the exchangers. Our blood goes from one heart to the lungs to the second heart to the rest of the body and then back to the first heart.

At once something distinctly queer about the arrangement jumps out. Two hearts located in quite different places hardly constitute a proper vision for St. Valentine, and they certainly don't correspond to our common notion of what we have inside. No mistake—in a functional sense each of us does have two hearts, but they just happen to be combined into one muscular organ, and they can beat only in synchrony. The anatomical combination obscures the functional distinction. That combination, though, is probably one of those accidents of "descent with modification," as Mr. Darwin put it, one of those odd quirks evolution leaves in its wake. Anyhow, half-heart one (right side) pushes blood through the lungs, and it's a little smaller; half-heart two (left side) is larger and pushes blood through the rest of the body.

The scheme makes good sense. As we'll see later, these pumps really expend energy pushing blood through the tiniest vessels, mainly capillaries, of both the lungs and all the other organs. In a plumbing system, loss of energy is associated with a decrease in pressure, which will be discussed further in Chapter 4. Therefore the pressure imparted by the pump to the blood decreases substantially as blood passes through a set of tiny vessels. Going through two sets in sequence (at a given speed) would require that the blood start with twice the pressure needed to push through one set. Among other difficulties, the pipes leaving the pump would need additional reinforcement or would be more susceptible to blow-outs (ruptured aneurysms, in the trade). Solution—a booster pump between first and second sets of tiny vessels.

(Again, to dismiss the single-hearted fishes as primitive would be an indefensibly anthropocentric attitude. Fish do quite nicely, thank you—they're the most numerous of all vertebrates. They, like alligators, just don't ordinarily go in for our profligate rates of oxygen use. Fish blood circulates more slowly than does our own, and the pressures involved are correspondingly lower.)

Which pump we call the main one and which the booster is more or less arbitrary. Our "lung" half-heart (right side) is the more immediate functional descendent of the sole piscine pump, so we might best regard the larger "body" half-heart (left side) as the secondary booster. Curiously, the creatures that stand between fish and us in an evolutionary sense, amphibians and reptiles, have various sorts of in-between arrangements about which more will be said later. The full, deluxe, duplex deal graces only birds and mammals. Odder still, these nearly identical hearts clearly represent two quite independently evolved modifications of the hearts of reptilian forebears. Possession of these fancy double hearts is surely related to the fact that only birds and mammals routinely maintain body temperatures well above those of their surroundings.

A few items of terminology are now unavoidable. (I only disparage terms as jargon when I don't need them.) Our mammalian system consists of two pumps, collectively called the heart, and three main kinds of pipes. *Arteries* have thick walls that withstand the full pressure generated by the squeeze of the heart; they carry blood away from the heart. (The largest artery, the one leading out to the body from the heart is called the *aorta*.) *Capillaries* are tiny pipes with very thin walls that are supplied with blood by the arteries. Whether in the lungs or elsewhere, they're the sites at which material is exchanged between blood and the tissues of the body. *Veins* have thinner walls and much lower internal pressures than the arteries. They drain the capillaries and return blood to the heart. Each side of the heart consists of two pumping chambers serially arranged, an *atrium* (sometimes called an "auricle" on account of being a bit ear-shaped) and a *ventricle*. Thus the heart has



four chambers in all. The system has other components, but these are the main ones.

What flows through the system is blood, consisting of a watery liquid (*plasma*) in which are suspended a variety of small entities—mainly cells of varying sorts and sizes. In addition, blood carries dissolved gases, salts, hormones, droplets of fat, energy-yielding molecules such as glucose, waste materials such as urea, and a wide variety of proteins involved in such functions as clotting and inflammatory responses. These materials enter and leave the blood as it passes through the capillaries of the various organs.

## Quantifying Things

Let's add some numbers to all the words, using the human circulation as source of data—adult humans of average size. At least in pushing blood around humans are not especially unusual mammals, lots of human data are available, and both reader and writer are without the slightest doubt quite human. While most of these numbers will come up again later, it will be handy to have them in one place.

**Blood volume:** 5.2 liters (5.5 quarts) in the body, about 5 percent of which is in the heart. Being relieved of a pint (half a quart or about half a liter) is no big deal if you're in normal health—it's less than 10 percent of your stock. Lady Macbeth, you may remember, found this large volume noteworthy.

**Output, left ventricle:** 5 liters (5.3 quarts) per minute for a person at rest, and about six times higher in strenuous exercise. The output of the right ventricle is, of course, precisely the same. When at rest, the whole blood volume of the body passes through the left heart every minute, or a bit of blood takes about a minute to make the complete circulatory circuit. During heavy exercise, the circuit takes only about 10 seconds.

**Stroke volume and heartbeat rate**: The 5 liters per minute is the product of about 70 milliliters (2.5 ounces) per stroke times about 72 strokes per minute.

**Fraction of blood occupied by cells** ("hematocrit"): from 37 to 52 percent. Most of this volume is occupied by the so-called red blood cells, of which you have 5 million per cubic millimeter or about 25,000,000,000,000 (25 trillion) in all.

**Speed of flow leaving heart**: 0.3 meters (about 1 foot) per second, resting. In maximal aerobic exercise in a well-conditioned person it rises to about 2 meters per second (about 6 feet per second or 2.5 miles per hour); a leisurely walking pace.

**Speed of flow in capillaries**: 0.4 millimeters per second at rest or about 800 times lower than the speed at the aorta, the exit from the heart. That's 50 days per mile, in our perceptual world exceedingly slow.

**Overall area of capillary wall**: 8000 square meters or all of 2 acres. That's the surface across which material can move between the circulatory system and the surrounding tissues.

**Combined length of pipes**: 100,000 kilometers (60,000 miles)—more than twice around the earth at the equator.

**Heart weight**: About 0.3 kilograms (11 ounces) or about half a percent of body weight. A heart isn't an especially large organ.

**Power output of heart**: 1.3 watts at rest, about 8 watts during exercise. The latter is about 30 times *less* than the power per unit weight of a good internal combustion piston engine of almost any size.

**Power consumption of heart**: At rest, this is 13 watts, or about a sixth of the body's resting power consumption of 80 watts, as mentioned earlier. 1.3 (earlier) divided by 13 is, of course, 10 percent. Thus about 10 percent of the fuel (fat, etc.) consumed by the heart appears as useful, blood propelling, output.

## And Questions Left Hanging

I've now sketched the main features of the circulatory systems that will occupy the forthcoming pages. All the rest, though, isn't just detail. The present description is about as bald as its author, only a little more user-friendly than a textbook, and without all of my favorite devices. Worst of all, it conveys little sense of the logic and elegance of the various features of these systems. To push one of my long-standing polemical themes, such features do not unfold from an evermore detailed study of the organisms, but from consideration of just what problems these circulatory systems are up against. It sounds backward—to imagine problems and then to investigate what animals have done about them—but the approach turns out to be useful both as a way to do science and as a way to talk about functional systems. The following, then, are a few of the problems.



