# In DARWIN'S Image

## How human biology confirms Evolution Theory

by Arndt von Hippel

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"This work contains hardly any original facts in regard to man; but as the conclusions at which I arrived, after drawing up a rough draft, appeared to me interesting, I thought they might interest others. It has often and confidently been asserted, that man's origin can never be known: but ignorance more frequently begets confidence than does knowledge: it is those who know little, and not those who know much, who so positively assert that this or that problem will never be solved by science."

*Charles Darwin* in The Descent of Man

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"The...process...by which any individual settles into new opinions...is always the same. The individual has a stock of old opinions already, but he meets a new experience that puts them to a strain. Somebody contradicts them; or in a reflective moment he discovers that they contradict each other; or he hears of facts with which they are incompatible; or desires arise in him which they cease to satisfy. The result is an inward trouble to which his mind till then had been a stranger, and from which he seeks to escape by modifying his previous mass of opinions. He saves as much of it as he can, for in this matter of belief we are all extreme conservatives. So he tries to change first this opinion, and then that (for they resist change very variously), until at last some new idea comes up which he can graft upon the ancient stock with a minimum of disturbance of the latter, some idea that mediates between the stock and the new experience and runs them into one another most felicitously and expediently."

*William James*

# Introduction

Earth without life is difficult to imagine. Yet life itself is so strange you could never imagine it, were it not already true. One of the hardest things to accept about life is death. But death defines and refines life by selectively removing the vast majority of living things before they can reproduce.

Although a simple “thumbs up” or “thumbs down” on reproductive success might seem an impossibly crude tool with which to fashion and detail life’s delicate complexity, that is how even the most hi-tech plant or animal breeders finally obtain their impressive results. For in this difficult and dangerous world, new life must acquire its competitive organization and basic operating skills from previous life.

The world should therefore be grateful that your ancestors were unfailingly amongst those naturally selected to reproduce in each of many hundred billion consecutive generations. Small wonder that your mind and body remain so attuned to reproductive concerns.

## *Life is a self-correcting, cumulative process, not a final result*

The fossil records of Earth’s first two billion years reveal only bacteria and single-cell life forms. Later strata include increasingly complex plants and animals. Worms show up before fish, amphibians before reptiles, Lucy and other pre-human primates before creationists.

Upon careful examination of this progression, it becomes evident that the cooperative hierarchical organization of present-day multicellular life is an inevitable outcome of competitive and informational pressures rather than a reflection of unique ancestral circumstance or divine design**.** Indeed, life is just one example of a fact-dependent competitive enterprise that must remain on top of its ever-expanding information base or die. Commercial and scientific endeavors are similarly information-driven.

## *Science is an objective (evidence-based), self-correcting, cumulative process, not a final result*

Regardless of whether an important discovery emerges from your garage or some world-famous laboratory, it adds to the knowledge base from which future research and invention will grow. Thus a chance observation led to careful studies of radioactive decay that soon provided enough evidence about atomic structure to initiate modern Atomic Theory and make possible the atom bomb.

Scientists then honed their newfound information and skills until they could produce and measure various products of radioactive decay with sufficient accuracy to determine the age of Moon rocks and Martian meteorites, illuminate the history of Neandertal campfires and the Shroud of Turin, and reveal which parts of your brain would guide you home. And the waves of derivative discovery from that early chance observation continue to spread.

Most scientific findings fit appropriately within the currently accepted view of reality. However, an occasional divergent discovery - or surprising verification of some controversial hypothesis - may bear such revolutionary implications that it takes one or more generations to become widely understood and accepted. But whether ordinary or outrageous - widely accepted or initially rejected - every bit of amply confirmed scientific evidence bears at least potential value for scientists or entrepreneurs.

Of course, important new information that alters human belief or behavior may initially benefit just a few, while degrading the lives of many who have successfully adjusted to the status quo. This unequal distribution of costs and benefits naturally causes controversy. Yet even the most controversial observations or ideas develop and replicate so rapidly upon release that they can never be recaptured, controlled or withdrawn from human memory.

## *Evolution Theory is inclusive, objective, self-correcting and cumulative - hence a scientific theory*

Scientists of all nations, cultures, backgrounds and beliefs obsessively elaborate upon, pore over and reconsider huge quantities of old and new information as they seek to understand our natural world. Atomic Theory, General Relativity, The Laws of Thermodynamics and Modern Evolution Theory are important outcomes of this collaborative effort. And ever since it was recognized as the organizing principle for life on Earth, Evolution Theory has guided and enriched all relevant investigations.

## *Creation tales are exclusive, subjective and conflicting*

Every human society treasures an ancient explanation for life and the universe that once glorified and sustained its early culture and traditions. Not surprisingly, modern science has shown these conflicting creation tales to be outmoded fabrications or erroneous conjectures rather than pure primitive perceptions of some underlying reality.

Even Genesis, the world’s most widely revered creation myth, is clearly false in every particular. Yet the incurably devout - and those who profit by keeping them so - reject much of modern science merely because it contradicts religious beliefs passed down from the Bronze Age.

Nonetheless, large numbers of carefully studied fossils bear silent witness to life's long history and gradual progression. And investigations in every field of science support and enlarge upon those fossil findings. That life is an outcome of ongoing physical and informational processes set in motion at the big bang is now beyond reasonable doubt. Indeed, this broad new scientific consensus about life's origin and development represents a major watershed in the history of human thought.

Furthermore, the organizing principles that underlie modern Evolution Theory (see Chapter 1) are so fundamental and inclusive that they apply equally to all forms of life, everywhere and always. So while those who study evolution will surely come up with additional insights and disagreements as fresh facts are integrated and old findings reinterpreted, the overall picture is clear. The facts are real. No fundamentally conflicting theory could be true.

**Life's origin provides the point of departure for this book.** After developing rules that all life must follow, we consider the incredible odds against any specific outcome such as yourself. A review of life's layered progression from bacterium to nucleated cell to multicellular organism, shows how inadvertent information transfers and accidental mergers of desperately competing life forms brought about important advances.

As we examine efficiencies gained through cell specialization, it becomes clear why the reorganization of specialized cells into complex organ systems brought additional reproductive advantages. Our overview of human biology concludes with evolutionary insights into human sexuality and embryonic development.

The facts presented herein are up-to-date and widely accepted. They have been garnered from many scientific fields and a lifetime of personal and professional experiences. So even if you already understand a lot about human biology, my report on how evolution underlies human form and function should interest and entertain you. As for those with little previous exposure to human physiology or modern Evolution Theory, this book can help bring you up to speed.

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# Chapter one

# How life came to be

Life's astounding diversity arises from the relentless regenerative interactions of a few simple rules. And the same evolutionary precepts underlie every forest, prairie, turkey farm, professional society, termite mound, bee hive, herd, flock, school, family, factory, church or other business. Indeed, they apply to life everywhere, always.

**1) Nature is prolific**
The overproduction of willows, dandelions, mice and mosquitoes is beyond dispute. Mighty oaks and ancient apple trees eventually litter their surroundings with millions of acorns and apple seeds. The pollen wasted up your nose might have fathered a forest; yet sufficient pollen remains airborne to service every hayfever victim, ragweed and spruce cone.
A newborn human female carries over a hundred thousand eggs.
One human male may release a trillion sperm during his lifetime.
*Life's reproductive rush leaves less avid replicators by the wayside.*

**2) so resources are limited**
Wherever land, water and sunlight coexist, at least one of the three is soon in short supply. *Life encounters limiting factors in any environment.*

**3) and competition is fierce**.
When vital resources are in short supply, getting more than one's fair share becomes a matter of life or death. *Life's excessive reproductive capacity arises from and intensifies the struggle to produce descendents.*

**4) Variation is inevitable**
*Biological reproduction is too complex to create exact copies.*
Individual variation reduces the risk of losing an entire cohort.
Identical-twin zebras display different stripes.
Identical-twin humans reveal different iris patterns.
*Sexual reproduction creates countless new genetic recombinations.*
*Environmental effects alter the expression of individual traits.*

**5) and times change.**
*Information growth knows no bounds, but life's ability to utilize information is limited.* So while opportunists always outnumber obvious opportunities, most opportunities are missed.

**6) Only the most fit survive to reproduce**.
*Chance, natural variation and information overload favor a few over the many. Life is fueled by the fallen.*

**7) Thus natural selection encourages endless adaptive changes,**
*and each of Earth's flourishing life forms remains uniquely suited to its changing environment.*

Darwin and Wallace independently developed the above evolutionary insights during extensive travels through exotic lands. Similar ideas had been broached before. Yet their evidence-based theory now seems stunningly obvious as we watch the diverse and prolific denizens of any back yard fight to the death over sunlight, water, nutrients and shelter.

Even after Darwin and Wallace convincingly demonstrated that natural selection underlay life's evolution, it still took many thousands of researchers another 150 years to define life's major molecular mechanisms. Those discoveries, in turn, opened the way toward amazing scientific insights into your humble origins, complex development and interactive operations.

## *You are truly impossible*

Life's tremendous complexity reaffirms how impossible you are, statistically speaking. Even were we to ignore the highly improbable circumstances that brought your father and mother together at just the right moment in both their lives, consider how unlikely it was that the only egg that ever could become exactly-you happened to respond most successfully during that hormonal cycle - before thousands of other eggs could rise to the call.

And look at the odds against your specific sperm triumphantly delivering its unique information - especially when your father may have pumped another billion unsuccessful sperm into your mother during that same passionate week. Talk about life or death competition! The world should surely be grateful that just the right sperm met your particular egg, since there was less than one chance in 100 trillion of this lucky outcome, even if pregnancy could have been guaranteed during that week.

Of course, the true odds against getting exactly-you are way worse, for our calculations ought to include every sperm ejaculated into your mother during her entire reproductive lifetime. In addition, we should figure in every other man your mother might possibly have chosen if your father had failed to fasten his seat belt, or had stayed around for just one more drink, or had strolled down that trail while your mother was on this one. And think how unlikely the births of your mother and father surely were - or try to imagine how many remarkable coincidences gave rise to each of their innumerable ancestors.

Yet what can these impossible odds possibly contribute except confusion, when you so obviously exist? Evidently we arrived at the infinitesimal likelihood of your parents producing exactly-you by asking the wrong question. Of course, had we not known that each sperm and egg was dealt a somewhat different set of genes during yet another reshuffle of the genes your parents received from each of their parents, we would never have come up with those mind-boggling odds in the first place.

But if individual sperm and eggs almost never succeed, why is Earth so crowded? Well, there are overwhelming odds that parents resembling yours will produce many fine children much like yourself. However, the principal reason that a specific rattlesnake sperm, rutabaga seed or redwood pollen so rarely realizes reproductive success is that it takes just a tiny percentage of their huge cohort to create the entire next generation.

Furthermore, far too many things occur simultaneously to ever allow an exact replication of any marathon race, traffic jam, cloud formation or fantastic individual such as yourself. Some view life as “just one damn thing after another.” And we all know something different is bound to happen soon. Yet life’s limitless possibilities also ensure that the details of whatever happens next will always appear outrageously improbable. Nonetheless, many comparable arrangements of runners, cars, clouds and genes are sure to occur - and that might be a useful way to approach the origin of life itself.

## *The origin of life*

A well-known recipe for chicken soup begins “First, catch a chicken.” But even when that chase requires significant exertion, it remains far easier to convert a chicken into soup than vice versa. And this common sense observation may be what encouraged my old construction boss to repeat the tale of a famous scientist whose long years of intensive study and arduous research finally allowed him to identify and collect all of life’s essential ingredients.

Presumably our somewhat daft scientist then mixed those secret materials on a particularly dark and stormy night while muttering strange incantations and emitting fiendish chuckles - unfortunately, my boss didn’t offer many details. Yet despite the most meticulous preparations, nothing ever slithered, hopped or flew out of his state-of-the-art research apparatus “for only God can create life!”

Whether or not such an experiment ever took place outside of Hollywood, this simple morality tale deserves our attention. For the spontaneous generation of lower life forms such as worms, flies and mice had been a commonplace observation until Pasteur confirmed that only live vermin could give rise to more of the same. And Pasteur’s scientific demonstration - repeated ever since in classrooms around the world - merely required a few days observation of appropriately cooked and isolated dead-tissue samples.

Yet in spite of Pasteur's small short-term study, it is generally accepted that life must have originated on Earth at a time when lifeless continents were still decorated with and surrounded by lifeless ponds, streams and seas that contained all sorts of complex energy-rich organic molecules interacting endlessly under an oxygen-free atmosphere.

Certain components of that rich organic broth undoubtedly arose in outer space before raining down upon Earth. Other ingredients surely derived from locally available materials under the influence of constant electrical storms, high levels of ultraviolet light and an endless array of peculiar local conditions including heat, cold, evaporative concentration, acid rain, alkaline ponds, solute-laden waters, sea-bottom pressures and unique particle surfaces.

So does Pasteur's conclusion that it takes life to produce life have any bearing upon the overwhelming likelihood that life emerged spontaneously on this broth-covered planet after millions of years? Or might these contradictory outcomes simply represent isolated observations made near the input and output ends of the same long-term project?

Perhaps Pasteur's broth is better viewed as inventory and all life as a product. Or maybe life has something in common with the nuclear fusion that defines a star, in that the fusion process cannot commence until a certain minimum mass has been achieved - any less mass and the outcome is something quite different, namely a planet-like body and no nuclear fusion.

## *Life is inevitable*

If we view the whole Earth as our sample and allow half a billion years for life's initial experiment, we are certain to encounter some really large numbers. For example, an ordinary gas molecule in Earth's lower atmosphere endures over ten thousand collisions during the exceedingly brief moment that it takes to travel one millimeter. And it is far worse in liquid water, where a single water molecule suffers a staggering 10 trillion collisions per second.

Such an immense number of collisions so encourages mixing and matching that nearby molecules in any water solution will surely meet and interact if at all suited to one another - and a sturdy molecular bond is easily made or broken within one trillionth of a second. Because the outcome of any chemical reaction depends upon the number and variety of molecules available, the inherent possibilities of this Whole Earth Experiment are so vast that any limits on conceivable reactions remain correspondingly distant and vague. After all, every five pound bag of glucose holds another trillion trillion molecules - and the world is ever so much larger.

In any case, the dilute molecular broth that made up early Earth's waters undoubtedly included endless variations on the hundred sorts of molecules most critical to life. And each of those dissolved molecules surely collided with other molecules more than a trillion times per second. Furthermore, even the many molecules present only in trace amounts still represented an impressive number of tons worldwide. Thus chemical activities of unending variety involving huge quantities of almost any conceivable substance recurred ceaselessly under every possible circumstance over, within and beneath Earth's primordial broth.

And if an average molecule had just one chance in a trillion of ever colliding in exactly the right way with some other molecule critical to life, such a molecule would still endure *a trillion times a trillion crashes* within a million years. Evidently Pasteur's result was inevitable for a small/short experiment whereas life becomes almost unavoidable in a large/long run. It is hard to imagine a better example of a small-batch study failing to predict the outcome of a large-scale continuous manufacturing process.

## *and thermodynamically correct*

The chemical reactions that build life's complex, energy-rich organic (carbon-containing) molecules are referred to as *anabolic*. Those of life's internal processes that release trapped solar energy by disassembling organic molecules are considered *catabolic*. The sum of all anabolic and catabolic reactions within an organism define its metabolism. And whether we measure the individual metabolism of a particular living thing, or calculate the inputs and outputs of all life on Earth, we find that the Laws of Thermodynamics limit life's operations as strictly as they limit any steam engine, cuckoo clock or bowling ball.

***The First Law of Thermodynamics*** declares that energy is neither created nor destroyed. In other words, the energy content of an isolated system cannot change. *Isolated* is the key word here. Quite obviously, no living thing anywhere near Earth's surface is ever isolated from all direct or indirect effects of solar energy, which include complex organic molecules, photosynthetically derived atmospheric oxygen, and the solar heat that prevents Earth's waters from freezing. Even the slow metabolism of seemingly isolated microbial life forms deep within Earth's rocky crust eventually depends upon external inputs from adjacent rocks and the radioactively heated mineral-laden waters that percolate past.

***The Second Law of Thermodynamics*** defines all real processes as irreversible. It holds perpetual motion to be impossible. It allows heat to pass from hotter to cooler objects but not the reverse. And it insists that entropy (disorder) always increases. So all systems eventually run down unless sufficient energy is added to overcome heat losses. Many creationists mistake the claim that "all systems eventually run down" for evidence that the Second Law does not apply to life. They assume that evolutionists have failed to note (or worse yet, tried to hide) the obvious-to-creationists fact that *birth and growth reduce disorder and enhance complexity.* So since life clearly fails to run down, The Second Law becomes a welcome scientific confirmation of life's Divine Origin. Right?

Well, no scientist could deny that life truly is remarkable. But Earth intercepts far more solar energy than is needed to compensate for life's energy losses. In fact, sunshine energizes Earth's photosynthetic bacteria and plants to produce 700 tons of new carbon compounds every second - and those same carbon compounds then support the impressive growth and development of all visible life forms.