- Liquids are, for all practical purposes, incompressible. If, in contracting, the heart's chambers get smaller, then blood pushed out must turn up as an increased volume elsewhere. One attractive fix, beating left and right hearts alternately, isn't used, perhaps because of the fact that the two ventricles are squeezed by the same muscle (—two hearts beat as one, even without romantic hyperbole). Are there functional consequences of this periodic variation of the volume of the rest of the system?
- If you blow into a cylindrical balloon it inevitably expands almost to full inflation in one portion before inflating anywhere else. The initial bulge is what we'd call an *aneurysm*. When you have one in any part of your circulatory system you're in mortal danger since aneurysms, like balloons, are prone to burst. Blood vessels don't ordinarily develop aneurysms, however, and one wonders why. They certainly have stretchy walls—the situation described in the previous item absolutely demands stretchy walls.
- Your circulatory system is a serial arrangement of pipes and pumps (as just described). Thus in any period of time as much blood must pass through the lungs as passes through the capillaries of every other organ in the body combined. Lungs are only a tiny fraction (about 1 percent) of the body's mass—are they really as bloody as this requirement seems to imply?
- A heart is mainly muscle; contraction of this muscle reduces the volume of the chambers inside. So blood gets squeezed out. Valves ensure that it always get squeezed out in one direction, and each valve dutifully opens and shuts once in each stroke. How can they perform their mechanical task when they have no nerve supply to ensure that they open and shut at the right points in the stroke cycle?
- Blood flows rapidly in the arteries but much more slowly in the capillaries, allowing time for diffusion of dissolved materials across

the capillary walls. But the blood speeds up again as it gets into the veins and is finally heartward bound. Where's the pump that so speeds venous blood on its return journey?

- The hearts of large animals beat less frequently than do those of small animals. Large animals live longer, usually, than do small ones. If you multiply the number of heartbeats per minute by the number of minutes per lifetime you get a figure for heartbeats per lifetime, certainly an odd datum. What makes the datum really strange is that its value, about 1 billion, is nearly the same for most mammals. Anything constant amid the great diversity of organisms catches our attention—but what functional significance, if any, might attach to *heartbeats per lifetime?*

It's easy to go on, but you surely get the idea. Most of a book lies ahead, and with some heartwrenching cardiac pun (your choice) we press on.

## Notes

1. I'll use the U.S., not the U.K., naming conventions for large numbers throughout.

2. A cat dealing with even a badly mouse-ridden house still has to be fed. By contrast, it takes an awkwardly large number of geckoes to keep the cockroaches at bay in a tropical home.

3. The *calorie* (or *Calorie*) used in the nutrition or diet business is technically a *kilocalorie*, 1000 of the calories of the physicist. I'll use kilocalorie to avoid any ambiguity. In fact, the preferred unit for energy in contemporary scientific practice is neither, but instead something called the *joule* (after James Joule, 1818–1889), equal to about a quarter of a calorie or a four-thousandth of a kilocalorie or one watt-second. A joule is thus the energy used by a one watt bulb kept on for one second.

4. As our bio-poet, John Burns, described the evolution of auditory ossicles, "With malleus Aforethought Mammals Got an earful Of their ancestors' Jaw."

# 2 *Pumps and Pipes*

In our unguarded moments, we biologists may admit a certain ambivalence about structure. On one hand it is the classical guts of our subject. At some level we carry the conviction that the fantastic structural complexity of cells, of organs, and of organisms wouldn't have evolved without some functional concomitants driving the process. After all, making some functionless structure is not going to improve a creature's procreative potential, and the latter is the very crux of natural selection and evolutionary change. On the other hand, that same complexity of living structure proves in practice to be a great curse for those of us trying to see common functional features amid the wild diversity of living systems.

Biology made its place as a respectable science by naming and classifying creatures and by describing structure; only secondarily (and less respectably) did it speculate about function. (About biology, for instance, Aristotle's explanations were right so infrequently that one suspects pure coincidence.) My own conviction is that this vaguely historical sequence, moving from studying structure to deciphering function has no special virtue for efficient and engaging explanations. It seems better to begin with a broad view of functional systems, using diagrams, models, and analogies—and only thereafter to get into anatomical detail and terminology.

### Further Functional Notions

We've seen that a circulatory system of our sort is made up of a bunch of pumps and pipes. By far the most important pumps are, of course, the two comprising the heart—they're the active components in the sense that only the heart requires a substantial supply of energy to operate. Still, as we'll see later, the heart is by no means the only pump in the system. The pipes are those arteries, capillaries, and veins mentioned in the last chapter—they're essentially passive components, "mere" conduits. While many of these vessels have muscle in their walls, the muscle isn't used to power a pump. Confusing—hearts are muscular pumps but aren't the only pumps; vessels may be muscular, but they don't pump. This was historically confusing, too. Arteries pulsate in opposite phase to the ventricles: when the ventricles contract, the arteries swell and you can feel a pulse wherever an artery runs just beneath the skin. That changes in arterial size are just passive consequences of the heartbeat was not, and is not, self-evident. True, yes; obvious, no.

Let's consider hearts first as simple squeezers and then look at their peculiarities as pumps. A heart is basically a bag with a muscular wall, and a muscle is an engine that puts out power by actively shortening. Upon receipt of an appropriate signal, it tries to pull its ends together—it generates a tensile force. If one or both ends are free to move, the muscle gets shorter—it contracts. If the muscle is wrapped around a squeezable container, then contraction reduces the diameter of the container. The engines of our technology work by either expansion or rotation, so one can't easily build a mechanical heart that works in the same way as a real one.

Putting the squeeze on a chamber using muscle has an oddly practical aspect that often escapes notice. Muscles shorten forcefully, but not especially far—a muscle ordinarily shortens only to something still well over half its resting length. Does this mean that in a beat a heart can at best squeeze out less than half the blood it contains? A model based on simple solid geometry suggests an answer. Imagine a sphere that can make its walls shorten. If, say, the wall circumference were to decrease by 20 percent, that would decrease the radius of the sphere by 20 percent. But the volume of a sphere doesn't follow its radius in such simple fashion—you may recall that volume changes with the radius cubed,[1] that is with radius twice multiplied by itself. The upshot is that a reduction in circumference of 20 percent gives a reduction in volume of fully 50 percent. Figure 2.1a represents the matter in a two-dimensional diagram.



Very roughly, then, if such a heart were to contract its muscle by 20 percent it should pump out half the blood it contains. That's about what happens during the normal heartbeat of a person at rest—2.5 ounces pumped, with the same amount remaining. In strenuous exercise the heart muscle contracts further, and it manages to squeeze out fully 78 percent of the blood it contains. If it worked just like our crude spherical model the heart would have to contract its muscle by only 40 percent of its resting length to do so.