Overall, the sun's core consumes 5,000,000 tons of hydrogen nuclei every second. And every gram of mass converted to energy during this solar nuclear fusion becomes almost 22 trillion calories. In contrast, a gram of life's carbon compounds oxidized to carbon dioxide and water, releases 4000 to 9000 calories of chemical bond energy.

Thus life on Earth captures $6 \times 10^{12}$ of the $10^{26}$ sunshine calories sent out all directions every second. And that intercepted energy easily supports the growth and development of creationists, apples, snakes and non-believers, without violating the Second Law. So while life has evolved deucedly clever molecular mechanisms, it remains subject to the ordinary rules of chemistry. Indeed, all scientific investigations to date confirm that life's growth, development and reproduction depend neither on metabolic miracles nor Divine support.

## *Early life was simpler*

A few fossilized remains of simple life forms can be found in rocks nearly four billion years old. Before that time, the disruptive impacts of massive comets, asteroids and meteorites may have extinguished early life repeatedly, forcing it to rise anew from the primordial soup after yet another few million years of brutal planetary and molecular battering. But if you stepped upon such a tiny quivering blob of self-replicating molecules today, or even examined that first ancestor carefully under a microscope, almost surely you would not recognize it as alive.

So can four billion years possibly be enough time for the birds and the bees and you and the trees to have come about through countless accidental upgrades of the old ancestral blob?

Probably not. Especially if each had to develop directly from that blob through tiny improvements along its own predetermined path. But, of course, there is ample evidence that it didn't happen that way at all. ***Not directly. Not repeatedly from scratch. And not one tiny step at a time.***

# Chapter two

## How simple life gave rise to complexity

In the beginning, all was chaos. Then gradually, imperceptibly, over hundreds of millions of years, Earth's self-replicating, ever-interacting, energy-laden organic molecules gave rise to and nourished the self-organizing complexity that finally became life. As self-amplifying life then depleted Earth's original dowry of complex carbon compounds, times became increasingly competitive.

Some circumstances favored solar-powered microbes - other situations encouraged those that could extract energy from mineral sources. The most successful of these tiny, naturally selected forms soon spread widely on wind and wave. But wherever they settled, even the most efficient photosynthetic or chemosynthetic bacteria only multiplied until essential nutrients were depleted, or new and improved descendents crowded out them out.

### *Those who cannot photosynthesize are doomed to consume the used parts and wastes of others*

However, every photosynthetic spurt also polluted its locality with complex organic debris that other microbes could utilize. So rather than Earth being clothed in peacefully coexisting photosynthetic communities that slowly depleted all available resources while smothering in their own wastes - every growing population and its wastes simply provided new opportunities for the latest opportunist.

As various metabolic skills developed randomly, innumerable individuals applied slightly different digestive skills to the energy-containing wastes of their neighbors, or to those neighbors themselves. And by making a consistent energy profit through recycling those wastes or neighbors, your "photosynthetically challenged" ancestors remained among the select few of each generation who survived long enough to reproduce.

Life's expanding diversity of precariously coexisting, endlessly interacting individuals progressively enriched and steadied the increasingly entangled relationships of Earth's biosphere. The surprising stability of our planet's free and growing economy came from innumerable negative feedbacks as repeated minor successes of individual predators, parasites and detrivores protected the biosphere from more violent oscillations of output and frequent population crashes.

Thus the ever-growing variety and complexity of life forms devoted to production or theft of energy-rich molecules, continually raised new information barriers that frustrated all but the most persistent or fortunate predators and parasites - each dependent upon its neighbor's assets or wastes in order to endure yet another day. Many metabolic and reproductive options became increasingly inaccessible except to those capable of cooperation.

## *From interactions to relationships to organizations*

No method of reproduction could deliver exact copies. Hence an entire spectrum of cooperative and hostile behaviors arose quite naturally within every species. Most circumstances favored kin-cooperative over kin-destructive responses, but endlessly varied relationships developed between individuals of widely different species as well.

Many interactions were brief and one-sided, as between a lynx and the squealing rabbit it carried gently back to the den. Others - like that between a rat and its fleas - proved more durable, though equally one-sided. But occasionally an entanglement dragged on with neither contestant gaining a decisive advantage, until both parties were able to adapt or even benefit.

Thus chronic conflict sometimes matured into codependence as survivors adjusted to the constraints of this new circumstance. Such a *symbiotic* relationship implied the sharing of assets and information by partners who differed sufficiently in metabolic skills and nutritional requirements to avoid mutually destructive competition.

A few symbiotic partnerships persisted over many generations when the entrapped parties reciprocated in ways that brought joint reproductive advantage under prevalent conditions. Yet even as associations adapted to the status quo finally flourished, gradual environmental change again stressed or undermined each hard-earned success.

## *Changing times benefit a few and hurt many*

Bacterial photosynthesis utilized solar energy to extract hydrogen atoms from water molecules, then combined those hydrogens with carbon dioxide to create carbohydrate (solar energy + $H_2O$ + $CO_2$ -> $CH_2O$ + $O_2$). The chemically active oxygen freed during carbohydrate manufacture swiftly reacted with susceptible elements at Earth's surface.

As the planet's exposed minerals became fully oxidized, oxygen began to accumulate in young Earth's pristine atmosphere. Eventually, that photosynthetic waste gas reached levels that proved poisonous to formerly flourishing populations of anaerobic bacteria.

A few amongst that vast bacterial horde were unusually tolerant to oxygen. Perhaps they survived their first minor exposures by combining oxygen with spare hydrogens to form water. And in time, a complete oxygen-based internal reversal of photosynthesis was finally achieved.

Undoubtedly, that complex and risky process of internal chemical combustion came about in many stages under Earth's early low-oxygen atmosphere. And only the most fruitful recombinations of metabolic pathways endured as innumerable bacteria bearing less handy modifications fell by the wayside.

An incredible number of simultaneous trials tested and retested every available option for combining more successful - hence more widely distributed and inherited - metabolic skills. A lucky few of each bacterial generation upgraded their inherent skills with complementary portions of metabolic pathways fortuitously acquired from those who had different endowments.

The incremental nature of these acquisitions naturally gave rise to chemical pathways defined by many small individually controllable steps. Gradually rising atmospheric oxygen concentrations tested each advance against ever more eager oxidations.

Fully aerobic bacteria ultimately emerged that could convert the solar energy trapped in chemical bonds of a glucose molecule, into immediately useful high-energy phosphate chemical bonds, without serious danger of spontaneous combustion. And their fully aerobic reversal of photosynthesis salvaged fourteen times more energy from each six-carbon sugar molecule than previous anaerobic fermentation-like processes had achieved.

## *Mergers and acquisitions made cells more competitive*

Those hyper-efficient aerobic proteobacteria were naturally drawn to the energy-packed three-carbon lactic acid wastes released when anaerobic cells digested glucose. And because their own aerobic activities consumed locally dissolved oxygen, these proteobacteria inadvertently helped anaerobic cells survive to attract and consume additional aerobic bacteria.

But on occasion, such an anaerobic cell found itself unable to digest a recently engulfed, live proteobacterium. Apparently, several such relationships persisted and developed through subsequent generations as the complementary skills of these metabolic partners brought reproductive benefit to both. So now every plant or animal cell inherits and sustains an ongoing partnership between aerobic bacteria and anaerobic cells.

Indeed, each of your cells includes hundreds of intracellular *mitochondria*. And these hard-working organelles - the descendents of formerly free-living aerobic proteobacteria - routinely complete the aerobic combustion (to $CO_2$

and $H_2O$) of three-carbon wastes still being generated during that cell's old-fashioned (anaerobic) initial breakdown of glucose.

However, nowadays, those mitochondria merely exchange high-energy phosphate (ATP) molecules for three-carbon wastes without themselves undergoing digestion by the surrounding cell. In this way, your modern two-stage, two-partner, cooperative intracellular completion of glucose oxidation, melds the ancient metabolic skills of your anaerobic cells with the aerobic efficiencies of their captive in-house bacterial work force.

*That hostile takeover by one cell of a fully competent metabolic partner with complementary skills, represented an enormous evolutionary advance*. After all, it would have taken forever for each species to independently devise an equivalent sequence of energy-releasing systems through selective survival of the fittest amongst countless naturally occurring minor metabolic variants.

And with the former surplus of energy-bearing three-carbon wastes now fully utilized inside the originating cell by its newly aerobic proteobacteria, there would not have been sufficient reproductive reward to drive another long sequence of microbes through that difficult chemical progression anyhow.

Apparently, the first life form to solve a difficult metabolic problem thereby derives an unbeatable advantage over its competitors - unless they then acquire the same informational upgrade through merger or theft. Furthermore, those who first develop or acquire important skills are likely to have many and varied descendents - which means their widespread genetic information is apt to survive the next population bottleneck or environmental catastrophe.

In contrast, information inherited by countless losers who can no longer compete, simply vanishes from the record. Modern genetic analyses of various cells and their organelles provide interesting hints about when and how some of these advances and takeovers may have occurred.

## *Why partnerships endure*

The high-energy phosphates you derive from glucose are mainly provided by hundreds of mitochondria in each of your cells. However, the local mitochondrial output of high-energy phosphates quickly falters when blood flow to strenuously exerted muscle fibers no longer meets mitochondrial oxygen needs - at which point, muscle exhaustion prevents your ATP-depleted fibers from performing further work.

Yet even during this critical period - while panting persists to repay an acute oxygen debt - the initial anaerobic steps of glucose breakdown continue their usual slow production of ATP inside each affected muscle fiber. So intracellular order - e.g., the ability to expel toxic calcium (see muscle chapter), and therefore cell survival - may temporarily be sustained by that small contribution of energy derived through old-fashioned anaerobic means.

Under such circumstances, lactic acid (a three-carbon anaerobic waste-product) builds up in nearby tissues until adequate oxygen delivery again allows the mitochondrial function in acutely overexerted muscles to resume. Quite clearly, your non-mitochondrial parts depend upon those domesticated microorganisms, and vice versa.

Of course, every partnership has its limits, and worn-out or redundant mitochondria are swiftly digested and recycled, just as they were in the good old pre-partnership hunter-gatherer days. But no matter how badly you may use or abuse them, your mitochondria can never abandon you to go off on their own.

For during the past two billion years, innumerable generations of intracellular mitochondria have miscopied or misplaced much of the original proteobacterial DNA information that their free-living ancestors depended upon in order to survive independently.

Additional cellular efficiencies were gained as important instructions relevant to all mitochondria became sequestered inside the cell nucleus. For that intranuclear positioning of essential information allowed the cell to maintain intracellular discipline and distribute important orders on a need-to-know basis - which greatly simplified the cell's supervision of organelles that might otherwise have become too independent for the general good.

## *Chloroplasts brought new skills to the cellular commune*

Plant photosynthesis - the sunshine-driven process of glucose creation - is carried out by *chloroplasts*. These intracellular organelles descend from free-living photosynthetic cyanobacteria.  As mentioned above, plant cells also utilize the catabolic skills of intracellular mitochondria to aerobically convert the solar energy stored in chemical bonds of glucose molecules, into more immediately useful and less stable, high-energy-phosphate bonds.

Though chloroplasts (glucose builders) and mitochondria (glucose combustors) might seem to be working at cross purposes when both organelles are active within the same plant cell at the same time, each thereby does its part to sustain the uninterrupted flow of energy that remains essential for any cell's selective utilization of life's information.

As these important intracellular arrangements were being perfected, new intercellular partnerships also arose between species - e.g., when algae and/or cyanobacteria combined their photosynthetic and nitrogen fixation skills with the abilities of certain fungi to access other important resources under difficult conditions. The slow-growing long-lived lichen that resulted were able to thrive where isolated algae, cyanobacteria and fungi would find little opportunity on their own.

Yet if a lichen is kept in the dark for a prolonged period, the fungal partner eventually devours its currently unproductive cyanobacterial or algal associate, just as a starving storm-bound trapper may reluctantly consume his hungry sled dogs. Indeed, it is a self-evident truth that some must die so that others may live.

Even among relatives, death can enrich the environment by releasing essential nutrients or other assets (a shelter, perhaps) to some more productive user. In the end, every individual has more value dead than alive. Life is based upon - and would soon end without - aggressive and opportunistic recycling.

## *Specialization can enhance productivity at all levels*

Whenever rapidly dividing single-cell life forms do not separate completely after cell division, this creates a multicellular group that represents a tempting collection of scarce resources and metabolic wastes. The tiny predators, parasites and prey drawn to such a feast, further enrich and complicate the neighborhood while themselves attracting additional codependents.

Effective cooperation can bring advantage to members of multicellular groups - as when the coordinated beating of their flagellae allows a group to travel or to maintain a flow of nutrient-and-oxygen-bearing fluid past the group. But even though a small group of cells may access new sources of food by combining their individual mechanical or chemical talents, increasing group size also creates new difficulties.

For merely doubling a group's diameter increases its volume and cell count eightfold. Hence diffusion soon becomes inadequate to ensure a timely delivery of essential supplies at the starving and suffocating center of such a growing group. And without costly extracellular support structures, any large gathering of undifferentiated or identical cells is likely to remain soft, shapeless and fragile.

Furthermore, the complexities of cooperative living rise rapidly as increasing group size burdens each cell with more information. After all, a solitary cell that does everything for itself can intercept and utilize only a limited amount of information. But as multicellular gatherings enlarge and begin to cooperate, information overload may actually reduce the ability of cells within the group to respond.

Therefore, the usual maximum size of any undifferentiated multicellular organism may simply reflect how much companion-cell effect each member cell is able to evaluate without "locking up". Comparable difficulties are encountered in many group situations where an obvious need to act is undermined by uncertainty about the intentions of others.

When a small and profitable business with limited information processing capabilities (a few interchangeable employees) enlarges, the natural tendency is to avoid altering what works - to continue doing everything the same way, only more so. But as the total number of loyal hardworking employees expands, the business soon encounters a drop in product quality and output per employee.

That reduction in productivity reflects a diffusion of responsibilities as well as the expansion of working time that every participant must now devote to communications (administration). As a result, it seems there is always too much to do, although less work is being done less well by each employee.

Consequently, a successfully expanding business or enlarging multicellular organism must undergo regular reorganizations merely to survive its own increasing complexity; for otherwise the gradual buildup and sharing (hence wasteful repetition and duplication) of potentially useful information will progressively interfere with adequate and timely responses. This is particularly a problem in small undifferentiated companies where everyone does everything.

So as organizations become increasingly complex, the only way to limit inefficiency from information overload is for workers or cells to specialize. Those specialists can then remain productive and responsive, no matter how the overall information burden may grow, since they only require information about their own small segment of the entire project. Hence the timely acquisition and distribution of information becomes a critical and specialized administrative function as organizations enlarge.

Specialization usually allows productivity to rise more rapidly than administrative costs for a while, but organizations of increasing size and complexity gradually encounter greater administrative indecision and delay despite devoting extra resources to their administrative bureaucracy. This occurs for the same reasons that two hard-working secretaries cannot double the output of one.

Hence savvy businesses often enhance their own efficiency by subcontracting with other firms that can provide more widely available items and services. For as the average growing company (or organism that still produces most of its own vitamins, amino acids and fatty acids) becomes established and productive - with more dependents, more inventory and more productive assets to lose - there is an inevitable decline in organizational flexibility - a reduced ability to benefit from breakthroughs or recover from mistakes.

Furthermore, it takes a greater disturbance to cause noticeable discomfort in a large organization - and a greater commitment of people and other resources before a complex organization can modify how it works or radically revise what it does. So while many expanding "do it all ourselves" businesses initially enrich themselves and enhance the marketplace, they gradually become unwieldy and conservative (avoid risk and change) even as changing times cause their entire organization to lose impact and relevance.

Eventually the resources sequestered within certain of their specialized parts become more valuable than the increasingly unresponsive whole - which remains only as effective as its weakest link. And that is why Mother Nature, and the more intelligent or lucky "corporate raiders," generally profit from the death of complex and outdated organizations - though these major disruptions always seem wasteful to the many losers at each redistribution.

## *Cell specialization made germ cells necessary*

Unicellular organisms have exceedingly high mortality rates. But after every cell division, each daughter cell still represents half of its entire parent. And unicellular life forms can continue to grow and divide endlessly. In contrast, as multicellular creatures enlarge and their cells specialize, they soon become too complex and unwieldy to simply split in two.

In fact, highly specialized tissues and organs tend to lose utility when disrupted. And even those descendents receiving the finest piece of their old parent's mind, leg, liver or gonad would begin life with seriously worn components. Hence it is usually safer to invest in small, appropriately proportioned "new beings" than risk reorganizing much of an old structure during a prolonged dysfunctional interlude.

Component cells of complex multicellular entities can usually make a greater contribution to their organism's efficiency - and therefore bring more reproductive advantage - if they specialize as stomach or liver or muscle or nerve cells. But the drastic changes that allow a cell to perform specialized functions more efficiently also undermine its reproductive abilities.

Hence successful multicellular life forms generally rely on specialized germ cells - eggs and sperm - to competitively sustain life's original reproductive function. Like many other specialized cells, eggs and sperm are most effective when supported and delivered by dedicated organs or structures. And as their efficiency increases, those sexual parts may utilize less and less of an individual's total resources. However, all components of the entire organization must directly or indirectly contribute to reproductive success if its genes are to appear in the next generation.

## *Complex multicellular life forms are programmed to die*

Many of us view death as Mother Nature's way of telling us to slow down, but it really is quite the opposite. For death restores vitality and productivity by forcing outmoded organizations burdened with worn or no-longer-relevant information and equipment to release their remaining useful assets. Thus the death of every complex multicellular life form is an unavoidable side-effect of successful multicellular specialization.

Indeed, death is the final contribution multicellular life can make to its own descendents and species. Ordinarily, there are enough predators, parasites and intra-species competitors to ensure that even reproductively successful individuals don't persist indefinitely - but a few specimens of every specialized multicellular life form still reach longevity's limits. So those limits surely make sense, since any old ones with an open-ended useful life span would inevitably constrain and compete with later generations instead of preparing and providing for them before passing on.

An occasional real revitalization remains possible with some life forms (caterpillar to butterfly, for example) or social organizations, but the major destruction of costly preexisting structures that occurs during every thorough reorganization represents such a turmoil and waste of resources that even preplanned revitalizations are unlikely to succeed more than once or twice - as Chairman Mao discovered during his repeated efforts to shake up an increasingly bureaucratic Communist China.

Despite its obvious inefficiencies, representative government survives in large part due to the regular death of incumbent administrations brought on by relatively free and honest elections. And just as the stock market realizes great profit through dismemberment of post-mature corporations, young adults become increasingly productive as the older generation regretfully releases its reserves and undergoes recycling.

## *What do predators, parasites and colleagues truly want?*

You are a complex multicellular organization. The many dozen trillion cells that make up your being must cooperate in an enormous variety of tasks, all essential to your survival and reproductive success. But those cells also represent a lush concentration of scarce resources. So as long as you live and for some time thereafter, you will be subject to vicious attacks by all manner of creatures, great and small.

Rest assured, however, that these attacks are usually opportunistic and should not be taken personally. It is simply that the survival and reproduction of those viruses, bacteria, insects, worms, vultures, colleagues and tigers depend upon their ability to access your resources or those of your neighbors.

Life's relentless do-or-die competition rewards efficiency and productivity. We may therefore assume that important efficiencies were realized each time your multicellular ancestors diverted precious resources into additional non-reproductive cells - otherwise you wouldn't be here. But as a result, your trillions of cells have become so specialized that they cannot even digest their own lunch.

Clearly your cells totally depend upon one another. Obviously the thankless service jobs that they so faithfully perform are what keep you in life's big game. But when it gets right down to the reproductive goal posts, almost all of your cells are relegated to the home-team cheering section.

A complex computer functions through its software. And your very complex multicellular persona would swiftly grind to a halt without ongoing access to your wealth of inherited DNA information. Nor could you utilize that valuable information as effectively if your cells were not so specialized. But that huge information content only brings reproductive advantage because it allows you to defend and stabilize your internal environment, and therefore respond more appropriately to the information that inundates you.

## *Competition leads to cooperation, ethics and morality*

Every organization has rules of conduct that regulate relationships amongst its members, for specialization only delivers reproductive advantage when codependents cooperate. While any sacrifice by one cell to benefit another might seem foolish, such altruism actually pays long-term rewards if it leads to the production or survival of more (and more closely related) descendents.

Indeed, harsh selective pressures often force closely related individual bacteria, cells, animals or humans to cooperate and even sacrifice for one another. We tend to admire such cooperation and sacrifice. In contrast, antisocial behavior may pay short-term dividends for the bank robber or cancer cell, but it usually fails to bring lasting advantage or enhance reproductive success.

An interesting computer challenge has clarified some aspects of how cooperation (reciprocal altruism) can benefit unrelated individuals - even though natural selection might appear to favor purely selfish behavior during such encounters. Our simplified example includes a buyer, a seller and an exchange of packages. One package allegedly contains certain goods while the other package allegedly contains an agreed upon payment, with packages to be opened later.

The options allowed were cooperation or cheating. The winning strategy of each round was the one that maximized wealth through buying and selling. Many complex programs were submitted but as the number of transactions increased, only a simple program called *Tit for Tat* remained consistently among top winners. That program merely directed its player to start honestly and thereafter respond in kind (either honestly or dishonestly) according to the previous move of its opponent.

Because Tit for Tat did not initially seek to exploit, it suffered early setbacks when competing with a large population of selfish participants. But a turnaround occurred as the population of suckers diminished, since exploiters were unable to do business with each other once their reputations became established. Reciprocators then flourished on the benefits of cooperation.

However, if the contest continued - and occasional errors allowed these competing programs to evolve - a generous and even more successful version of Tit for Tat developed that forgave the occasional lapse in order to retain the benefits of cooperation. A recent entry may be even more effective because it uses a flexible *Win Stay, Lose Shift* strategy that can prevent all trading from coming to a halt - as when Tit for Tat stops trading because only cheaters remain. Under such circumstances Win Stay, Lose Shift may alter its tactics in order to benefit from continued trading.

So even amongst computer programs, a reputation for rectitude, cooperation and reciprocity appears to be important for successful long-term relationships. Society, too, may benefit by forgiving the occasional transgression rather than always insisting upon getting even. For sometimes it is just not practical to be perfectly honest or completely fair, or even to drive within the speed limit. And in order to prosper, we have all learned to respond in Tit for Tat fashion (or its more generous version) as well as with Win Stay, Lose Shift behavior.

Cooperation arises naturally at home where early dealings are mostly with relatives. Except for that behavioral start, however, different groups tend to view morals and ethical conduct quite differently, depending upon whether they are headhunters or Quakers, lobbyists for a tobacco firm or Amish farmers, members of a large corporate hierarchy or Iranian Mullahs, radical environmentalists or anti-abortionists.

One gathers that the definitions of moral or ethical behavior vary so widely because - rather than being universal truths, as often portrayed - they merely reflect the dominant or leadership consensus on goal-oriented rules that ought to govern social conduct within and outside the group. In most societies, therefore, ethical conduct includes any behavior that is regularly accorded social approval because it benefits a greater number of related individuals or interests than other competing behaviors that were adequately tested.

The above considerations may partially explain why tribalism is such a tough habit to break. Nonetheless, tribal behavior usually declines during good times when those primitive and usually unkind support systems seem less essential for survival - which suggests that you will personally be better off when most others become better off as well.

# Chapter three

# Multicellularity

Multicellular animals remained small, inactive and easily disrupted until sturdy extracellular collagen-fiber-supported frameworks became available. Before collagen, every cell had to be ready to fend for itself if the group broke up. After collagen, the reproductive odds shifted to favor major investments in specialized *germ cell support-and-delivery systems*.

From an evolutionary perspective, eggs and sperm are destiny - the rest of your body is mere hype. And the several dozen trillion highly specialized non-germ cells that collectively account for your brain, brawn, beauty and metabolic skills, simply reveal the huge initial investment any human must make before she or he can even try to market a single tiny egg or sperm.

Genes are more likely to be reappear in the next generation if they encourage their current owner's growth, development, physiology and mind-set in accordance with whether she is female or he is male - which explains why you find it so hard to keep your mind off sex.

Indeed, it is a delicate balance - any more time and attention devoted to sex might prove a serious reproductive disadvantage, if you then starved or otherwise neglected your daily duties, needs and safety, or landed in jail for stalking. On the other hand, any less time and energy dedicated to reproductive pursuits could leave the best opportunities to those more eager.

After all, you exist because your parents went to a lot of trouble (pizzas, roses, a wedding, tolerating each other's relatives or whatever) so they could engage in repeated and ultimately successful sexual intercourse - even though any number of less repetitive, more educational activities might have left them healthier, wealthier, wiser and better rested.

## *Collagen allowed multicellular life to flourish*

A glance from the window of an average American home suggests that Earth is owned and operated by humans. Yet we represent just a tiny subset of all the wild and wonderful creatures that have roamed the sea, land and sky. This may be your big moment in life's endless succession, but collagen was what initiated the entire competitive escalation of multicellular complexity and information processing capability.

For only collagen could support full cell specialization and thereby enhance the likelihood that altruistic sacrifices by closely related cells for their peers would not be in vain. Small wonder that collagen is the most common animal protein - one quarter of your dry weight.

Fossil evidence reveals that life struggled onward for three billion years before collagen was invented. An endless number of more immediate concerns - widespread volcanism, a major release of continental shelf methane, runaway greenhouse effects, ice ages with major oceans freezing over, huge meteorite impacts and so on - surely affected evolutionary progress as well.

But just imagine how far you might have evolved, and what sort of place Earth might now be, if these sturdy extracellular protein fibers had entered common usage one or two billion years earlier. Could some of this delay reflect a simple conceptual impasse - that a cell dare not relinquish its individual reproductive capabilities until its multicellular group is stabilized by collagen fibers - yet a cell cannot specialize sufficiently to produce collagen fibers without abandoning its reproductive capabilities?

In any case, the basic structure that possibly delayed your advent for billions of years is a simple, regularly repeated sequence of three amino acids in each of three long tightly twisted amino acid chains that together form a straight triple-stranded protein fiber capable of resisting great tension.

And as each specialized fiber-producing cell extrudes its bundles of fibers into the extracellular space, these fibers are enzymatically trimmed, which causes them to undergo rapid self-assembly into a sturdy fibrous connective tissue that can resist your strongest muscle contractions and hold you together despite gravity and other accelerating forces.

Elastin - another important extracellular protein fiber - can steadily resist tension while being stretched to several times its original length, and then spring back to the starting condition. Apparently it has a self-attracting meshwork configuration that allows easy extensibility in all directions.

But elastin remains a minor constituent of collagenous connective tissues except where its ability to store tension can reduce work - as in the leg tendons that lend bounce to horses and kangaroos - or in the neck tendons of grazing animals that frequently raise their heads to detect approaching carnivores - or in the stretchy aorta that stores your arterial blood at elevated pressures.

## *You are a monkey's aunt (or uncle)*

Successful collagen formation requires an adequate supply of Vitamin C (ascorbic acid) to maintain an important collagen-building enzyme in its active state. Most animals prepare their own Vitamin C, but all primates (you and your ape and monkey relatives) and guinea pigs as well, have lost that ability.

Presumably that dependence upon dietary Vitamin C arose through similar mutations in an ancestral primate and an ancestral rodent, since other mammals and most rodents do not have this problem. In any case, the live or recently deceased victims that enter an ordinary hunter/scavenger/gatherer's diet contain plenty of Vitamin C. However, overcooking, or the prolonged storage of dead animal or vegetable parts, can deplete them of ascorbic acid.

So if you eat only such Vitamin C deficient foods for several months, your continuously reconstructed collagen fibers will become so poorly bonded that they start falling apart at ordinary body temperatures. Signs of Vitamin C deficiency disease (scurvy) therefore include loosening of teeth, spontaneous bruising, poor healing of wounds, weakening of blood vessels and a great many other distressing complications of weak collagen up to and including death.

## *After life comes glue*

The name "collagen" comes from a Greek term "to produce glue." But what possible relationship can there be between glue and this strong fibrous protein? Well, more than half a century ago, as automobiles rapidly replaced horses, the perplexed driver of an obviously disabled vehicle at the roadside often received merry but unwanted advice such as "Get a horse!" from passers-by whose own transport still happened to be working.

Yet while dead and disabled vehicles increasingly littered the countryside, the quiet patiently plodding hayburners of yesteryear were rarely encountered in a disabled or terminal condition. That absence of end-stage horses lying about was primarily due to their large stores of readily recyclable organic materials.

For unlike a dead car that might remain more or less intact for recycling at one's convenience - at least till a good-sized tree grew through it - dead horses rapidly became rather offensive as they decayed with the assistance of their intestinal bacteria, plus maggots, birds, foxes and your freshly washed dog.

On the other hand, if delivered to a glue factory (rendering plant) under its own power in a timely fashion, that faithful worked-out old dobbin could continue to serve as soap, explosives, cat food, leather belts, cowboy boots and fertilizer - while any collagenous left-overs like bones, tendons, ligaments and noses were boiled down to create animal glue or flavorless packets of cooking gelatin.

So how does boiling convert water-insoluble collagen into an easily dissolved, permanently denatured protein that can fasten wood surfaces together or stiffen your cold soup or dessert into a tastefully jiggling solid? Apparently the boiling of these sturdy protein fibers causes their individual strands to separate and flail about so vigorously that they become inextricably entangled.

When those boiled collagen (now gelatin) molecules cool (slow) down, their interlocking water-attracting lattice structure stiffens sufficiently to attractively support whatever animal or vegetable parts were mixed in. Dissolved gelatin also adheres to any wettable surface as its multitude of bonds become available through evaporation or absorption of water molecules into the wood or other porous material.

Gelatin glue holds those surfaces together because its stretchy entangled strands are extended or torn with difficulty. But despite its usefulness as glue, gelatin lacks an organized linear fibrous structure. Hence a thin strip of gelatin could not resist tissue tension as well as the most defective tendon of a scorbutic primate or guinea pig.

## *Extracellular space*

Collagen is laid down in large parallel bundles at locations where it must transfer a great deal of tension between two bones (as a ligament) or between a muscle and a bone (as a tendon). In contrast, the collagen fibers of most connective tissues are randomly deposited between cells. In fact, many of your connective tissues appear relatively empty under the microscope, except for occasional fiber-forming cells, fat cells and a scattering of collagen and other fibers.

Functionally, this absence of cells in connective tissues makes sense, for your body requires flexibility between its solid tissues and organs in order to change shape during different positions and movements - as when tying your shoes. The stresses of such deformations are taken up by your soft, fatty, fibrous and not very cellular connective tissues.

## *Why doesn't extracellular water settle to your bottom?*

Indeed, what fills that apparently empty space between your scattered connective tissue cells and those many fibers? We assume that fluid is present, since connective tissues that are low in fat have nearly the same density as water. Furthermore, the water, salts, gases and small nutrient molecules distributed by your blood seem to diffuse readily through connective tissues.

Your occasionally sunken eyes, parched lips and dry wrinkly tongue also confirm that tissue fluids are easily withdrawn to replenish your circulation when you are dehydrated. This dynamic distribution of your body fluids makes it even more remarkable that free fluid does not quickly settle to your most dependent sites.

Admittedly, your ankles may swell a bit with prolonged standing, but what stops all of that extracellular (outside of cells) water from flowing to your buttocks when you sit or sloshing down around your ankles when you stand? What keeps just the right amount of tissue fluid in the right place so you don't puff down there as you shrivel up here? How does that fluid know where to go and how much of is required?

It turns out that connective tissue fluid is held in place by very large water-loving multi-branched extracellular molecules that resemble microscopic feathers or ferns. Those proteoglycan molecules may be several microns in length - which is comparable to the width of some cells. Hence they tend to remain wherever they are deposited. Widely distributed negative charges on each of these huge molecules additionally attract many positively charged sodium ions, along with the tissue fluids these ions are dissolved in.

So considering how much water is necessary to dissolve proteoglycan molecules, and the volume of water tied up by their electrically attracted sodium ions, it is not so surprising that extracellular fluids and solutes tend to stay in place rather than drain off in response to gravity.

# Chapter four

# Skin

You relate to the world through your skin. You expect it to locate hot stoves or drafty doors in the dark without contact, and to detect tiny insects in time for a preemptive strike. You assume that your water-resistant covering will neither leak body fluids nor absorb water from the hot tub. You are not surprised when your attractive comfortable seamless skin unfailingly makes alterations to suit your changing size and shape over a lifetime, or that it warms you in winter and cools you in summer.

Nor are you impressed when it darkens in response to excess light or becomes increasingly translucent under pale northern skies to ensure adequate Vitamin D formation. You know that your skin will stretch without binding to allow your most violent movements - still you expect it to adhere tightly so that you don't slip about inside it as you run, or lose your grip on a tree branch or baseball bat.

You gripe about how long a cut bleeds or a scrape takes to become invisible. You complain endlessly about pimples or freckles, your hair's color and location, loss or gain. You are annoyed that your skin flushes when you are embarrassed. You hate the wrinkles. Smelly perspiration drives you up the wall. And just one little skin infection can make you completely forget the trillions of times that your skin has silently defended you from bacterial attack.

## *Your skin touches the world*

When you reach out and touch someone, you touch skin to skin. If something is irritating, you have let it get under your skin. Not only do you manipulate the world through contact with your skin, but even the way you move or display your skin can drive humans and mosquitoes wild.

About two square meters of skin provides you with a surface that is very sensitive to your surroundings. It can detect tiny temperature changes or the lightest touch. Through various pain signals, your skin also identifies all manner of hazardous conditions such as having your finger caught in the car door.