Still, even 40% is awkward. A muscle develops its best power with much less drastic shortening, so our model asks the heart to run rather inefficiently just when called upon for its best effort. Adding two additional elements of realism to the model turns out to help matters. Assume that the squeezing sphere has thick walls and that these are incompressible, both quite reasonable for hearts. Assume further that at rest the volume of wall is twice the volume of the chamber inside, as shown in Figure 2.1b. The calculations are only a little more complicated; they reveal that to expel half of the contents of the chamber, the outer layer of muscle need shorten only by 6 percent. To expel the entire volume of the chamber, the contraction needs to be only about 13 percent. Both of these are very nice figures from what we know of the performance of muscle—they ask that heart muscle operate in a range of shortening in which muscles work well.

I go through this slightly artificial exercise to make a general point as well. Models get used all through science. In essence, a *model* is a hypothesis about how some real thing works. To the extent that the model's performance matches reality, we have evidence (not proof!) that the model is a good one. Its behavior might even be used to predict unknown aspects of the behavior of the real thing. Often a lot of insight can be obtained by considering a series of models running from especially simple and abstract to fairly realistic but more complex. Much can be inferred from the places in the series where particular problems first emerge or where performance takes on specific aspects of reality.

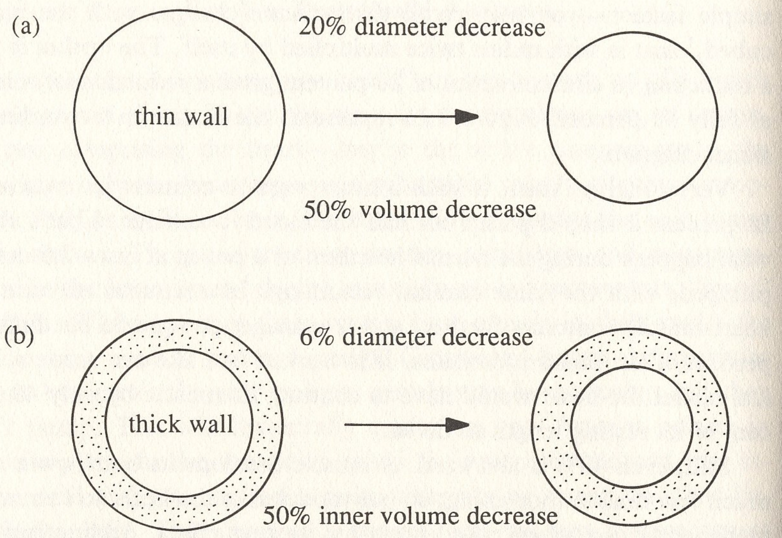


*Figure 2.1.* (a) A small change (20 percent) in the diameter or circumference of a spherical shell gives a large change (50 percent) in the volume enclosed. (b) If we assume a massive, incompressible wall, an even smaller change (6 percent) in circumference gives the same change in the volume of the central chamber.

Creating the series is a little like planning a construction project, with a sequence from sketch to scale drawing to specification of procedural details; the main difference is that our series of models has an analytic rather than a synthetic goal.

To go much further, it's handiest to put aside simple, squeezing spheres and turn to hearts themselves. Earlier, the existence of entrance chambers attached to a heart was mentioned without comment. These atria are invariably found in the hearts of our fellow vertebrates, and they're parts of the hearts of many of the active kinds of other biggish animals. They're most often muscular chambers, but they are never anywhere near as massively and powerfully muscular as are ventricles. Despite this difference they pump blood at precisely the same rates as the ventricles to which they're attached.

What seems to be going on is more or less the following. A pressure difference is what drives flow through circulatory systems, or through any other plumbing for that matter. More explicitly, an initial high



pressure provides the push, and a heart provides that high pressure. A pressure difference, though, demands that pressure at the other end be low—again, it's the difference that matters. High pressures, as we'll see, are not without costs and dangers; and these argue that the pressure of blood returning to the heart should be kept as low as possible. Yet another problem thereby arises. How can the main pump, a ventricle, be rapidly refilled if blood returns at low pressure? It cannot actively expand, as we'll see shortly, so blood must be forced in. And that's where these weak little auxiliary pumps, the atria, come in. They are, in a word, *superchargers*. Figure 2.2 shows the arrangement schematically.

For people who fondle (at least mentally) automobile engines the idea will be nothing new. An ordinary car sucks its explosive mixture into a cylinder because the piston goes downward and reduces the local pressure below ambient. So the fuel and air[2] enter at this low pressure, and the useful pressure caused by combustion builds from this low ebb. One can extract more power if an external pump, a supercharger, is used to force in the mixture. The mixture is compressed, so more goes in, and the baseline pressure before combustion is higher. Vertebrates and mollusks—two of the three great culminations of complex animals—have separately evolved atrial superchargers. The main difference between hearts and fancy cars is that hearts use the supercharging to increase the volume per stroke more than the maximum pressure. More mixture enters because ventricles are stretchy not because the fluid is compressible (blood isn't).

Back to muscular pumps. A muscle can only contract; if it surrounds a chamber its contraction can increase the internal pressure in the chamber, squeeze out some of the contents, or both. A little more machinery is needed to make a practical pump that does more than merely stir things up. In practice, nature uses two versions of that "little more machinery" in making muscles run pumps. (Some living pumps have other power sources, but we'll not be distracted by them here.)

One arrangement is the one used by our intestines. It involves waves of contraction running down the length of the pipe, each wave pushing a bolus of fluid ahead of it. The scheme is called *peristalsis* (Figure 2.3), and it approximates what you do when trying to get the last bit of toothpaste from the bottom of the tube. The same machinery can push

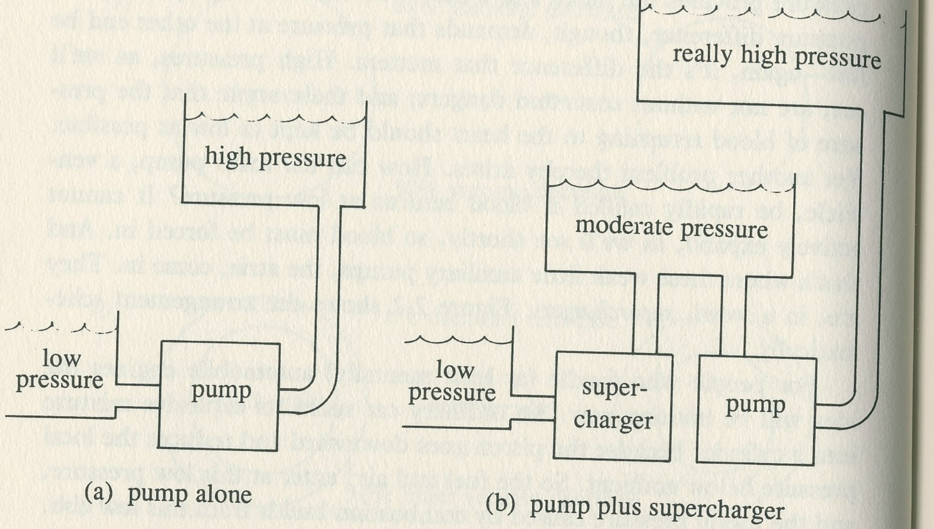


*Figure 2.2.* A hypothetical pump before and after the addition of a supercharger or atrium: (a) pump alone; (b) pump plus supercharger.