And while ordinary sensations of pressure and temperature may not reach your attention, you can always inquire of any skin surface by concentrating upon that part. Your tongue, lips and fingertips are particularly sensitive areas, due to their closely spaced receptors, but even the thick skin of your back has sufficient sensitivity to warn of potential problems, if not evaluate them in detail.

Except for pain receptors that continue to complain, your skin usually reports only changes rather than absolute values, for little is gained from messages of "nothing new to report". When two individuals at normal body temperature maintain steady contact, the lack of reports from their opposing skin surfaces can have a soothing effect. Young pigs, people of all ages, and many other creatures appreciate and seek out this sensation of a disappearing surface between individuals, whenever an opportunity arises to cuddle.

## *Hair*

Gradual environmental changes drove your African or Southeast Asian primate ancestors down from the trees - then brought their knuckle-walking days to a close. At that point, nothing about those forlorn, out-of-place, poorly equipped apes even hinted at greatness; or at the huge impact their upright offspring would have on other life forms around the globe.

Yet that involuntary shift to a two-legged stance on risky solid ground was what started pre-human primates down the long trail a'windin' toward modern civilization. For only by giving up their branch swinging, insect grabbing, knuckle walking ways - to which lengthy powerful arms were so supremely suited - could your ancestors blend their cognitive abilities and manipulative skills in a mutually reinforcing, truly unprecedented fashion.

Gazelles, lions and hyenas have always endured brutal environmental pressures. Those surviving long enough to reproduce were about as smart as they needed to be. Indeed, where strength or speed finally determine reproductive success, excessive curiosity or an ability to think more deeply might simply raise risks and metabolic costs without delivering benefit.

Similarly, in the good old tree-dwelling days - before idle hands became available full-time for making trouble or technological progress - the whole primate body had served as the mind's primary tool. Under such circumstances, a small increase in brain power meant little unless it happened to augment offensive, defensive or reproductive capabilities.

However, unlike sturdy hooves or sharp claws - those superbly effective but dedicated, hence self-limiting, developments - the open-ended possibilities inherent in clever fingers proved to be the missing link between brain capacity and technological, as well as social, empowerment.

Thus when newly freed primate hands began to carry, manipulate and smite, the reproductive advantages previously inherent in being a bit stronger or faster, gradually became subsumed within the information processing capabilities of those who could contemplate, communicate, cooperate and use tools more creatively.

Now that every advance in mental function and communication was likely to multiply an individual's clout and capabilities, Nature began consistently favoring upgrades in cognition and technology. So the cleverest tool-makers increasingly displaced or overcame their powerful but less brainy opponents.

Early gains came painfully in tiny increments, secured by equally tenuous improvements in abstract thinking and verbal intercourse. The march toward civilization moved at a glacial pace. And every advance in human versatility or social complexity again destabilized the latest status quo.

Their relentless competition over scarce resources prompted early humans to develop useful combinations of the actual and the abstract such as fire, weapons, agriculture and the domestication of animals. With power, cognition, cooperation, technology and productivity so inextricably entangled, emergent challenges intensified the contest for all.

The most effective information handlers gradually won the race to pass along competitive genes and hard-earned knowledge. Their legacy allowed humans to invent symbolic concepts, numbering systems, the written word and modern science.

A surprising number and variety of anatomical adaptations to the two-legged stance paralleled these mental/behavioral advances. For example, merely standing upon their hind legs allowed your pre-human ancestors to markedly reduce the skin surface area they directly exposed to the noonday tropical sun. In turn, that made it possible for them to travel and survive on less fluids in dry lands.

In addition, that newly upright position - together with body warmth - induced a constant adjacent updraft of air that proved particularly helpful at cooling the sweaty skin of those who happened to have less body hair - so that trait became reproductively advantageous.

When descendents of such tropically appropriate, relatively hairless pre-humans later entered colder climates, their growing cognitive/manipulative abilities enabled them to insulate naked skin surfaces with lightweight fur and feathers stolen from smaller victims.

That impressive development of appropriate clothing when the need arose, was just one early demonstration of how swiftly cultural evolution could forestall further genetic evolution. And it saved naked humans from shivering and freezing through many centuries while descendents of the hairiest few again prospered and became dominant.

The warm updraft generated by an upstanding naked body had other unexpected anatomical impacts as well. For example, it delivered odors from near and far most efficiently into nostrils that opened downward - as human noses now do.

In contrast, the sideways-directed nostrils of four-legged animals remained ideal for intercepting the usual horizontally drifting odors, especially when stratified and strengthened by temperature differences between near-ground air layers. For feeding animals inadvertently sampled those odors each time they raised their heads to view the surroundings.

And even at rest, large herbivores move significant volumes of air while breathing. Such an herbivore expelling air through forward or downward directed nostrils would stir up and breathe in a whole lot of dust, as well as blow desirable vegetation away from its own grasping mouth.

If a strange dog barks right behind you, a great many tiny hair-raising muscles contract all at once to form goose bumps, especially on the back of your neck. By increasing an animal’s apparent size and clearly signaling its agitated, possibly aggressive mood, that simple mammalian reflex has frightened or warned off many intruders.

The same hairs stand on end when you feel the instinctive patriotic surge of belonging to a larger group. And your scattered body hairs arise in unison when you feel cold, thereby impeding air movements across body surfaces and reducing heat losses.

Oily secretions oozing from each hair follicle, help waterproof your hair and skin - for water droplets roll easily across greasy skin surfaces to fall from downward-pointing hairs. Unshaven hairy legs stay warmer and drier while walking through wet grass.

Each of your body hairs acts as a delicate lever that detects air movements caused by approaching animals and reports contact before insects or stationary objects can touch the skin. A sensitive nerve ending at each hair root refers such information centrally for evaluation. Hence leg and body hairs help you feel your way along in the dark, or when not looking where you are going.

Your hair, outermost skin layers and fingernails are primarily composed of keratin - a fibrous water-resistant protein. Keratin also serves as the principal constituent of hooves, feathers, claws and beaks, fish scales, silk, spider webs and rhinoceros horns. Evidently, it was easier to evolve many variations on one keratin gene than develop entirely new genes for each of these functions.

Dead cells packed with keratin make up all but the growing root of each hair. These cells are layered like shingles in an outward direction, so hair only combs easily away from your body. As you age, your hair roots lose their ability to produce and incorporate melanin pigment. And your hair length is limited even if you do not cut it, for hair follicles intermittently quit working after 2-5 years of growth.

A discontinued hair may fall out during that non-functional time, or as production of a new hair resumes from below. The ordinary progressive hair loss of aging is due to diminished hair production, thinning of individual hairs and shallower hair follicles. Hair loss may also result from fungus infections, chemical exposures and various medical treatments.

Most young adults have about 100,000 scalp hairs. Those of Asians are round in cross-section (therefore Asian hairs are straight) while African hairs are flat (curling easily) and Caucasian hairs are elliptical. Many forms of chronic poisoning (arsenic, for example) can be detected by chemical analysis of your hair. Even a single hair shed at the scene of a crime may carry sufficient DNA to identify its former owner, if his/her body fluids or cells can be obtained for comparison.

## *Epidermis*

If you stand near a beam of sunlight and rub your dry skin, dead skin cells become visible as dust motes rising in the updraft of air warmed by your erect body. Nearly half of ordinary house dust is keratinized skin surface cells plus the microscopic insects that eat those cells and the bacteria and fungi that live off those insects and their wastes. So the occasional tiny bite or itch that occurs with no visible flies or mosquitoes to swat might as well be blamed upon hungry little bugs, too impatient to wait, prying loose still-adherent skin cells for lunch.

As you scratch and remove skin flakes, the progressive exposure and stimulation of fine nerve endings and receptors causes increasing discomfort. Persist with that friction and soon clear tissue fluid seeps from between deeper still-living cells. A sterile pocket of this fluid often accumulates beneath a surface layer of epidermal cells that has been loosened from deeper epidermal cells by a friction injury.

Such a blister may become quite tense when high-pressure sweat gland secretions no longer can reach the skin surface through their sheared-off ducts. An intact blister protects underlying cells from drying, cracking and infection while they generate new surface cells.

Skin cells divide into daughter cells along the supportive basement layer at the bottom of your epidermis. Surplus cells pushed away from nourishing fluids of this area, suffer various chemical changes including loss of cell nucleus, dehydration and death. Their remnants reach the skin surface within three or four weeks as flattened water-resistant micro-shingles that temporarily protect underlying tissues from abrasion.

The wavy irregular fibrous basement layer provides an oversized surface on which to produce skin cells that will soon shrivel and keratinize. That expanded permeable layer also enhances the diffusion of nourishing tissue fluids into your epidermis, for epidermis contains no blood vessels and soon dies if deprived of nutrients moving in from below.

In addition to being packed with sturdy keratin fibers and strongly linked together, your epidermal cells are individually embedded in fibrous proteins and surrounded by a fatty layer. Consequently, your skin resists penetration by both water and fat.

## *Skin color*

Human skin color is mostly determined by how much dark brown melanin pigment resides within epidermal cells. Special melanocytes (pigment cells) alter their production of melanin in response to sunlight or hormone signals from the pituitary gland. Various human races differ noticeably in the average amount of melanin stored within their epidermal cells.

In general, the optimum (hence prevalent) skin color of long-established populations at any latitude reveals just how much melanin is needed to protect deep epidermal cells from excessive ultraviolet light, yet allow passage of enough sunlight to ensure adequate Vitamin D production.

Those who inherit darker skin suffer less damage from exposure to sunlight. Wrinkles and abnormalities of skin cell pigmentation or growth also result from smoking cigarettes and other chemical exposures. Asians often have a yellowish skin color attributed to carotene - a light-absorbing pigment related to Vitamin A.

Caucasians do not deposit much melanin so the pink color of underlying blood capillaries often shows through. Occasional individuals of any race (or indeed, of any mammalian species) may carry no functional genes for the production of melanin pigment. The skin, hair and eyes of these albino individuals therefore remain pale white or pink.

Melanocytes distribute their melanin through long cellular extensions for engulfment by nearby live skin cells. That slow incremental method of skin coloration differs markedly from the momentary adjustments of skin color made possible by pigment-containing sacs in the skin of squid, octopus, flounders, chameleons and many other creatures.

These creatures can rapidly enhance their color by contracting skin muscles to spread the pigment, or fade by gathering the pigment beneath small reflective areas. Some even make ongoing patchy color changes in order to blend with their current background.

Octopuses release a cloud of ink that hides them from danger. Squid expel a mucoid glob of ink as a decoy when threatened, then fade to transparency as they flee. The complex patterns and pulses of color that pass over a squid dying on the beach are due to uncoordinated contraction and relaxation of many chromatophores. Would that we might die so beautifully!

## *Dermis*

Your tough epidermal (outside of dermis) cells adhere to each other at many reinforced cell-surface sites. In contrast, the underlying dermis is extensively reinforced by sturdy bundles of collagen fibers. Animal dermis becomes leather when those tissue fibers are tanned (cross-linked) into a sturdy sheet. Tanning of leather is unrelated to a suntan.

The granular surface of a football displays the normal irregularity of cattle dermal/epidermal boundaries - each little pore formerly enclosed a hair. Hair follicles require deep dermal support for their muscle attachment and nerve supply. Sweat glands originate near deep dermal blood vessels in order to produce lots of sweat.

Blood vessels are always located as deeply as possible for protection. Your frequently injured outermost dermis contains only the tiny tufts of permeable capillaries needed to nourish your epidermis. In addition to blood vessels, lymph vessels, fat cells and specialized nerve endings, the dermis includes fiber-forming cells and mobile defense cells awaiting bacteria and other invaders. Many of these dendritic cells wander within the epidermis, waiting to rush samples of new invaders to your lymph nodes for identification (a bad idea in the case of the HIV virus that causes AIDS).

## *Heat and fluid losses through your skin*

The temperature of a gas, fluid or solid reflects the average speed of its colliding atoms or molecules. Fluid and gas particles change their speed, direction and location with each intermolecular collision. A water molecule may evaporate (be bounced out of solution) if several unusually vigorous collisions bring it to boiling speed or steam temperature. Since every escaping molecule absconds with more than its fair share of heat energy or molecular momentum, the water left behind is cooled - just as the departure of an honor student lowers average test scores in a class.

Because warmer water molecules move at higher average speeds, they are less likely to cling together in liquid drops. Hence hot air can hold more invisible water vapor than cold air. Conversely, when moist air cools, its excess water content becomes apparent as tiny water droplets that form clouds and fog, or deposit dew or frost on cold surfaces. Thus clouds, fog, dew and frost form wherever the local humidity exceeds 100%.

A cubic meter of air at room temperature can hold more than 30 milliliters (an ounce) of water as an invisible gas, but evaporation ceases when air becomes water-saturated. So you drip sweat on a hot and humid day without enjoying significant evaporative cooling, while a similar output of perspiration on a hot day with low humidity could leave you comfortably cool and dry.

The evaporation of a cubic centimeter (cc) or milliliter (ml) of water will cool 500 cc (500 grams or just over a pound) of water or blood or other body tissue by more than 1°C. Water has a higher heat capacity (meaning it absorbs more heat energy with less change in temperature) than other common materials. The convective turnover of the uppermost fifty meters of sea water allows near-surface waters to exchange heat efficiently with the atmosphere during each season - deeper waters are less affected.

Hence persons living near large bodies of water enjoy a more moderate climate than those who live amidst rocky mountains. Indeed, heat penetrates and escapes from rock so slowly that deep rock temperatures reveal past climatic conditions. Many of our ancestors, and countless other animals, sought shelter from cold winters in deep caves where room temperatures hardly budged with the seasons.

Frugal rural mothers often provided a hot baked potato for each coat pocket in winter - to warm the child's hands on the way to school and then serve as lunch. Like those potatoes, you are mostly water. Since water has 4000 times the heat capacity of air, your body temperature only changes slowly on exposure to hot or cold calm air. And air trapped next to your body by whiskers or a fur coat will insulate you from (reduce further heat loss to) a cold environment. On the other hand, a cold wind swiftly chills warm skin.

The swimmer's body heat soon escapes into cold water, for objects at different temperatures that are in close thermal contact will approach the same temperature unless one is additionally heated or cooled. The outer surfaces of non-tropical marine mammals are usually cold and wet. Most insulate their warm heat-producing inner selves from that cold skin surface with a thick layer of light-weight fat, for fat conducts and stores heat poorly.

The fatty acids of cold-water-tolerant sea creatures tend to be unsaturated (include rigid double-bonds between their carbon atoms). These sites of molecular angulation impair the usual close fit and mutual attraction between long, skinny, fat-molecules. Consequently, the unsaturated fats of tiny high-latitude marine life forms remain flexible at low temperatures.

These unsaturated fat molecules then contribute to limber cell membranes and soft fat deposits all the way up the food chain. In contrast, tropical oils are almost fully saturated (completely hydrogenated - without double bonds) so they won't be too runny at equatorial temperatures.

At rest you put out about as much heat as an 80 watt light bulb - barely enough to warm a bed with several blankets on a cold winter's night. A big meal or physical activity will markedly increase your heat output since your animal and vegetable victims are inefficiently converted into power for your movements. Indeed, far more of their chemically trapped solar energy is lost as heat than used to perform work.

The insulation value of your subcutaneous fat is easily adjusted as smooth muscle cells in blood vessel walls relax or contract, thereby opening or narrowing your superficial vessels in response to nerve, hormone and other chemical signals. As you exercise, subcutaneous and dermal blood vessels dilate so that your warm flushed skin can radiate or conduct excess heat from your blood to the adjacent air, water or solids.

When you are too warm, your dilated deep dermal blood vessels filter more water into the ducts of your sweat glands. Sweat then pours onto your skin surfaces so evaporation can cool you down. Perspiration also minimizes the insulating layer of still air next to your body by flattening and clumping your wet hairs.

Small amounts of salt and other solutes are left behind as sweat evaporates. Eventually these salts may form a visible whitish deposit on your skin surfaces or hat band. On hot days and after heavy physical exertion, you crave fluid and salty foods. The early replacement of salt and fluid losses can minimize fatigue and muscle cramps.

In former times, table salt (NaCl or sodium chloride) was often an expensive delicacy conveyed by camel caravans across far deserts. For salt is most efficiently produced in hot dry climates where shallow pools of sea water evaporate rapidly.

Sodium chloride is the principal salt of your extracellular fluids, and of the salty seas where your single-celled ancestors once thrived. You can taste that salt in your sweat, or in bloody tissue fluid that drips from roasting meat.

By weight you are one-half to three-fourths water. At any moment about one-third of your body water surrounds your cells while two-thirds remains intracellular. Your extracellular water is one-third as salty (0.9 %) as ocean water (3 %).

Just as all things run down, and cream eventually spreads throughout your coffee, water tends to diffuse away from areas of greater water concentration, and toward areas of greater solute concentration. Living cells enclose a variety of essential solutes. Your cells manage to stay in water balance with surrounding tissue fluids by expelling almost all of their sodium chloride. For those cells would swell and burst if - in addition to life's other essential solutes - they also retained the same concentration of salt as was present in nearby outside-of-cell tissue fluids.

When you are salt-deprived, your sweat glands reduce their salt output and alter other sweat solutes appropriately - just as kidney tubules regulate the water and salt content of your urine. Your sweat, and the oily secretions of your skin, both exert a moderate antibacterial effect that helps to limit skin-surface bacterial populations. Those bacteria compete viciously with each other and with fungi for living space on your moist and nutritive skin areas. Fortunately, the more harmful bacteria are often crowded out and chemically suppressed by less nasty types.

## *Your sweaty hands and feet*

Sweat glands continuously moisten the palms of your hands and the soles of your feet. Because your palms and soles lack hair follicles, they also lack greasy secretions - which is reproductively advantageous since greasy or hairy palms and soles would readily lose grip or traction.

But why do your hands get so embarrassingly wet when you are nervous? That too involves grip. For those thousands of ducts depositing sweat onto the fine ridges of your palms and soles, greatly improve your grip - just as moistening a suction cup improves its adherence to a smooth dry surface.

A good grip was especially important for your ancestors when they were frightened - allowing them to swing safely away through the tree branches, or grip a club or sword more securely. The tough guys in old movies used to spit into their own hands and rub them together before engaging in a bar-room brawl. The subliminal message was, "My hands are real dry 'cause you don't scare me a bit".

Baseball pitchers find that a moist hand improves control and delivery. Persons with abnormally dry skin often drop dry objects such as clean silverware because their continually loosening surface epithelial cells act as surface roller bearings.

## *Modified sweat glands*

Certain complex sweat glands - in your armpits and around your genitalia - secrete increasingly elaborate chemicals after puberty under the influence of your male and female hormones. Armpits become quite smelly as those complex secretions are broken down by ever-present skin bacteria. So the onset of adolescence often has friends recommending antiperspirants to dry such secretions, or deodorants to suppress odor-causing bacteria. Of course, when lesser remedies fail, you might consider a shower or bath.

Armpits sweat more and may smell worse when you are nervous, for your sweat glands modify their output in response to nerve and hormone signals. If you worry that your smell is noticed by others, you are probably correct in a way, for sweat smells include certain pheromones (chemical signals with hormonal effects) that may disturb the physiology and rational thought processes of others nearby without their being aware of the cause.

Thus your ancestors economically modified their sweat glands to fight infection, to stay cool and help maintain an appropriate salt and fluid balance, and to send urgent messages and export specific molecules, all without altering the basic sweat gland motif. And their finest sweat gland conversion does most of the above beautifully while also producing an even more complex fluid under close nervous system and hormonal supervision.

Certain cloud formations and our entire class of vertebrates (animals with backbones) have been named in honor of those highly admired, modified sweat glands - long glorified in art, poetry and song and variously known as mammary glands, udders, teats or breasts. For they, along with our hair and specialized inner-ear bones, define us as mammals - those who suckle their young. So the next time you pour modified sweat onto your breakfast cereal, just think about how it all evolved.

# Chapter five

# Your skeleton

Mollusks combine their carbon dioxide wastes with free calcium from adjacent waters to create beautifully variegated external support structures that - unlike your house - can be enlarged economically without loss of strength, form or function. Unfortunately, a comparably sculpted and polished calcium carbonate (limestone or marble) shell around you would weigh many hundred pounds.

The lightweight chitin-based external skeletons of shrimp, crabs and insects combine great mobility with adequate support and protection. But in order to grow, these creatures must periodically discard and replace their increasingly restrictive exoskeletons by molting - an awkward process that temporarily increases vulnerability to predation.

Thus it was animal forms braced by internal struts that finally opened the way toward unprecedented size, mobility and function. For both cartilaginous and bony endoskeletons allow ongoing growth, repairs and revisions with no loss of shielding or support. And by basing their bony skeletons on phosphate (essential inventory) rather than carbonate (metabolic waste), vertebrates eliminated unnecessary weight as well.

Nature sorted through countless incremental improvements over millions of years before optimizing the competitive, lightweight, bony skeleton - based upon sturdy collagen fibers stiffened with metabolically essential calcium phosphate salts - that allowed your fishy ancestors to rule the seas. Similar bones now support and protect your otherwise soft and shapeless substance, just as tent poles bring order and function to a floppy tent.

## *Springs and shock absorbers reduce structural stress*

To ensure mobility as well as support, your incompressible internal skeleton is broken into hundreds of independent, metabolically active bones, each firmly anchored to the next by heavy collagenous restraining straps and hinges. Those sturdy bonds limit the movement of every bone with respect to its neighbors, for an excessively mobile joint could easily overstress adjacent soft tissues, leading to catastrophic loss of leverage and structural collapse.

Strong muscles and their tendon extensions contribute important spring and stability to every joint, giving way slowly and elastically to reduce the impact of sudden strains and movements. And wherever your rock-hard bones would otherwise contact or grind across one another, soft water-filled cartilages provide essential hydraulic cushioning.

Clearly, you are held in shape by an endless array of interwoven threads, strings, ropes and cables - ranging from the fine collagen meshwork of your loose connective tissues and skin to the taut collagen fibers that convey the pull of each muscle fiber into the thick collagen bundles of your tendons that then penetrate the fibrous collagen wrapping of your bones to meld with the organized collagen bundles of your skeleton.

There is far more to life than just collagen, but if you could somehow dissolve away their other molecules while keeping every collagen fiber intact and in place, your best friends would remain readily recognizable. They might seem a bit pale and ghostly from your harsh chemical treatments, but their entire structure, even eyes and teeth, would remain fully formed.

## *Collagen pulls, calcium lifts, cartilage sucks*

Your cartilages and other connective tissues are primarily composed of collagen fibers and proteoglycan-trapped extracellular water with the usual salts, gases and nutrients. But cartilage includes a very high concentration of proteoglycans that attracts sufficient water to maintain full turgor.

Your backbone hasn't much flexibility because each bony vertebra is firmly fastened to the next by an intervening chunk of collagen-rich cartilage. In contrast, the bones of your extremities have slick cartilaginous caps that cover and separate all bony surfaces in each joint. These mobile joints are also lubricated by slippery gas-and-nutrient-laden joint fluid.

Because they slide easily across each other, the hyaline (less fibrous) cartilages of your mobile joints usually encounter only compressive and not shear or frictional forces. However, a fully compressed hyaline cartilage no longer slides freely so it may be torn by severe shear forces. For example, the meniscus cartilage - which intervenes between major weight-bearing cartilaginous surfaces of the knee joint - is easily injured when football players are hit while their foot is firmly planted.

Unfortunately, a badly torn cartilage cannot heal without careful surgical revision, for it takes a good circulation to support the removal and repair of damaged tissues, and cartilage contains no blood vessels at all. This absence of blood vessels might seem surprising but, on balance, it is advantageous since so many cartilages serve within tightly enclosed mobile joints that are easily disabled by significant accumulations of bloody fluid - and such accumulations would surely be more common if easily overstressed joint cartilages bore blood vessels.

Consequently, cartilage cells obtain their oxygen and nutrients indirectly by slow diffusion from the blood capillaries of adjacent tissues or via joint fluid. And repeated compressions of cartilage encourage that passage of gases and nutrients. As a result, joint cartilages shrink with disuse and flourish or thicken consequent to vigorous but not excessive activity.

However, the persistent and extreme stresses applied to various joints by gymnasts and distance runners can eventually disrupt cartilage, as may local infections or misdirected antibodies. Many varieties of painful joint dysfunction are descriptively bundled together as "arthritis". Even ordinary wear and tear will damage joint cartilages over a lifetime.

Furthermore, joint damage tends to provoke an inflammatory response which may leave behind enough collagenous scar tissue to interfere with smooth and painless joint movement. And if blood vessels invade joint cartilage as part of an inflammatory process, the invaded cartilage usually matures into (misplaced) bone.

Cartilage rebounds easily from a brief compression but deforms progressively under ongoing pressure. This accounts for your half centimeter (1/4 inch) loss of height during an ordinary day's upright activities. You regain that height while lying down at night, as those cartilages again imbibe fluid until fully distended. Weightless space-persons temporarily gain an inch in height by the same mechanism.

Thus all vertebrates walk, swim and fly on trapped water. For without water-inflated cartilage to separate their weight-bearing surfaces, bones would crunch and grind until they finally became fused together by scar tissue and calcium phosphate deposits - leaving them as immobile as the joints of a rock-bound dinosaur fossil.

## *Cartilage came first*

Every cartilage surface within your many mobile joints seems perfectly sculpted for its setting. But detailed design specifications need not clutter your DNA, as cartilage tends to arise and assume proper shape wherever it is needed. For example, if a congenitally displaced hip with no pelvic socket is properly positioned and stabilized against the pelvic bone by a plaster cast or other simple device soon after birth, a fully functional normal hip joint develops, complete with proper ligaments and cartilages.

Even the occasional broken bone that fails to mend can develop smooth cartilaginous surfaces where fractured pieces rub together. But such a false joint is still disabling, since weight bearing or nearby muscle contractions cause painful displacement of those unstable bone ends into the surrounding soft tissues.

Sharks and rays of all sizes prosper with their flexible, easily modified, cartilage skeletons. But to remain competitive, fish and land-dwelling animals replace their cartilaginous pre-skeletons with a more rigid bony structure. Larger land-based herbivores depend upon early skeletal bone formation in order to flee for their lives soon after birth.

On the other hand, the limber mostly-cartilaginous skeleton of a human newborn minimizes the likelihood of birth injury to mother or child while still providing sufficient support for eating, excreting, screaming and smiling. And at certain sites where flexibility can reduce the risk or severity of injury - such as external ears, nose and forward ribs - cartilage persists into adulthood.

A variety of signal and support molecules attract bone-producing cells to replace preexisting cartilage cells. Size, shape, location and use all affect a bone's final structure. Bones generally retain an open (often cross-braced) interior surrounded by a sturdy dense-bone cortex. Tensile and compressive forces act mainly upon a bone's outer edges, so such a hollow design reduces weight without a significant loss of strength.

The open bone interior may contain fat cells (yellow bone marrow) or blood-forming cells (red marrow). Dense or compact bone of a long narrow bone shaft can twist or bend slightly to reduce the impact of a temporary overload. Long bones widen or flare out near joint surfaces where they must resist oblique compressive strains.

Those bulbous bone ends at your mobile joints are then more easily stabilized and cushioned, so they can be made of lighter spongy bone. A hypothetical hollow long bone of uniform diameter and equivalent strength would be far heavier and totally inflexible.

Collagen fibers self-assemble into parallel overlapping rows. Regular gaps between fiber tips in each row provide innumerable sites where bone deposition can commence. Like most rocks, hydroxyapatite - the crystalline calcium phosphate mineral that stiffens your bones and teeth - is relatively insoluble in water.

The advanced composite structure created when strong collagen fibers interlock with sturdy calcium phosphate crystals has provided the vertebrate skeleton with reproductively advantageous strength and resilience for half a billion years. But bone flexibility depends upon the ratio of collagen to calcium.

A high proportion of collagen allows deer antler bone to absorb repeated severe impacts with low likelihood of antler fracture or serious headache that might delay mating. In contrast, their rigid, mostly mineral construction allows whale ear bones to transfer sound vibrations with high fidelity.

Unfortunately, those stiff ear bones are easily broken by nearby underwater explosions, for evolution is adaptive, not anticipatory.

## *Bones rarely break*

To split firewood, you must initiate and then advance a crack that parallels the majority of structural fibers. By suddenly prying the two sides apart, an entering wedge or ax head delivers much of its force at the point of the crack. But a split may not develop if that force is dissipated by excessive flexibility of the sides.

Hence, frozen or dried wood is much easier to split than a fresh green log, and a harder blow generally has far more effect. A knot (old branch buried deep inside younger wood) can stop a split because tension at the crack tip spreads out along (and is resisted by) those knotty cross-fibers. This may explain why your ax is now stuck in the log, though it won't help you extract it.

Similarly, a short crack in your automobile windshield tends to lengthen as temperature stresses or movements of the two sides exert their leverage at the tip of the crack. Indeed, the more that crack (lever arm) lengthens, the more rapidly it advances thereafter. Some windshield cracks can be arrested at an early stage by injecting strong plastic glue of appropriate optical density to serve as knotty cross-fibers in a log.

Biological materials generally have a grain - or construction-related alignment of cellulose or collagen fibers - along which separation or cleavage is most readily achieved. These natural planes are generously cross-braced by fibers that help them resist overloads.

Nonetheless, small cracks in bones and minor tears in other tissues are an inevitable accompaniment to life's activities. Consequently, the fibrous proteins of your body are routinely resorbed, redeposited and remodeled. In fact, about 5% of your bone mass is currently undergoing reconstruction, even if not broken or cracked.

Your bones are continuously remodeled as you grow and your activities change. This lifelong remodeling process depends upon very large bone-removal cells that respond to local intercellular signals as well as systemic (body-wide) conditions.

Reproductive advantage goes with speed and maneuverability as well as sturdy construction. Being unbreakable brings no benefit if it leaves you too heavy to catch lunch or escape. Fortunately, your structure was optimized by your long-suffering ancestors through an unending series of actual life-and-death field trials. As a result, the size, collagen content and mineralization of your skeleton ordinarily allows it to resist an occasional 50% overload above your usual maximum.

However, that safety margin may not exist or suffice in individual cases. So fractures (strut failures) or dislocations (joint disruptions) do occur in the face of repeated as well as excessive stresses. But while your bones often crack - creating a persistently sore spot that you may refer to as a bone bruise - they infrequently break, and then only due to stresses well above their structural limits.

Pathological fractures are those that occur in bone already weakened by osteoporosis, cancer or other disease. Normal bones can be overstressed by repeated flexion without adequate rest for routine repairs. For example, stress fractures may occur in a foot bone of the military recruit who is forced to carry a heavy pack on an excessively long march.

In other words, unreasonable stress not subject to ordinary commonsense limitations (by soreness and fatigue) may cause a bone crack to progress into a fracture - or lead to inflammation with painful swelling of the affected soft tissues (as seen with tennis elbow and comparable occupation-related repetitive motion injuries).

Along with muscles and other support tissues, bones adapt to less extreme stresses by thickening and becoming stronger. On the other hand, disuse (being immobilized in a cast, for example) weakens the bone structure by promoting calcium removal. The prolonged weightlessness of space flight is associated with bone demineralization and reduced new bone formation. Clearly you are a responsive and adaptable creature built of responsive and adaptable cells, tissues and organs - up to a point.

## *Bone remodeling stabilizes blood calcium levels*

Proper cell function depends upon a appropriate stable level of free calcium ions in your extracellular fluids. So whenever blood calcium ion concentrations decline, a responsive release of parathyroid hormone encourages bone destruction until blood calcium levels return to normal. On the other hand, high blood calcium levels suppress parathyroid hormone secretion until bone rebuilding takes up the excess blood calcium.

Your thyroid gland releases a different hormone that encourages bone reconstruction whenever blood calcium levels are high. Vitamin D, the fat-soluble “sunshine” vitamin, additionally affects your calcium uptake and utilization. However, each Vitamin D molecule must first be modified by ultraviolet light in the dermis of your skin before it can undergo further changes in your liver and finally be activated in your kidney.

Fully effective Vitamin D3 increases calcium absorption from the gut and reduces calcium loss in the urine, thereby helping to maintain adequate blood levels of calcium and phosphate for normal bone production. And Vitamin D serves other important functions throughout your body.

Rather than tunneling noisily through hard bones by mechanical means, your large bone-removal cells silently secrete a strong hydrochloric acid solution on their advancing side. Many small bone-producing cells follow along to deposit concentric layers of new bone that soon refill each laboriously created tunnel.

The variable orientation of those freshly filled-in tunnels protects your bones against splitting - just as knots protect a tree - by stopping most bony cracks before they can turn into a fracture. That lack of bone uniformity may explain why geese can migrate for thousands of miles without suffering wing-bone stress fractures, even though engineering calculations predict failures after about 100,000 wing strokes. Of course, old tales allege that similar calculations once proved bumblebees couldn’t fly.

Large quadrupeds reduce stress on their muscles, tendons, bones and joints in various ways, such as regularly switching lead limbs during galloping in order to redistribute peak impacts. With a horse’s feet hitting the ground 7000 times per hour of trotting, even its normal safety factor of three times the usual loading in a single event may become inadequate, especially with those repetitive impacts occurring on uneven surfaces.

The trot/gallop transition of large four-legged mammals seems designed to minimize peak forces rather than reduce energy costs. However, migrating herds of herbivores usually travel within narrow speed ranges that require the least energy output for the gait being utilized.

All life forms accumulate metabolic reserves with which they produce and provision descendents. Female mammals release bone calcium and phosphate into their circulation to support the growing fetus, then provide additional supplies to the newborn through milk. Human female bone-removal cell activity again exceeds bone deposition rates when estrogen levels decline with the menopause, so regardless of whether they have reproduced or supplied milk by breast feeding, menopausal females tend to undergo excessive bone demineralization.