fluid in either direction, and it can deal with sludgy fluids, but it's relatively inefficient in its use of power. Peristaltic hearts exist, but in neither fish nor fowl nor, for that matter, in any other vertebrate. Some worms have them, as do a curious group of creatures in the same larger lineage as vertebrates—they're called sea squirts, or sea pork, or tunicates, or ascidians—that for unknown reasons have hearts that periodically reverse their direction of pumping.

What our hearts do is quite different. Those supercharging auxiliary chambers, the atria, squeeze and drive blood into the ventricles. The ventricles then give discrete, simultaneous squeezes, and blood flows out into the arteries. The two sounds you hear when you put your ear against someone's chest indirectly reflect those contractions—the gentler atrial contraction followed by the stronger ventricular contraction. But what prevents ventricular contraction from driving blood back into the atria and the veins as well as into the arteries? And what prevents the ventricles from being recharged from the largest arteries rather than from the atria? In short, what makes the pump decently directional?

Consider the squeeze-bulb of a kitchen baster as a crude model of a



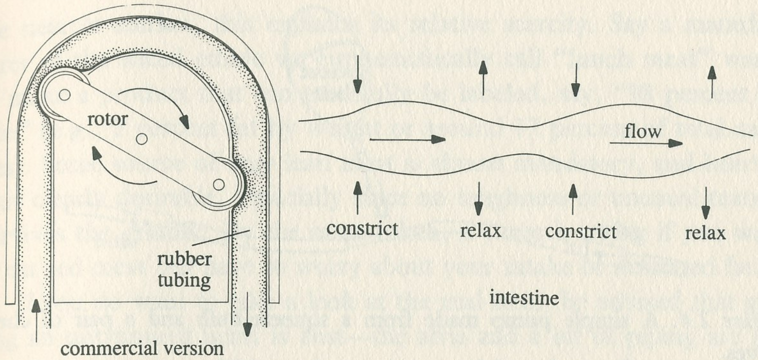


*Figure 2.3.* Pumping by using traveling waves of constriction in machine and intestine. Neither system is especially efficient in terms of energy, but the scheme has other compensating virtues. Peristaltic pumps will push semi-solid slurries, and by staying in a pipe the contents avoid contamination in valves and chambers.

muscular chamber such as a ventricle. What is the minimum additional machinery necessary to make it into a one-way pump? One answer, and I think the simplest, is a pair of "check valves"—devices that allow fluid to pass in only one direction. Arrange the squeeze-bulb and check valves as in Figure 2.4 and you have a one-way pump. A single valve is better than none, but it allows a lot of back flow; more than two accomplishes nothing further. One neat feature of this scheme may escape your notice since what's neat is that something proves unnecessary. An automobile engine has valves to let air and fuel into the cylinders and to let exhaust out of them. Timing the opening and closing of all those valves must be carefully controlled by timing belt, camshaft, lifters, and so forth. Both the baster with check valves and our ventricular chambers have automatically self-synchronizing valves! They open and shut in response to nothing fancier than the pressure changes caused by squeezing the bulb or contracting the chambers of the heart. That, incidentally, answers the question left hanging in the last chapter about how heart valves manage without nerves.

If one ventricle needs two valves, an input one and an output one, then two ventricles require four valves in all. And these we have. One might reasonably expect that the presence of the pair of atrial ante-

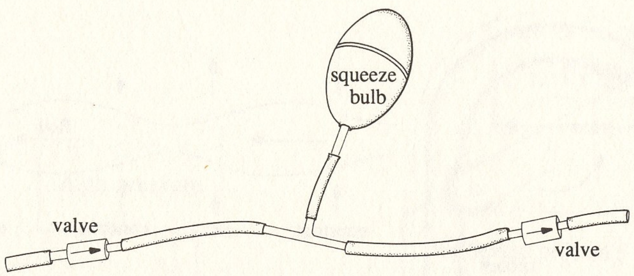


*Figure 2.4.* A simple pump made from a squeeze-bulb and a pair of check valves.

chambers would entail provision of two further valves. Reality is just a little more complicated. A valve is present between the vein from the lower part of the body and the right atrium but not between the vein from the upper part of the body and that same atrium. Nor are there ones between pulmonary (lung) veins and left atrium. Contraction of the atrial wall effectively closes these inlets, so functional valving is accomplished even without specific structures. Not only don't nerves supply our heart valves, the valves don't even need muscles. And if you have trouble with leaky or otherwise faulty valves, fairly good replacements can be installed. These replacement valves are either artificial, mechanical components, or else are valves "borrowed" from, most commonly, defunct pigs or people. Once installed, they're quite dependable. (One might say that they last a lifetime, but they sometimes do need replacement, and using the word *lifetime* in this context makes one a little uneasy.)

### Looking at a Heart

At this point, I originally planned to advise the especially devoted or compulsive reader to abandon hearth and chair, to rush forth, and to purchase a heart from the nearest purveyor of such items. However, ordering an untrimmed heart from a butcher shop turns out to be not as simple as it used to be. Heart is the least fatty of any meat from the large mammals we commonly eat;[3] according to my informant at



the nearest market, this explains its relative scarcity. Say a manufacturer of the sliced edible we euphemistically call "lunch meat" wants to make a product that can truthfully be labeled, say, "98 percent fat free" (e.g., 2 percent fat by weight or around 17 percent of total calories). Some source of very lean meat is almost mandatory, and heart is thus clearly desirable, especially since no toughness or unusual texture survives the grinder. By the same token, it's worth trying if you want to eat red meat but have to worry about your intake of saturated fat.

If you do want to take a look at the real item, be advised that getting an untrimmed heart is best—the atria and a bit of piping are left attached. A "trimmed" heart has only ventricles (the really meaty since the most muscular part), so that's the next best thing. Usually it's slit lengthwise in order, presumably, to lie flat between plastic wrap and styrofoam; but you can easily truss it up again. In any case whether you get a heart or a piece of one and are at all carnivorous, you really shouldn't waste it. But don't cook heart as if it were some commonplace skeletal muscle—I've provided a little more guidance and a recipe at the end of the chapter. In our household, beef heart is purchased, when available, as a special treat for the feline who supervises the establishment.