The likelihood of postmenopausal osteoporosis can be reduced by regular exercise and by maintaining an appropriate intake of calcium and Vitamin D3 as each of these interventions tilts the balance back toward bone mineralization. Excessive menopausal demineralization leaves an older woman susceptible to osteoporotic bone fractures - especially in the metabolically active porous bone within her vertebrae and at the ends of her long bones.

Bone demineralization of any degree mobilizes a similar percentage of the bone-lead burden acquired over a lifetime from leaded gasoline, peeling paint, lead-sealed water pipe joints, soldered food cans and the like. Consequently, symptom-causing blood lead levels are more likely in menopausal females who have never had children or lactated.

Lead's nasty effects on physical and mental functions range from abdominal discomfort and chronic fatigue, to ashen face and premature aging, to deterioration of mental functions and irritability. Those symptoms and signs were once viewed as a natural part of menopause.

These difficulties occur because lead enters into the same reactions as calcium does, but then remains when calcium would leave. Elevated lead levels are easily detected with a blood test. Certain medicines can tie up blood-borne lead chemically and hasten its excretion through the urine.

Those who lose weight rapidly may similarly poison themselves from within, as their shrinking fat deposits release the fat-soluble pesticides accumulated over a lifetime of minor exposures. "Everything in moderation" (even weight loss) seems appropriate advice for those seeking to preserve their health. In fact, repeated bouts of unsuccessful dieting pose a greater health risk than remaining pleasingly plump.

And despite Popeye's or your mother's advice, children ought not eat much spinach or rhubarb since both contain sufficient oxalate to bind calcium within the gut - which could reduce dietary calcium absorption below levels needed for the construction of sturdy bones.

# Chapter six

## Life depends upon death

According to **The Second Law of Thermodynamics**, all mechanisms or processes eventually grind to a halt if isolated from external energy inputs. Hence living things starve if they cannot extract enough energy from the environment or each other.

Modern **Evolution Theory** recognizes that the great number and variety of living things born far exceeds what the environment can support. Hence only the fittest survive long enough to pass on their successful traits. In this way, death determines life's character, significance and prospects.

### *Instability exists at every level*

At the subatomic level we find only tiny particles (localized packets of energy, actually) circling each other at relatively enormous distances and incredibly high speeds. In this emptiness, the strong and electromagnetic interactions rule; indefinite things become tangible only as they are measured; and the very nature of subatomic particles prevents us from simultaneously establishing their position and momentum.

In comparison, atoms seem reassuringly substantial, and their chemical (electromagnetic) interactions far easier to describe. And when brokered by molecular facilitators known as enzymes, life's atoms are regularly lured into useful relationships. But here again, selectivity and instability remain essential, for your life would suddenly cease if all of your atoms bonded into one huge molecule - no matter how cleverly constructed.

Consequently, most relationships amongst your component atoms remain fleeting - a brief bump and change of partners in the heat of the moment, driven by apparent fit or the temporarily irresistible charms of one with an opposite electrical persuasion.

As for your frantically writhing molecules, their average shape and disposition reflect which atoms they currently hold in custody, the way those atoms are arranged, and how each part is attracted, repulsed and twisted by the ceaselessly crashing molecules of your internal salty seas.

At this scale, life merely seems agitated, crowded and confused. So it is a relief to leave molecules behind and focus upon relationships within and between the living assemblages known as cells, although disconcerting to reflect that those cells - and the multicellular life forms to which they contribute - are actual bacterial cooperatives.

However, the excitement of deciphering the first few mystical words and even phrases of your ancient four-letter DNA language - faithfully recopied and passionately passed onward over billions of years - soon allows you to forget that these runes also confirm your less than exalted origins.

For as is so often the case when ancient records are finally translated, it turns out that your early chromosomal literature mostly concerns mundane matters like supervisory structures, cellular obligations and just-in-time deliveries.

Indeed, it is surprising to see how your primitive multicellular ancestors with their unsophisticated tools evolved such ingenious methods to monitor and regulate the endless trillions of simultaneous transactions that allow your internal economy and external relationships to flourish.

And as they now uncover and interpret the 30,000 genes that send out over 100,000 different proteins and other molecules bearing “Thou shalts” and “Thou shalt nots”, modern translators of human DNA have also unearthed endlessly jumbled and shattered DNA fragments bearing apparently meaningless words and phrases.

By fitting those shards together and determining linguistic relationships between different life forms, these researchers increasingly enhance our understanding of how evolving molecular species contribute to efficiencies, affect the flow of energy, alter the balance of trade and improve control over profits and losses, oxidations and reductions - thereby ever again contributing to that bottom line, your total metabolism.

Those who concern themselves with intracellular and multicellular relationships have long realized that to really understand cellular politics, one must trace the flow of energy dollars. As always, some transactions are readily visible while others tend to be obscure and based more upon a wink or a nod and who knows how to get to whom.

Furthermore, those energy dollars are laundered through numerous accounts, starting with the photosynthetic peasants who so laboriously trap solar energy from dawn’s early light. Much of that original glucose product is soon acquired by unsympathetic herbivorous tax collectors who, in turn, only relinquish their growing hoards of chemical energy reluctantly when finally apprehended by the carnivorous authorities.

Although you currently live high on this food chain, all living things eventually tumble to the bottom for recycling. And to put off that fateful moment, you frugally distribute your spoils of glucose and other organic molecules amongst the many cells that are you, so that each of those cells can bribe, cajole or coerce its own endosymbiotic colleagues and slaves to produce the high energy phosphates and trans-membrane ion gradients that will keep your thieving organization at work till the end of your days.

Well, so far, so good, even if less than inspiring. But as we now approach the entire organism, we find that there is more to the whole than just its parts. For somewhere along the line, all of this incredible complexity was subtly transformed into the real you. And clearly you are far more than just a coherent collection of point-like subatomic particles, colliding molecules, cooperating microorganisms and stolen nutrients.

## *Only your information abides*

Your atoms, molecules and cells have undergone continuous replacement, revision and repair ever since the fateful day when father's sperm penetrated mother's egg. Indeed, almost every part of you has been replaced or rebuilt over the past few hours, days, weeks and years. So when next you greet an adult friend after five years absence, both of you will have been almost totally exchanged.

So whom or what is it that you now encounter, half a decade later? It is only a pattern, a complex design, a unique arrangement of information being continuously impressed upon new material. The material part is essential, of course, for like those computers that lose all track of what they were doing when their power fails, the delightful design of your friend could never persist through any intervening discontinuities or dematerializations.

Similarly, the special coherence of your wonderful information will forever be lost to us at the moment your superbly run organization loses its sustaining flow of energy. Experts may one day be able to recover some of that information, but still, dead is dead. Apparently, the real you is an uninterruptible sequence of operations that depends upon a fail-safe power supply.

So while you actually exist only in the present, and that present is most accurately defined as the shortest possible interval we can identify, it is clear that you were, are and will continue to be *an information-guided flow of energy imposed upon matter* rather than a molecular collage that somehow walks and talks. Nevertheless, we still can learn a lot about other creatures by studying their material parts, whether these are fossilized and fragmented or intact and still in use.

## *Your bones are unstable too*

The squirrel skeleton freshly deprived of its supporting soft tissues - or a dinosaur fossil just released from its rock of the ages - will collapse into a disorganized clutter under the influence of gravity. Yet the original function of those bones was to counter gravity and other accelerations. And unlike the average jigsaw puzzle, either set of bony supporting elements is easily reassembled in countless different ways - or artfully combined with similar size bones from an unrelated species - without offending the untrained eye.

Furthermore, regardless of how correctly any skeleton is mounted for display, no bone in that arrangement will remain in place - let alone exert leverage upon the outside world - unless firmly wired to its neighbors. And similarly ill-fitting bony parts currently support your own sturdy, gracefully mobile structure. Once again, on this still larger scale, you have successfully integrated thousands of individually unstable, dynamically interacting bones, cartilages, ligaments, muscles and tendons into a single functional living whole.

In addition, despite their large number and evident redundancy, you would not work nearly as well if even a few of those many parts had been left out to simplify matters for the average anatomy student. Apparently instability and complexity bring major advantages when combined with sufficient processing capacity to ensure the timely acquisition of important information, appropriate responses and adequate maintenance. These same principles underlie the design of ever-smarter military aircraft.

## *Using leverage*

Muscle contractions perform work. Muscle relaxation is passive. Although many muscles contract with great power, no voluntary skeletal muscle can actively shorten to less than two-thirds of its resting length. Even a muscle the length of your thigh can only pull in a few inches. So how are such short and powerful muscle contractions converted into the agile "fight or flight" movements that kept your ancestors alive and reproducing against all odds?

Sometimes the best answer to a question is another question. So we ask, "How does a seesaw work?," and "How can an ordinary person exert sufficient muscular force on screw jacks to lift an entire house?" An obvious partial answer to the last question must be "very slowly and carefully". For we all recognize the reciprocal relationship between speed and power - between the gearing of a sports car and that of a tractor. Similarly, we anticipate obvious differences between the body build of a champion high jumper and that of a successful sumo wrestler.

Long ago we learned that a seesaw would balance if the lighter individual sat farther from the fulcrum (pivot point) - which meant the lighter one traveled a greater distance at higher speeds during each up-and-down cycle. Hence one could say that the lighter one used the mechanical advantage provided by a longer lever arm to lift the other, or else that the heavier chap used the shorter lever arm at a mechanical disadvantage to propel the lighter blighter at greater speed over a longer distance.

By analogy, how muscle attaches to bone with respect to a neighboring joint (fulcrum) ought to determine whether that muscle sacrifices power to gain range of motion and speed, or sacrifices speed to gain power - just as you willingly give up speed to enhance your own power when you slowly turn the screw jack with a long steel bar in order to lift a house.

The enormous mechanical advantage provided by the screw jack is determined by the circumference of the circle made by your working hand on the jack handle (pi times the diameter [d] of that circle - the diameter being about two times the length of the jack handle), compared to the gain in height (h) achieved during one full turn, as the house rises the width of one thread on the screw jack. In other words, pi times d/h.

Consider also the multiple pulley systems so often utilized for lifting heavy loads. To determine your mechanical advantage with such a complex system, simply divide the length of rope you have pulled in while raising that load by the distance the load has been lifted. Indeed, if that inverse relationship between power and speed did not exist, some clever person would have invented perpetual motion a long time ago, thereby liberating us all from the cruel dictatorship of the Second Law of Thermodynamics.

But since this has not occurred, you must swing a long handle over a wide arc in order to ratchet your car up a single notch on that bumper jack. And watch that the handle does not snap back at very high speed if the jack ratchet somehow fails to engage and is pushed back down one notch. For then the automobile would be using its mechanical disadvantage to exchange power (its great weight moving over a short distance) for speed (the rapid and wide swing of that jack handle).

## *Why you are as you are*

When compared with the animated glucose-grabbing version of a skeleton regularly encountered at Halloween, an actual human skeleton is rather ungainly. Indeed, your adult skeleton becomes noticeably thicker and heavier from top to bottom, since lower sections support everything above.

More generally, since blood vessels and nerve cells are easily lengthened, an animal’s size, shape and structure reflect an endless number of other limitations and trade-offs. For example, a giraffe’s long neck would be cumbersome in the jungle where pigmy stature has obvious advantages.

And while longer limbs may increase your running speed and reduce transportation costs, they also slow your reflexes and enhance body surface heat loss. So look for long limbs among traditional nomads who regularly walk considerable distances in hot climates. Expect short legs among traditional human populations in the frozen far north where distance walking remains impractical much of the year.

The soft skull of a newborn is obviously reshaped by its passage through the birth canal. Those temporary deformations are usually well tolerated. But even after birth, it is important that skull bones around the brain not bond firmly together until rapid brain growth has been completed.

In the meanwhile, a soft anterior fontanelle (midline skull gap) persists where frontal and temporal skull bones fail to meet. That site may bulge noticeably when the infant screams and strains, or with increased pressure inside the skull from other cause. But eventually those skull plates expand, thicken and fuse at their lengthy interlocking edges to provide lifelong protection for the brain.

Shallow sinuses (air-filled cavities) at the front of the skull can deflect or absorb impacts that otherwise might damage the front of your solid brain case. Sinuses also reduce skull weight, increase the resonance and carry of your voice, and contribute secretions to your nose. And along with your cheek bones, those bulging frontal and maxillary sinuses support and protect your eyes.

Your upper teeth are firmly fastened to the base of your skull while your lower teeth grow from the mobile lower jaw bone. Unlike your fishy ancestors, you no longer need to open wide and ingest your dinner in one struggling piece, for you have flat cutting teeth (incisors) in front of those grabbing slicing canines, and thick grinding molars provide powerful backup.

The seven vertebrae of your neck allow back and forth, as well as rotating movements; hence you can tilt or turn your head rapidly without also tilting or turning your body. The weight-bearing surfaces of your neck vertebrae are narrow front-to-back so that the spinal canal and its enclosed spinal cord remain undisturbed at the center of rotation. Indeed, your first cervical vertebra is little more than a bony ring that supports your skull while pivoting on the upward extension of your second cervical vertebra.

Your thoracic and lumbar vertebrae show increasingly heavy construction and marked front-to-back elongation - here less rotation and far greater strength are required. Soft-centered fibrocartilaginous discs between each of your vertebral bodies readily absorb all reasonable compressive forces while still permitting adequate movement. These discs gradually stiffen and indent adjacent vertebral bodies as those porous bones become osteoporotic - hence older people lose height and have to walk or jump more carefully.

At times, pulpy disc content will herniate (bulge out) through the more fibrous disc capsule, perhaps compressing a nerve root or even the spinal cord. Such a “slipped” disc is most common in the strong and flexible lower back, but also frequent in the less strong, more flexible neck. Aging and aching vertebrae that come into direct bony contact eventually form a bony union. The resulting stabilization reduces the risk of intervening disc-material extrusion but may increase the leverage exerted by ordinary movements on adjacent disc spaces.

## *Location is everything*

At this point one could reasonably ask a few general questions about how you are put together. For example, would it be advantageous to place your central nervous system or important sensors more centrally? Well, such a location might speed messages and keep your ears warmer alongside your abdomen but it certainly would interfere with your wide visual fields, unobstructed hearing with minimal echoes, and smelling of things other than self.

Furthermore, you barely float in water as it is, and there are many streams to cross in your endless quest for food and romance. So it is advantageous to bunch important sensors and your air intake where all can usually remain above water. Since your eyes are in front, it must be more important for you to see where you are going and what you are pursuing than look where you have been or contemplate what is chasing you.

As halibut and flounder settle into one-side-down life on the sea floor, they benefit by moving their bottom eye around to the top side where there is more in view than just mud. On the other hand, herbivores generally look sideways, trading the advantages of binocular vision for wider visual fields that allow earlier detection of carnivores and keep them in view during flight. For one cannot flee or fly safely while turning the head to look back.

It also makes sense to bunch your more delicate functions and sensors up front where they can better serve and be protected from cold and injury - the other (back) side can then be made tougher and stronger.

## *Should you have three legs?*

Why walk on two legs when three would improve stability? To a considerable extent, mobility and stability are opposites. Furthermore, you do not remain alive because of how steadily you stand. Rather you may survive due to how rapidly you move in any direction from a standing start. A nervous moose puts all four feet close together until it decides which way to go. Small mammals such as chipmunks routinely run on bent legs - despite the obvious inefficiencies and reduced leverage of such a gait - because it allows an instant leap.

So what are the advantages of rear-limb drive over making your forward limbs stronger? Only those mammals that must dig or fly to their lunch need stronger front limbs than rear. Bats (and birds) use powerful chest wall muscles to flap thin wings, but diggers and runners locate bulky muscles on the limb itself to stabilize the joints of that structure against heavy and variable loads. Rear limb drive also helps you to raise your sensors above tall grass and low scrub, or reach higher fruit in the tree.

With four legs on the ground, more weight is transferred to the rear on starting and to the front during braking. Thus rear limb drive emphasizes starting power over braking while also providing sturdy support so those weaker forelimbs can reach, grab and fight under direct sensor supervision.

As your front limbs move forward in four-legged running, you simultaneously extend the vertebrae (arch the back) to lengthen the stride. Your forelimbs can then pull the ground farther back by flexing (hunching) your back vertebrae before the next big push by the rear limbs.

For the galloping horse, back extension is a routine part of the powerful leap while back flexion enhances the follow-through. Longer legs and longer strides reduce the cost of transportation since each step entails a similar energy expenditure per pound transported by a mammal of any size, moving at comfortable speeds.

Among running animals, back and buttock (rear leg extensor) muscles normally are stronger than flexors. And those easily displaced soft tissues and organs in front of the lower vertebral column offer little resistance to marked flexion of the torso.

## *Reproduction matters*

Why is your pelvis so wide, with the greater trochanters of the femur coming off sideways? Why not place the pelvis directly over the legs? Well, first of all, there is value in pelvic width and instability. As for bringing the hips more medially (toward the middle), that could increase stability but also reduce muscle leverage (see elbow below) as well as make a running start more difficult. For in order to run, you must first fall away from dead center. Having very laterally placed hip bones lets you start quickly in any direction by reducing support on that side. It also provides space for thicker, more muscular legs.

The female pelvis has a relatively larger circumference than the pelvis of a similar-size male. Not surprisingly, that relative increase in female bony girth (and therefore weight) reduces peak athletic performance in many sports, especially since fertile females must carry extra energy as fat in order to successfully complete pregnancy and lactation.

Given that the female pelvis is barely large enough for an infant head to pass, it also is advantageous to loosen all pelvic joints before giving birth. A larger pelvis that made such loosening unnecessary would be heavier - just as a water pitcher requires thicker walls than a water glass. And when catching lunch, escaping from carnivores or leaving lost battles, it would be reproductively disadvantageous to run more slowly on account of additional pelvic weight.

The lighter, less muscular female upper torso reduces stress on that pelvis. As in automobile design, weight saved in one place allows further reductions in the strength and weight of other components, thereby improving performance and reducing power requirements.

## *Mobility matters too*

Your massive and powerful legs are stabilized - and their range of movement is limited - by your heavy pelvis and its associated musculature. But you wouldn't want your arms to originate from a comparably sturdy, bulky upper pelvis that would limit arm movements or restrict chest expansion for air exchange.

Therefore, each arm hangs from its own mobile, muscle-enclosed scapula (shoulder blade) that can shift and rotate around your rib cage to extend your reach, mitigate the stress of sudden loads and allow distant muscles to help power your pull or "crack the whip" on your throw (making baseball pitchers look strange when photographed in mid-fling).

Note that there is no bony connection between your vertebrae and your scapulae. The flimsy, mobile clavicle is the sole rigid link between your scapula at the shoulder and your skeleton at the sternum. The human clavicle is a functionally unimportant bone that serves mostly to steady the arc of shoulder movement and protect underlying nerves and vessels as they enter the arm.

Horses have no clavicles and derive powerful scapular support from very strong muscles attached to the elongated spinous processes of nearby vertebrae - those muscles and posterior vertebral spines produce the hump in front of your saddle. By eliminating clavicles, cats maximize scapular mobility and running efficiency for the short high-speed dashes that allow them to feast on fleet-footed vegetarians.

The otherwise close correspondence between bones of your upper and lower extremities doesn't include each knee cap within its quadriceps tendon. But that patella improves leverage in the same fashion as the elbow extension on each ulna. However, the mobile patella is less likely to be injured - and better suited to falling or kneeling - than an "elbow-like" tibial extension at the front of the knee would be.

The lower extremity emphasis on strength and stability over maneuverability is evident from the way your sturdy tibia serves as the dominant weight-bearing leg-bone between knee and ankle joints. Compare this to the forearm where your ulna dominates the elbow joint while your radius provides the main bearing surface at the wrist.

Although less sturdy, that alternate arrangement of arm bones markedly enhances your dexterity and agility by permitting easy pronation and supination (palms down and up) of the hand. Note also that the radius contributes slightly to the elbow joint, but the fibula plays no role at all in the knee.

And while your wrist bones permit a wide range of hand movements, the analogous lower extremity bones form the relatively immobile but springy arch of your foot. Furthermore, your nimble fingers contribute almost as much palmar surface as the palm itself - but unlike those long fingers, and the comparable toes of your primate ancestors, your short and ugly toes barely suffice to pick up your dirty laundry or help your weight-bearing foot balance and shove off.

The relatively long flat feet of bears and people make their strong calf muscles work at a marked mechanical disadvantage through the achilles tendon, which allows a fast and moderately strong, running takeoff.

Those who wear pointy-toed shoes and high heels often develop a bunion (prominent painful head of the first metatarsal) due to persistent lateral displacement of the great toe. Such an abnormal concentration of weight on the first metatarsal eventually results in permanent discomfort while standing or walking.

Presumably this inane clothing fashion has persisted - despite causing innumerable sore feet - because attractive balancing movements imparted by high heels to the female pelvis provide compensatory reproductive advantage.

# Chapter seven

# Muscle

For four billion years, by fair means and foul, your ancestors unfailingly forwarded their inherited DNA to the next generation. So now you replicate and recombine the half of each parents' remarkably successful DNA that became you, in order to prepare yet another unique egg for next month's ovulation - or create hundreds of millions of individually unique sperm for your next ejaculation - and everyone else does the same.

But just as an uninteresting novel has less value than blank paper, each tiny reproductive packet of your personally prized DNA is less useful than the individual nucleotides that spell out its unique message - unless those eggs or sperm fulfill a need. From an evolutionary perspective, eggs and sperm are destiny. The rest of your body is just hype.

Indeed, the sharp contrast between your low-budget, reliable, redundant, egg or sperm production lines and your expensive, easily deranged eyes, brain, gut or muscles, simply emphasizes how far the multicellular competition for reproductive advantage has gotten away from the basics.

Human intelligence reached its current formidable state along a haphazard route littered by the sun-bleached bones of innumerable incremental changes that failed miserably or almost worked - perhaps because their time had not yet come. Nonetheless, a tiny fraction of all those changes endured and multiplied because they brought reproductive advantage.

But except for health-and-immunity related genes, the impact of that slow natural accumulation of favorable DNA-based traits has finally been reduced to near insignificance by the exponential growth of cultural, and especially scientific, information.

As a result, many successful participants in our modern competition-driven information-based economies would rather devote the majority of their efforts to intellectual/commercial pursuits than to reproduction - and logic is increasingly on their side.

After all, the unprecedented accumulation of scientific and technological information that underlies modern civilization already dwarfs the total information content of the human genome. So while intellectual and sexual intercourse both remain potentially pleasurable ways to share slightly altered information, intellectual discourse has become far more exacting, efficient and potentially far-reaching.

And regardless of effort and expense, your selection of a mate exerts surprisingly little influence over which unique array of genetic information your descendants may inherit - or how effectively they then assimilate and interact with critically important cultural knowledge. On the other hand, if you devote your growing intellect and skills to the sharing of useful ideas through verbal, written or electronic means, you may - like Dr. Seuss - eventually acquire millions of intellectual descendants without ever having faced the challenges and rewards of child rearing.

With humanity already consuming a significant fraction of Earth's entire bioproduct, any shift in emphasis from raw reproductive success to improving the education and environment for the next generation is surely no bad thing. Furthermore, despite significant regional differences in human appearance, our common ancestry has endowed ordinary humans around the world with nearly identical genes and possibilities.

So with scientific information essentially free and technological opportunities seemingly unlimited, life can no longer be considered just a zero sum game in which some must lose so that others may gain. Indeed, the old fight to the finish so that Nature can select the fittest DNA upgrades no longer appears either rewarding or relevant.

Instead, to maximize its own wealth and productivity, every society must henceforth encourage life-long informational upgrades for most of its citizens. Yet despite all of this theory, young human adults will surely continue to view their personal egg or sperm production as supremely important, even though that inherent presumption seems less germane with each passing day.

## *Move it or lose it*

It is all very well to distribute your genetic information widely in hopes that a few copies might land where they can flourish and reproduce, but "almost" or "close" or "nearly" are not necessarily winning reproductive strategies. So while innumerable small packets bearing hopeful upgrades of life's ancient information are routinely released for passive distribution over varying distances on land, sea and air, many can markedly improve their options through purposeful movement when nearly there.

A sperm capable of swimming those final few centimeters is far more likely to succeed than one unable to propel itself. A bacterium may gain significant advantage by moving just a few millimeters or even microns. Certain bacteria of spiral shape simply flex and twist ahead through the water, which to them is a very dense medium.

Others incorporate rotating flagella to propel themselves forward or back. Many single-cell protozoa row about with cilia or scull along with flagella.

And amoebae travel efficiently but tediously along surfaces by extending their leading edge while retracting the trailing portion of their fluidized anatomy.

The advantages of movement have also encouraged most multicellular animals to invest in specialized muscle cells (collectively referred to as meat) that can lift many times their own weight. But muscles only justify their cost if they support and deliver eggs or sperm more effectively.

Of course, regardless of how individual animal size and metabolic cost may increase, the total population cannot long exceed what the environment will support. And muscles also allow larger animals to relocate for refreshments and reproduction as local possibilities become exhausted.

## *Muscle contraction makes sense*

Regardless of scale, there are only a few basic ways to move through any environment in purposeful fashion. One can push ahead, pull ahead, row ahead or rotate (screw) one's way to reproductive success. However, for larger animals with muscle cells, the basic choice was whether those cells should push or pull. And there really was no contest, for pushing requires rigid internal pushrods that are difficult to direct while pulling creates tension and tension results in alignment and alignment allows multiple units to coordinate their efforts along the straight line between puller and pullee.

Because something pushed is unlikely to go where intended (thereby reducing the efficiency or even usefulness of that push), it is a classic sign of poor judgment to put the cart before the horse. Even such specialized push-devices as the wheelbarrow and wheelchair are slow and hard to handle. So while some single cells still advance by pushing their cell membranes forward in front as they retract their rears, larger groups of muscle cells brought reproductive advantage to their specialized multicellular cohort when all pulled in unison.

Thus muscles never push directly while doing work or, to put it more accurately (see octopus below), muscles contract (shorten) actively and lengthen passively. In other words, muscle cells only perform work during their contraction - which means your skeleton is both stabilized and manipulated by groups of muscles pulling against each other at every joint.

Some of those muscles are so situated that their contractions extend (or straighten) a joint, while other muscles actively flex (fold) a joint as they contract. And because of the way they cross one or more joints, a few muscles also twist. Where tendons cross more than one joint, contraction of the muscle also might either flex or extend a particular joint, depending upon current skeletal position and the contractile state of other muscles.

The strength of your various muscle groups adapts rather quickly to their customary workload; to how much leverage - mechanical advantage or more commonly, mechanical disadvantage - is involved. Furthermore, most of your muscles maintain some tone (contractile activity) while strenuous physical work is underway, regardless of whether the current effort is primarily powered by themselves or by an opposing muscle group.

After all, it takes a smoothly yielding counterforce to provide positive (moment to moment) control and thereby prevent unopposed flinging sorts of movements - just as an effective opposition party and a free press can reduce erratic behavior by the party in power.

Your voluntary or skeletal muscles are able to contract individually or together in countless combinations and sequences because every voluntary muscle includes many motor units - and each motor unit consists of several muscle fibers that respond simultaneously to any stimulus from the motor nerve cell that they share.

But while you can endlessly adjust the output of your individual muscles, even maximal stimulation can only shorten a muscle to about two-thirds of its resting length. And where the load is excessive, a muscle may not shorten at all - it might even lengthen despite your best contractile efforts.

If muscle activation leads to definite contraction but no noticeable muscle shortening, this is referred to as an isometric contraction. It takes the ongoing isometric contractions of a great many opposing muscle groups to stabilize your weight-bearing bones and joints so you can stand or walk - otherwise you would collapse in a heap.

At any given moment within any particular voluntary muscle, some motor units are likely to be relaxing as others contract. For only a frog making the big jump would want all motor units of an entire muscle to contract at once. So how is muscle contraction accomplished? By what mechanism does an individual muscle cell or long skeletal muscle fiber shorten so forcefully? And are there any predictable consequences to such a shortening?

Well, any contracting muscle cell or muscle fiber necessarily becomes wider as it shortens, for its considerable water content is essentially incompressible. So when many transversely oriented muscle cells in the octopus arm or lizard tongue contract simultaneously, these structures suddenly become thinner, hence longer.

Thus the contraction of longitudinally oriented muscle cells or muscle fibers shorten a structure while the shortening of transversely oriented muscle cells can constrict your blood vessels or forcefully and rapidly drive an octopus arm or lizard tongue ahead. Octopus arms need no bones to stiffen them underwater since they too are of water density.

However, a lizard only propels its tongue through the air after first reefing or gathering it accordion-style on an internal forward-pointing extension of the hyoid bone. And it has been suggested that the last heart muscle cells to shorten during an ordinary cardiac contraction (heart beat) are so arranged that their simultaneous widening smoothly initiates the next cardiac expansion.

The stationary display of muscles in a "beauty" contest or for intimidation, becomes more impressive when forceful contractions of opposed muscle groups emphasizes muscle bulk. However, muscles that were enlarged by prolonged and strenuous isometric exercises tend to fatigue readily during ongoing use. So regardless of their formidable appearance, heavily muscled individuals often have little endurance - which suggests that you might be able to outrun one if by chance you kick a little sand in his face.

Many such trade-offs explain the variable distribution of the three principal sorts of muscle fibers within different muscles of different individuals. Isometric or weight-lifter's exercises enhance fast-twitch white muscle fibers. These contain ample stores of carbohydrate but few mitochondria, very little oxygen-storing myoglobin and relatively few blood capillaries.

Fast-twitch white muscle fibers predominate in upper extremity muscles that are occasionally called upon for quick, powerful, possibly lifesaving contractions. On the other hand, postural muscles need to contract slowly and evenly - often they must remain partially contracted over long periods of time while you are active.

Not surprisingly, therefore, your postural muscles contain high concentrations of mitochondria, myoglobin and blood capillaries, and include mostly slow-twitch red muscle fibers. As you would also expect, the percentage of slow-twitch red fibers declines with disuse - e.g. during a prolonged space flight.

Fast-twitch red fibers are found where speed and endurance are essential, as in the running muscles of your lower extremities. Although fast-twitch red fibers might seem ideal for every purpose, slow-twitch red fibers achieve body support functions more efficiently because every individual muscle fiber contraction carries a similar energy cost regardless of its duration.

Fast-twitch white muscles can support brief, intense exertions without diverting your limited blood supply away from essential red muscles at their moment of greatest need (having arms that rarely tire does not help if your legs then give out). Although any muscle can be made stronger or more resistant to fatigue by appropriate exercises, there are marked differences between individuals in what can be achieved. Age, nutrition and health are obvious limiting factors. Nonetheless, quite remarkable gains have been elicited from suitably exercised muscles.

## *The muscle arms race eventually depends upon death*

Our earliest ancestors were totally dedicated to the process of replication. At an appropriate time they simply split in two. All parental resources transferred automatically to both daughter cells. Nothing was left over. Fierce competition permitted no waste.

In marked contrast, you represent a cooperative state-of-the-art system for the production and delivery of sex cells. And that tremendous investment in marketing your information is a natural outcome of the ever-escalating biological arms and legs race that began with First Life.

As with all arms races, you now get far less bang for the buck (many fewer descendents per unit of recycled solar energy) than did your simpler multicellular ocean-dwelling ancestors - some of whom may have generated millions of eggs in a year's time. So despite the comparatively immense metabolic investment in you as an individual, you will leave relatively few descendents no matter how hard you may try.

Furthermore, like all departments of defense, you have become very adept at sequestering resources. Thus, for the sake of those to follow, you are destined to die so that your assets can be recycled after your reproductive days have passed.

In the good old single-cell days, death called often but not for all. And newborn single-celled competitors began life more or less even with others of the same sort - unlike your own young descendents whose survival, sustenance, education and even replication may depend upon uninterrupted access to the resources that you struggle to acquire.

However, the successful rarely recognize when they have enough. Indeed, how much would surely be enough when you might live forever? Hence if humans lived on endlessly - and could continue their mindless accumulation of resources - the old ones would soon dominate, compete with and impoverish the younger generations rather than becoming their inevitable, if unwilling, benefactors.

Therefore, the possibility of a markedly lengthened life span with sustained vitality should be viewed as an unprecedented threat to future human generations. For soon enough, social unrest or some newly evolved disease or other major challenge, would eliminate the increasingly out-of-touch, decreasingly adaptable, ever less self-sufficient conservative oldsters that remained.

Of course, those most desperately seeking immortality - or at least a greatly prolonged and healthy existence - could in fairness point out that natural selection and reproductive advantage no longer drive human progress. Rather, it is how we process and pass along non-genetic information that will henceforth determine the fate of our civilization. And since older humans are the storehouse of traditional knowledge, they also represent an essential resource to be prolonged and cherished. Right?

Well, not exactly. For the most significant advances in production, utilization, storage and retrieval of information, upon which humanity's future finally rests, tend to come from younger individuals - while many oldsters are unproductive and computer illiterate. Yet even our young may soon be outflanked by - or meld with - their potentially immortal silicon-based servants. And under these new, rapidly evolving, information-driven circumstances, what will life or death or "natural" selection really mean?

As for the ancient ceremonies and traditional wisdom that once brought continuity and meaning to the daily lives of Australian aborigines or the Inuit - or that codified successful farming practices among Balinese or Chinese farmers - or that formerly lent life-and-death authority to the aged leaders of European and middle-Eastern religions - many of those persistent admixtures of history and dream-time beliefs seem increasingly irrelevant to the scientifically literate. Of course, change is generally resisted by the old, who quite rightly declare "Over my dead body!"

## *Muscles allow you to acquire and deliver information*

To determine how it all evolved, this emphasis on muscle-based speed and power, we must extend our imaginations back to the early days of multicellular life. There we encounter all manner of weird and wonderful life forms displaying various contrivances for getting even or getting ahead, some of which were far more effective than others.