An alternative hands-on approach to a heart is to order an embalmed one. These are cheap and not as unpleasant as you might think. The biological supply companies do a good job at preservation, so the texture and even color are surprisingly lifelike, and they can be handled quite leisurely at room temperature. Also, the days of formaldehyde fumes are past—an embalmed heart has almost no odor. A few addresses are given at the end of the chapter. You usually have a choice of cow, sheep, or pig. No one is clearly preferable, inasmuch as beef hearts are nice and big, pig hearts are usually cheapest, and sheep (lamb, really) hearts are about the size of our own. Anatomical differences are trivial. Not that one absolutely must get quite so unvicariously immersed in the subject—illustrations do accompany the words that follow.

In a mammal, the volume of the chest or thorax beneath the ribs is mainly filled by a pair of lungs, one on each side and each in its separate cavity (Figure 2.5). Between them is a substantial wall, called the mediastinum (accent on the penultimate syllable), extending from ster-

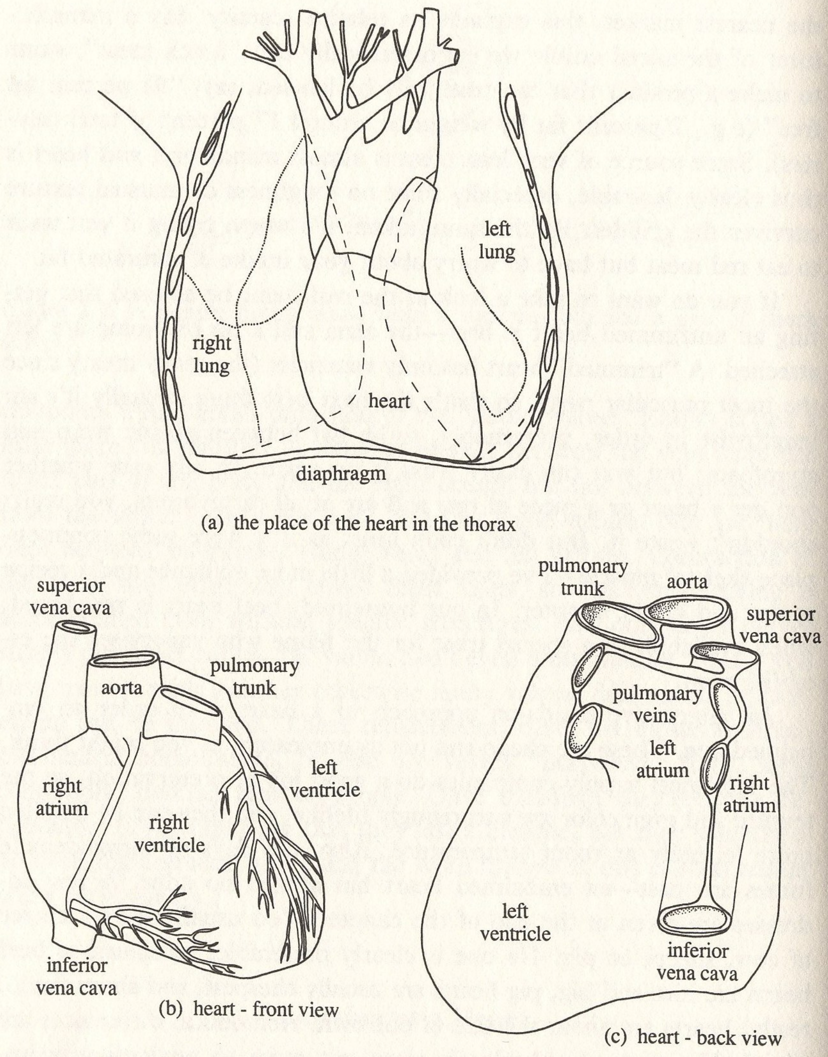


*Figure 2.5.* (a) The location of the human heart in the chest, with the items normally in front of it removed. Dashed lines mark the inner margins of the lungs. (b) The heart itself in front view, with its coronary arteries. (c) And the same from behind.





num in front to backbone behind[4] and from the top of the thorax to the diaphragm at the bottom. Down through that wall, in the back, runs the esophagus, carrying food from the head above to the stomach in the abdominal cavity beneath. And in that same wall the heart is located, a little to the left of the midline. It's located within the so-called pericardial cavity. Thus the heart's surface is not attached to the wall of the mediastinum, and it's free to slide around as the animal moves and the heart beats. The cavity contains a few ounces of fluid that, among other things, provides lubrication. When lubrication is inadequate a frictional rub—acute pericarditis, is audible through a stethoscope.

If you were to remove the sternum and a bit more of this and that, you'd see the heart from what we're calling the front, the view most often illustrated. (Pardon me if I'm getting a bit graphic—I do really understand that some people are normally squeamish.) This puts the ventricles down and the atria up, a little like a dangling strawberry or an upside-down pear. (If you have an intact heart, you ought to orient it as if viewed from the front—put the two biggest and sturdiest pipes upward and less well-defined connections around back.) Since you're facing the heart, its left side is on your right and its right side is on your left.

The right ventricle is mostly what you're now facing, with the left partially rotated around behind to the right. In fact the right ventricle wraps a bit around the left. As you can see from Figure 2.6, the right ventricle has much thinner walls, concomitant with the lower arterial pressures in the circuitry of the lungs. (The wrap-around arrangement and the very different thicknesses of the ventricular walls are quite obvious in a duck or goose heart.) The venous pipes leading into the atria are mostly hidden behind, and the pipes leading out from the ventricles emerge on top, between the atria. The left top pipe as we face it (on the right with respect to the body) is the great aorta, about an inch in internal diameter, which carries blood to the body from the left ventricle. The right top pipe (on the left of the body) is the pulmonary (lung) trunk, which branches into the left and right pulmonary arteries—one for each lung. The right atrium is visible at the upper left; the left atrium is mainly around behind.

The arrangement is almost certain to confuse you at first sight—

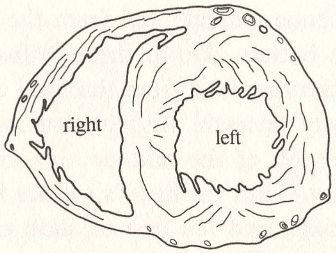


*Figure 2.6.* A cross section of the heart through the ventricles—to show the great difference in the thickness of their walls.

while the right atrium seems to be in the right place, it looks as if the right ventricle is on the wrong side. The problem is that the whole organ is twisted, obliquely mounted in the body, and mildly asymmetrical. Looking back at our earlier diagrammatic representation, Figure 1.3, on page 13, ought to keep you from getting too badly disoriented. I think anatomists (and many other biologists) have unusually well-developed visual perceptions that work well with oddly shaped, three-dimensional representations. The way I cling to diagrams (even when I taught anatomy) is probably an aspect of the same personal defect that almost drove me out of biology when a freshman course demanded proper drawings. Dissection was easy—my manual dexterity later proved adequate to attach little wires onto fruit-flies.[5] Nonetheless, I have horrible memories of my attempts to get images down on papers that would be graded.

So—blood goes forward into the atria, down diagonally into the ventricles, and upward as it heads out to lungs or elsewhere. Into the right atrium, thence to the right ventricle, and out to the lungs in the *pulmonary* circuit. In from the lungs to the left atrium, down into the left ventricle, and out the aorta to the rest of the body in the *systemic* circuit. Heart to heart, twice over.

A few more blood vessels, much smaller ones, are visible in the drawing of the front of the heart or on the surface of the real heart. These are the coronary arteries that supply oxygen and the other metabolic desiderata to the heart muscle. From our present vantage point, on the right lies the main branch of the left coronary artery. This branch



of the left artery conveniently marks the approximate boundary between right and left ventricles. On the left lies the right coronary artery, running in a groove between the right atrium and the right ventricle. Finally, we have some structures helpfully located! As you can see from the drawing, both of these arteries receive blood directly from the aorta. Adjacent and somewhat beneath each is the corresponding vein, carrying blood back to a junction at the right atrium. The right coronary artery branches near the bottom of the drawing, with one part going along the bottom margin of the heart and the other going around behind and out of view. The left artery branches near the top of the heart, with the branch not shown going around behind. Thus the back of the heart gets supplied by vessels coming in from opposite points from the front—lower right and upper left instead of upper right and lower left.

(Coronary arteries are prone to suffer internal narrowing as fatty material gets deposited on their walls; the result is a reduced blood supply to the heart muscle, not at all a good thing. The condition, *coronary artery disease*, is extremely common, particularly in elderly, obese, and inactive people who eat a lot of animal fat, and in those with strong hereditary predispositions. Two invasive treatments are used these days. One is *balloon angioplasty*, a kind of internal wall-smoothing. The other is *coronary bypass surgery*, in which the narrowed vessels are bypassed by new ones, spliced between the aorta and the lower reaches of the coronary arteries. The new vessels are merely some surface veins from the same person's legs, veins that are parallel to other veins and therefore mildly redundant.)

We can now turn the heart over, either figuratively (Figure 2.5, again), or on your cutting board. Looking from the back, left on paper is now really left and right is rightly right. In the middle is the left atrium; below and off to the left is the left ventricle. The edges of right atrium and ventricle are visible on the right and bottom. Details of the pipes coming into the atria vary a little, even among such a conservative bunch as the mammals, but the human pattern isn't in any significant way deviant. (Humans may be special in lots of respects, but we should be reminded that we have unexceptional mammalian circulatory systems.) Four large pulmonary veins come in from the lungs (two from each) and separately enter the left atrium. And two even larger veins carry blood to the right atrium, the inferior vena cava ("hollow vein") from the lower part of the body and the superior vena cava from the upper part (some mammals have a pair in place of a single superior one). That's it on the outside.

Inside (Figure 2.7), the most conspicuous item is, I suppose, the thick muscular wall that separates the ventricles. If you're working on a real heart, slitting it lengthwise will expose the interior of one or the other ventricle, the choice determined by just which side of the interventricular branch of the left coronary artery receives your knife. The interiors of the two ventricles are similar; what is for some reason surprising is just how unsmooth are the inside walls. Folds and columns (*trabeculae*) of flexible but strong and inextensible tissue run across the ventricles, mostly in an up-and-down direction, as do some muscles (*papillary muscles*). Together, these assist in the operation of the heart valves and probably help prevent any overdistention of the ventricles.

The most interesting internal structures are certainly those valves. As explained earlier, they're critically necessary to get unidirectional flow, but they're nonmuscular, noninnervated, passively operating structures. While much has been made of differences among them in structure, to me they look quite similar. Two or three pieces of flexible sheet (*valvules*) extend inward from the circular periphery of an orifice, pieces large enough to completely occlude the opening (Figure 2.8a). If the pressure is higher on the normally upstream side, then the individual valvules flap back against the adjacent walls, permitting free flow of fluid. If the pressure is higher on the normally downstream side, it forces the valvules to move toward the center, where they meet and block flow. The pulmonary valve controls the exit from the right ventricle; the aortic valve does the same for the left ventricle. Between the right atrium and its ventricle stands the tricuspid (or right atrioventricular) valve; between the left atrium and ventricle is the mitral (or left atrioventricular) valve. These latter two are the valves that the papillary muscles of the ventricles help keep closed when the ventricle squeezes.

A few other valves are almost always present, but their functioning isn't quite so critical. There's one between the inferior vena cava and the right atrium, although a few of us lack it as adults. As mentioned, no valve intervenes between superior vena cava and atrium, but there are small ones where the coronary veins return blood to the right atrium.



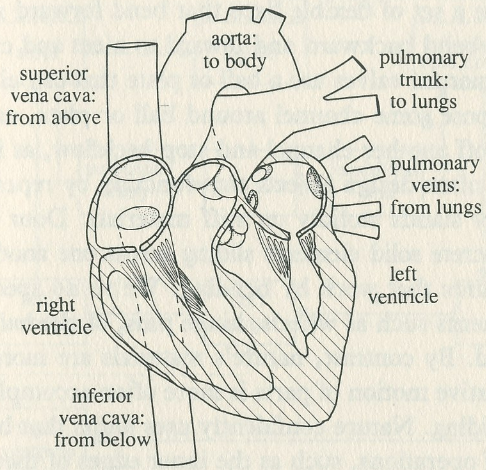


*Figure 2.7.* The heart, a somewhat diagrammatic cut-away viewed from the front.

Heart valves generally work well, although some incomplete sealing, with consequent backflow, isn't uncommon. The backflow frequently makes noise detectable with a stethoscope—it's called a *murmur*.

Passively operating one-way valves aren't anything very special—we use lots of them in our technology. Commercial and biological check valves achieve their identical result in quite different ways, though, ways that reflect one of the great divides between human and natural technology. All of the natural valves we've been considering (and most oth-

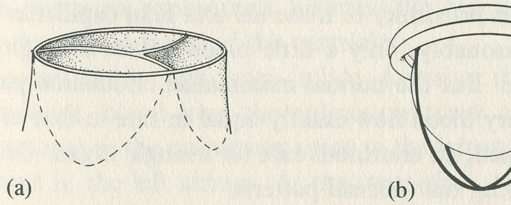


*Figure 2.8.* One way valves. (a) is a typical heart valve; (b) is a commercial ball-in-cage valve. The latter happens to be one designed to replace a heart valve. As shown, both permit flow from top to bottom and prevent flow from bottom to top.

ers as well) use a set of flexible flaps that bend forward and outward to open and that bend backward and inward to meet and close. The most common commercial valves use a ball or plate that can either be pushed forward to expose some channel around ball or plate, or pushed backward to close off another channel and stop backflow, as in Figure 2.8b. We just don't often design objects that function by repeated bending—our technology stands stolidly on stiff materials. Door hinges, for instance, use discrete solid elements sliding across one another rather than flexible structures that work by bending. We've no special aversion to unbound elements such as wheels, hinge pins, or the balls in the valves just mentioned. By contrast, nature's materials are more often flexible than stiff. Relative motion of parts is more often accomplished by bending than by sliding. Nature confidently uses joints that bend repeatedly for millions of operations, such as the inner edges of these heart valves. On the other hand, nature appears to abhor all but very tiny detached elements—in organisms everything is usually connected somewhere with everything else, not just in direct contact.

### Mammals without Functional Lungs

At first, the image doesn't sound at all nice. Still, we were all that way, once, since a mammal must be born before it can breathe. The consequences for circulatory systems and for hearts in particular constitute what must be the most amazing of all the events attending a mammalian birth. Fetal blood, of course, gets its oxygen from the maternal blood, so mother acts like a surrogate set of lungs. The arrangement involves the close proximity of maternal and fetal capillaries in the placenta. Quite reasonably, only a little blood passes through the developing fetal lungs. But the normal mammalian circulation pattern mandates a pulmonary blood flow exactly equal in rate to that of the rest of the body combined, an enormous rate for a single organ. Obviously the fetus can't be using that normal pattern.

What happens is shown in Figure 2.9. Blood from the placenta enters the inferior vena cava of the fetus via the umbilical vein and passes, in normal fashion, to the right atrium. Most of this blood, however, now passes through an opening between the two atria and thus gets to



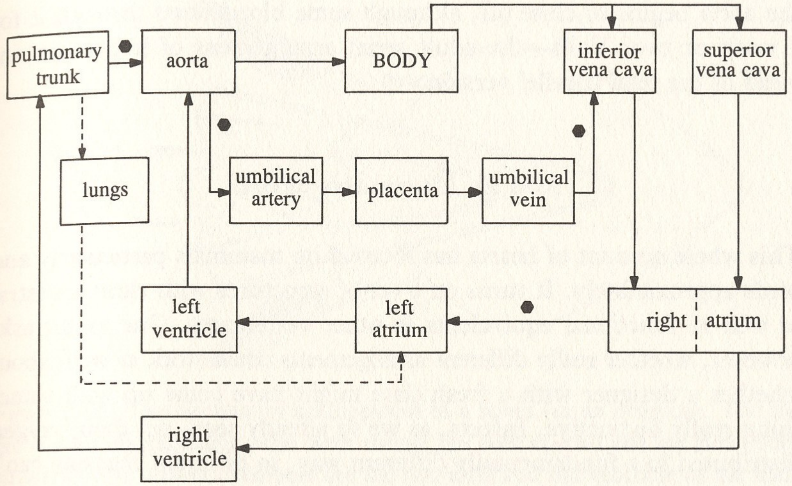


*Figure 2.9.* Something this complex only a mother could love! This is the path of the blood in a fetal mammal; you might compare this to the diagram of Figure 1.3, page 13. At or shortly after birth, the connections shown dashed open up, and those marked with hexagons close off.

the left side of the heart without going through the lungs. What of blood from the superior vena cava? It also goes to the right atrium, but most of it flows normally into the right ventricle. (The right atrium is doing two things at once, in a fine bit of fluid-mechanical sleight of hand.) Coming out of the right ventricle most of it passes, not to the lungs, but through an opening between the pulmonary trunk and the aorta. In effect, the four chambers are pumping as a parallel pair of two each, with upstream connections between the two atria and another connection just downstream of the ventricles.

Then comes birth. The lungs inflate, lowering their resistance to flow. As a result, blood from the pulmonary trunk goes freely to the lungs and returns in the pulmonary veins to the left atrium. As a result, pressure rises in the left atrium. At the same time, the umbilical vein begins to close off, and pressure drops in the right atrium. This shift in the relative pressures of the atria closes the valvular opening between them, and tissue eventually grows over the structure, usually sealing it for life. At the same time the duct between the pulmonary trunk and the aorta begins to close off, although some blood flows through it for a week or two. Voilà—the adult serial arrangement of half-hearts instead of the fetal parallel version.

### And an Alternative World

This whole account of hearts has focused on mammals particularly and birds approximately. It turns on a set of structures with clear ancestral as well as functional equivalents in other vertebrates. One might ask, however, whether really different arrangements could work as well, about whether a designer with a fresh slate might have come up with something really distinctive. Insects, as we've already seen, get their oxygen distributed in a fundamentally different way, so different that one can't make easy point by point comparisons. Another group of animals, again quite out of the lineage that gave rise to vertebrates, has produced large and active creatures; looking at them (which will happen repeatedly as we go on) provides as nice a contrasting perspective on circulation as one could wish. These are squids, cuttlefish, and octopuses—the class of mollusks called *cephalopods*.

These cephalopods, it's a pleasure to report, have come up with the same scheme as the mammals and birds. It's the same, though, only in a purely functional sense—the components look quite a lot different and are spread around in far from corresponding places. The cephalopods have moved beyond the single hearts of their molluscan ancestors just as we have transcended those of our fishier vertebrate forebears. And, just as in our lineage, a second pumping system gets around the problem of making blood go through two exchangers, two capillary beds in sequence. But the cephalopods do the trick, not by partitioning a single contractile machine, but by the addition of a pair of booster hearts that force blood through their gills. In short, as shown in Figure 2.10, cephalopods have three hearts. The main, systemic heart receives blood from the gills and pumps it fore and aft through arteries to the tissues of the body as does our left half-heart. The two gill hearts, one on each side, receive blood from the body and send it to the gills. The main heart has not one but two atria, each passing along blood from one side of the animal.



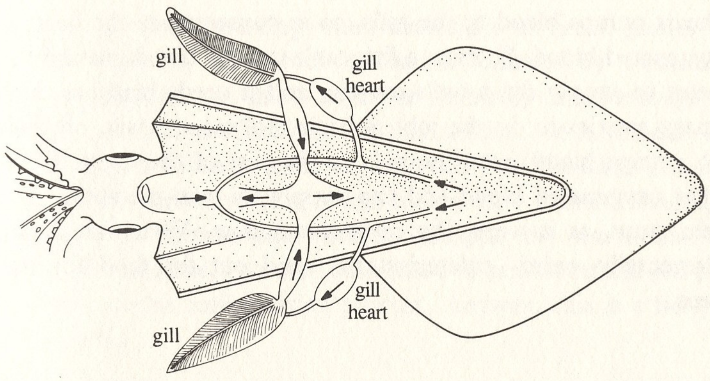


*Figure 2.10.* The circulatory arrangement of a squid (or an octopus). The figure is a bit diagrammatic—the outer mantle has been opened and the gills folded outward. The central chambers are the two atria and the ventricle of the main (systemic) heart.

In a way, the circulatory system of these cephalopods appears a little more logical than ours. The secondarily evolved pumps are clearly boosters serving the respiratory organs, and the system is bilaterally symmetrical. That means it can be divided by a plane into left and right mirror images, the symmetry both we and the cephalopods show on the outside. Our booster pump, as mentioned earlier, is the old main one of the fish; our external symmetry belies a heart asymmetrical in shape and asymmetrically located to the left of the midplane of the body. Again, though, no judgment is implied. My guess is that we're just the confused result of evolution both of a dual-pump system and of new gas-exchange organs, with lungs replacing gills in the transition to air-breathing. But although lungs do the old gill function, as we noted in the last chapter, they aren't made, evolutionarily or embryologically, from gills or the precursors of gills. Thus there's no reason to expect them to be hooked to the circulatory system with the equivalent vessels. By contrast cephalopods are now and have always been marine creatures; their gills aren't fundamentally different structures from those of less active mollusks such as clams.

The cephalopod arrangement and the molluscan system in general seems a more reasonable design in another respect, one probably reflecting a much earlier evolutionary event. In the basic vertebrate scheme the heart pumps blood to the gills, so in consequence the heart moves deoxygenated blood. So even a fish can't use the blood passing through its heart to supply the heart's muscle, and it needs (and has) auxiliary coronary arteries to do the job. A basic molluscan heart, on the other hand, pumps blood from the gills to the rest of the body. It thereby handles oxygenated blood and can supply its own metabolic need for oxygen from, as it were, the mainstream flow. Vertebrate hearts are fundamentally weird—cafeterias that send out for food for the employees.

## Cooking with Heart

Back to the here and now with the promised guidance for cooking heart, either for what you have left over from your anatomical explorations or if you want to eat cheap red meat without worrying about your own heart and coronary arteries. (But don't try to cook embalmed heart!) The basic culinary problem isn't the muscle, it's the other main structural component of heart, a protein called *collagen*. The name means, from the Greek, "glue source"—"colla" as in "collage" and "gen" as in "genesis."

Collagen is the ultimate source of old-fashioned glue made from bones, skin (hide glue), fish offal, and other such food byproducts. It's also the source of gelatin. Within organisms, collagen is a fibrous, water-insoluble protein, perhaps the most common of all animal proteins. Its fibers are strong and flexible, but they are ropey rather than elastic or, put another way, not very stretchy. Thus when pulled on by contracting muscles they convey that shortening to bone, skin, or some other muscle rather than themselves stretching. Contract your calf muscles and you stand on tip-toes—your collagenous Achilles tendons pull on the heels. Literally laced with collagen are boneless muscular organs—the outer mantle of a squid, many tongues, and, of present interest, hearts.

This ropey material, collagen, is the very essence of toughness. Roast or grill heart, and you've a real jaw-wearying product. You have to do a mild version of what the gluemakers do, solubilizing the fibers by chopping up the long molecules. The process is termed *acid hydrolysis*



since it amounts to inserting water molecules at break points under acidic conditions. A long, cool incubation followed by a shorter hot treatment works fine—in short, what one ordinarily does for tough meat. The choice of acids is more cultural than critical, with vinegar, lemon juice, and tomato sauce as common contenders for the task. The following is a recipe derivative of a south Indian stew called a *vindaloo;* an alternative is a German sauerbraten. (Despite the traditionally fiery character of vindaloos, you may be pleased to know that the red pepper isn't critical to the tenderization process. Anyway, this is a fairly non-corrosive one.)

1/2 tsp crushed red pepper
10–20 garlic cloves, sliced
1 tsp ground cumin
1 tsp powdered mustard
1 tsp ground turmeric
2 cubic inches ginger root, chopped (or 2 tsp ground ginger)
1 tbsp lemon pulp
1 tbsp sugar
4 tbsp poppy seeds
3/4 cup vinegar
2 lbs heart (ventricle), cut into small cubes
2 tbsp vegetable oil
4 cloves
1 onion, half-rings
1/2 cup tomato sauce

Blend pepper, garlic, cumin, mustard, turmeric, ginger, lemon pulp, sugar, salt, poppy seeds, and vinegar at high speed until homogeneous. Mix with meat in a bowl and marinate overnight. Heat oil in a Dutch oven, add cloves, and fry a few minutes. Then add onions and fry until they're soft. Cool a bit to lessen the danger of sticking or splattering and add the marinated mix. Cook slowly, covered, for an hour or two. Add tomato sauce and cook until meat is tender, usually about another hour. Uncover and cook off extra liquid if necessary.

## Sources of Preserved Hearts

All of these vendors offer embalmed cow or calf, sheep or lamb, and pig hearts. They all have horribly expensive anatomical models, but Fisher and Wards have less costly ones as well. For nonfondlers NASCO has a reasonably priced sheep heart sliced open and embedded in plastic, and Wards has freeze-dried whole and bisected (as opposed to dissected) sheep hearts. Addresses:

Carolina Biological Supply Co.
Burlington, NC 27215
919-584-0381

NASCO
901 Janesville Ave, Box 901
Ft. Atkinson, WI 53538
414-563-2446

Fisher Scientific Company
Educational Materials Division
4901 W. LeMoyne Street
Chicago, IL 60651
312-378-7770

Ward's Natural Science Establishment
P.O. Box 92912
Rochester, NY 14692
716-359-2502

A good source for inexpensive models (but whose catalog may be dangerous to your financial security) is

Edmund Scientific Co.
101 E. Glouchester Pike
Barrington, NJ 08007
609-573-6259

## Notes

1. For lack of day-to-day utility it may be only a distant memory, but you probably once learned that the volume of a sphere was four-thirds times pi times the cube of its radius.
2. Just air if you have an engine that uses fuel injection.
3. According to the U.S. Department of Agriculture's book, *Composition of Food*, heart, even with a little superficial fat layer, has only 3.6 percent fat. For comparison, flank steak has 5.7 percent, round has 12.3 percent, and the really fancy cuts around 35 percent. The book, from the Superintendent of Documents, Printing Office, Washington, D.C. 20402, is something no home should be without.
4. You can guess that I'm assuming a bipedal, upright animal such as one of us. I'm trying to avoid using *dorsal*, *ventral*, *sagittal*, and such other directional descriptors. Anyhow, one usually draws even dissected quadrupeds as if the head were up and the tail down.
5. Not really as difficult as it sounds—with fruit-flies one can tolerate a very large failure rate. More impressive are the people who do delicate work on other people, where the Damocles' sword of a malpractice suit may be more than a match for a scalpel.