Among the most vicious and violent participants in that passing parade, your newly specializing multicellular ancestors managed - by the desperate contractions of their primitive muscle cells - to consistently seize energy-laden organic molecules from the less muscular, less intelligent or less fortunate.

But nowadays most humans are far too fat, skinny, sick, old, weak, young, inept, specialized, clueless or crippled to successfully feed, shelter or defend themselves in that traditional cold, cruel world. So except for the most confirmed survivalists among us, a significant subset of whom are angry (because increasingly irrelevant) religious fundamentalists eagerly awaiting Armageddon, we should be grateful that science and technology have relegated human muscle to such a minor supporting role.

For it is our ability to process great quantities of non-DNA-based information that now prevents various microorganisms or the few remaining large carnivores from culling human populations down to more appropriate, environmentally sustainable levels. Given half a chance, those carnivores would gladly consume the old, young, weak and diseased human majority and thereby restore The Balance of Nature (meaning more large carnivores and fewer humans) to this dynamically unstable biosphere.

But at least for now, humans continue to rule the world with their antibiotics and refrigerators, houses and window screens, fire, clubs, spears, guns and explosives - because those powerful defenses have replaced our comparatively puny muscles as the most effective way to fend off the predators and parasites (including other humans) that lust endlessly after our assets.

Indeed, science and technology have become such a routine part of modern life that we feel no surprise when some beer-bellied weak-limbed attorney with a few extra dollars is able to best the mightiest bear. And as long as your muscles still pump enough air and blood to get you in and out of the car and grocery store, those muscles will probably allow you to achieve reproductive success as well.

So just relax, lean back in the old easy chair, close your eyes and contemplate yourself - a complex collage of bacterial ancestry that still remains totally dependent upon the other bacteria-based life forms that you routinely befriend, enslave and slaughter. For it is their repeatedly recycled solar energy - so laboriously trapped within chemical bonds - that must power your every muscle contraction till the last.

Still you remain susceptible to the old signals - so you suffer uncomfortable diversions and highly emotional dislocations of your self-centered subjectivity whenever you encounter even the most implausible reproductive opportunity. And challenges to your reproductive power or its equivalent (your car, your money, your weapons, your tribal background, your religious beliefs) tend to provoke the most violent, sometimes even muscle-dominated, reactions.

## *Better muscle contractions through chemistry*

So how on Earth are the golden rays of sunlight trapped in amber fields of grain, finally converted to useful muscle contractions? What brand of quiet, efficient, self-maintaining and eventually edible, solar-powered micro-engine could one possibly buy that would work as neatly and cooperatively within your smallest muscle cells? How do your muscle cells do it?

Well, the forceful shortening of any cell is likely to involve traction upon fine filaments within that cell. And only an equal pull in both directions can allow an elongated muscle fiber to shorten symmetrically in place. Such a muscle contraction might proceed by actively trimming or coiling individual filaments, but it seems simpler and more controllable for muscles to contract by ratcheting active filaments along passive ones - and that is exactly how it works.

Of course, since active and passive filaments must always overlap in order to interact, even maximal skeletal muscle contractions merely shorten a muscle by one third. Fortunately, such contractions may be powered by a remarkable range of fuels, ranging from live ants and pan-fried armadillo steaks to dried sunflower seeds, boiled zucchini and salted herring roe on seaweed.

However, in order to access that stolen solar power, you must first digest those unwilling donors outside of your cells. Molecules thereby released are then cracked and refined within your cells for final conversion by your mitochondria into the unstable high-energy phosphate bonds that directly power your muscles.

Clearly, the candle-lit enjoyment of another creature’s properly prepared flesh is merely the first in a long series of metabolic and micromechanical events that eventually allows a flavorful morsel to repair or shorten your own muscles. And since every intermediate step leaks energy, most of the solar energy trapped within those tasty organic molecules escapes as heat before or during your muscle contraction, rather than accomplishing work. So a big meal and physical exertion both warm you up.

During mild exercise, your muscles preferentially combust free fatty acids rather than glucose. But since your cells extract chemical power more easily from glucose than from fatty acids, you naturally blend more carbohydrate into your fuel mixture during heavy exertion. But once your carbohydrate stores are depleted, those muscles can only work at the slower rate sustainable through fatty acid mobilization and oxidation.

## *Making it work*

To be useful, muscle contractions must include ON and OFF controls that intervene in a responsive and timely fashion. The timely part is mostly a matter of definition, since predator and prey both rely upon the same basic muscle mechanisms. In other words, whether your fastest muscles are contracting swiftly or slowly may simply depend upon your perspective or leverage - who is being chased and which has the longer stride.

Your ON and OFF controls both rely upon special proteins that change shape and move aside in response to free intracellular calcium ions. As a result, calcium ion entry into the muscle fiber unblocks the ratcheting process so muscle fiber shortening can commence.

Muscle contraction then continues as long as calcium and ATP remain available. And when calcium ions finally are expelled or sequestered, the ON proteins resume their original blocking shape - and that OFF position again prevents muscle fiber filaments from interacting. Actively shortened muscle fibers then regain length passively under the pull of opposing muscles.

## *Powered by ATP*

The rapid ATP-powered expulsion of calcium ions from intracellular fluids is a necessary talent for all cells. A number of different protein transport systems are able to eject calcium ions. This redundancy reflects the critical role played by phosphate ions in life's intracellular energy exchanges (as ATP, GTP and so forth).

For with intracellular phosphate levels kept consistently high, intracellular calcium levels must remain correspondingly low through constant out-pumping, in order to prevent calcium and phosphate ions from combining into insoluble intracellular mineral deposits. In other words, unrestricted calcium entry soon poisons a cell by damaging its power supply.

Since calcium expulsion is one of life's essential skills, brief low-level calcium incursions can serve as economical signals for specialized cell functions, while simultaneously keeping important calcium export mechanisms in good shape - just as mandatory fire drills can be combined with other useful activities (e.g., group exercises, an attendance check or a communication opportunity).

Ordinary extracellular fluids contain plenty of calcium. Nonetheless, your muscle fibers maintain additional calcium reserves in special intracellular compartments to speed their own contractions. Of course, predators and prey are equally adept at that old trick so nothing really changes - everyone simply runs a bit faster to stay alive.

## *Overview of the muscle contraction process*

When a motor nerve cell impulse releases signal molecules onto the muscle fibers controlled by that motor nerve cell, those signal molecules stimulate new electrical impulses that pass swiftly over the muscle fiber surfaces, allowing momentary calcium ion entry. As long as that intracellular calcium then remains available, muscle filaments will ratchet along each other to shorten their muscle fiber. That ratcheting process ends - and the muscle fiber again relaxes - when the calcium is expelled.

But when a muscle cell or muscle fiber runs out of ATP, the ratcheting process arrests in mid-stroke with adjacent filaments still locked together - for the ratchet power-stroke and calcium ion expulsion both require ATP. The early postmortem muscle rigidity known as rigor mortis indicates that mitochondrial ATP production ended when circulatory arrest terminated oxygen and nutrient deliveries.

# Chapter eight

# Mind and brain

All living things receive, replicate and release unique information. Each must sense and respond to predators, prey and reproductive opportunities. Every interaction presents risks and rewards. All decisions are final.

## *Life gets organized*

Early cells extracted energy and nutrients from the environment and released metabolic wastes. Other cells ignored those chemical changes or reacted in their own fashion. Natural selection graded each signal and response for timeliness, pertinence and impact. Reliable signals elicited more relevant responses.

Similar cells sometimes gained reproductive advantage by coordinating their feeding or replication. When small groups of related cells failed to separate, they inadvertently explored the costs and benefits of group living. More advanced multicellular units that regulated their own internal fluids, were able to coordinate member cells by an increasing variety of chemical interactions.

Specialized cells responded to relevant data. The first nerve cells hardly differed from their peers - a few extra ion channels made some more irritable - an unusually branched or elongated shape allowed others to sense and signal more effectively. And as these proto-nerve cells extended branches more widely, their brisk reactions came to dominate and coordinate each group's responses to its ever-changing environment.

With competition fierce, relentless, unending, there was no such thing as smart enough. Inevitably the number of nerve cells increased. Regularly they developed more effective interconnections that clarified which would sense, which command and which obey. But no matter how efficient an individual organism might become, there was always too much information. Many organisms gained reproductive advantage through cooperation.

***Conflict -> competition -> codependence -> cooperation -> caring***

Solar power - trapped in chemical bonds by photosynthetic bacteria or their chloroplast kin - ultimately supports all visible life on Earth. Other life forms help these photosynthesizers obtain important nutrients. Fungal and bacterial infestations of plant roots improve plant access to water, minerals and nitrogen. Detrivores release useful gases and minerals.

All cells partially break down glucose for their intracellular mitochondria, in exchange for high-energy phosphate molecules. Bats, birds, bees, butterflies and bears regularly redistribute plant pollen or seeds. Ants herd and protect aphids, tend underground fungus gardens or defend certain thorn trees from encroachment by insects and vegetation. The customary compensation for all essential services is sugar. So who is working for whom?

Well, ordinarily, we view the employer as boss. She who pays the piper calls the tune. But relationships among businesspersons, unions, politicians and bankers really are far more complex. And alliances only endure while they enhance the fortunes or reproductive success of all parties. So just as politics and politicians cannot be understood without tracking open and hidden flows of money, biological relationships reflect both obvious and inapparent transfers of solar energy trapped in glucose.

Many humans take pride in having ancestors who domesticated rice, beans, corn, wheat, oats, barley, squash, potatoes, sunflowers and so on. Yet some day soon, scientists expect to break the photosynthetic monopoly of special plant interests that have enslaved so many millions of humans for so many thousands of years.

In the meanwhile, farmers toil innumerable hours and take countless risks in order to plant, nurture and harvest crops and suppress competing species. And when yields are insufficient, humans have starved their own children rather than consume the seeds of next year's crop.

A close alliance with humans brought domesticated pigs, sheep, chickens and camels huge reproductive advantages over still-wild peers, predators and parasites. So is the hard-working shepherd in charge when he provides food, shelter and protection so his flock can enjoy a life of leisure? Or did sheep make the better bargain when they exchanged waste body hair, spare male descendents and the freedom to roam for reduced risk and ensured reproductive success? And where does the sheep dog fit in?

Other life forms ranging from garden slugs, coyotes and malaria organisms to rabbits, nettles, dandelions and deer - flourish through human activities without entering into such formal codependency arrangements. And humanity's expanding control over Earth's productive resources virtually guarantees the appearance of ever more effective and specialized predators, parasites, competitors and codependents - while those living things that cannot adapt to the human presence simply fade away.

## *Information growth drives socialization and specialization*

The irresistible growth of useful information drives socialization and specialization. Civilization is an inevitable response to chronic information overload. And the socially empowered (those who control resources with which to reward their allies) gain increasing advantage over the solitary - no matter how strong their armor, sharp their claws, rapid their reflexes, sturdy their skeletons, clever their responses or righteous their behavior.

The rise and fall of human cultures correlates crudely with how effectively each obtained, processed and responded to information. Recent human history demonstrates the progressive empowerment of societies that encourage universal education, free access to information, private property rights and similar actions that promote information utilization, creativity and wealth.

But regardless of how any family, tribe, society, profession or religion may be structured, fierce competition persists within and between all groups. You cannot long escape sibling rivalry, teenage rebellion or the urge to get ahead, even when out for a relaxing Sunday drive.

In humanity's ceaseless contests, greater intelligence often brought reproductive advantage. Yet despite the brilliance of its members, or how readily they accessed important information, sooner or later every human association was overwhelmed by the sheer volume of incoming data.

That is why all organizations remain selectively blind to important input, misguided by outdated processing routines and erratic in their responses. Furthermore, larger groups are increasingly unable to identify or deal with the next most threatening input without declaring a crisis - or even then.

Hence it is hardly surprising that your 100 billion nerve cells barely suffice to keep you out of serious trouble. You are lucky to get by, let alone deal optimally with any tiny sample of that uncontrollable information deluge. So you detect very little of what goes on around you, you ignore a lot of what you detect, you forget a great deal of what you don't ignore and you misinterpret much of the rest. And all too often, you wish you had responded differently.

Welcome to the real world, or at least to the insignificant bit of it that you attempt to display internally in your hormone-addled fashion. But you shouldn't feel too badly about such information processing limitations. After all, no one else really understands why the last rain dance didn't work, or why your team lost though you wore those lucky shorts, or why your head aches and aspirin won't help.

At least you usually know whether to fight or run, you generally can tell which food is rotten, and you probably will reproduce successfully if you devote a sufficient and timely effort to that project. Furthermore, you may be about as smart as an ordinary human will ever be.

For modern civilizations increasingly produce, convey, detect, display, decipher and respond to information in ways that bypass human information processing limitations altogether, or exceed our abilities to comprehend. So just as innumerable fossil-fueled mechanical devices undercut the reproductive advantage of brute strength, comparable advances in widely available intelligence-support machines - involving automation, computers, electronics, photonics, radar, satellites, etc. - now reduce the reproductive benefit of minor gains in human intelligence.

But even if the further slow expansion of individual human mental capacities now seems out of reach, we have not nearly achieved optimal use of the neurons we already possess. Bored elephants perk up when they get a chance to paint pictures. Monkeys work harder to satisfy their curiosity than for a treat. Yet school lessons and homework too often dictate to memory rather than tantalizing with ideas and soluble puzzles.

From a average child's point of view, an isolated lesson or fact that doesn't explain or relate to something of interest, is neither readily acquired nor easily applied. And it merely betrays and corrupts a child's interests and goals to force-feed irrelevant information because "You'll need to know this for the test". On the other hand, useful information of appropriate complexity will be sucked up by any healthy rested mind.

## *"Give me a child until he is five and I will give you a good Catholic" (Protestant, Muslim, Jew, whatever)*

No mind can approach its full adult potential unless freed from the pressures, constraints and self-limiting perspectives of fundamentalist religious authority. An "education" is wasted - indeed, harmful - if the maturing recipient cannot then use her own judgment to make independent decisions based upon available evidence.

It is especially difficult for a young mind just developing its language/logic facility to resist mentally destructive counter-factual information provided as part of a "good religious upbringing"- particularly when all participants claim to believe in and fear a hypothetical higher authority whose postulated existence is totally at odds with ordinary experience.

Confirmed scientific evidence has long contradicted every aspect of the Bible's Genesis story, even though this tale was presumably told directly to Moses by God. Yet each of our competing monotheistic religions still claims to be God's sole Earthly Rep. Furthermore, to attract and retain believers, each of these faiths also offers its own unique interpretation of God – who He is and what He wants. Since none among our conflicting religions can provide evidence of divine appointment that the others find convincing, most defend their own beliefs by labeling all others as "false" or even "evil."

Any logical adult would therefore likely accept the current consensus of all monotheistic religions regarding their competitors – that they cannot possibly be "true." As a result, to survive and prosper, religions must pre-load their self-serving myths into as many unprepared minds of defenseless children as possible.*
*see An Evolutionist Deconstructs Creationism by Arndt von Hippel

## *Information processing goes inorganic*

Your remote multicellular ancestors had so few neurons that adding more nerve cells could easily augment their overall processing capabilities. However, we may now be approaching a practical limit on the number of nerve cells per human individual. And it seems unlikely that adding a number of more generalized neurons to your current hundred billion can noticeably upgrade your performance.

Achieving more than such a minor increase within current design limitations (organization, support, circulation, cooling, birth constraints) also appears fraught with difficulties. After all, a newborn's brain already grows and develops for many years after birth. And the infant remains helpless - and the child completely dependent - for as long as most parents can endure and support.

Yet merely to reach the stage of brain development displayed by other primates at birth, you should have remained in mother's uterus for 21 months rather than nine - an obvious impossibility. So does this apparent limit on human brain-size and brain-development permit any useful predictions?

Well, first of all, don't expect ever more intelligent descendents to evolve who will solve every problem on Earth. Rather, assume that your descendents will cause many more problems than they could possibly solve or even recognize, just as you have.

Also keep in mind that life inevitably undermines that to which it adapts - for a) life is opportunistic as well as opportunity providing, and b) changing times present countless new opportunities and c) life flourishes at the edge between stability/instability while d) complete stability is equivalent to stagnation and soon, death.

But on the other hand, the irreversible integration of humans with their increasingly effective inorganic thinking machines has just begun. So while the long-term social implications of these self-organizing competition-driven technological developments remain unclear, humanity's information handling possibilities no longer face any obvious limits.

Yet regardless of how much and how swiftly civilizations may change, the same old biological wants and needs will continue to drive humanity across this immensely rich, increasingly abstract wilderness, so we need to understand ourselves as well as possible.

## *Useful information spreads and enhances wealth while reducing disorder (take that, Second Law!)*

Recent advances suggest that inherently formless and increasingly uncontrollable flows of electronic information will finally make it possible for all humans to share in the Commonwealth of Information. Here "Commonwealth" takes on a special meaning, for information is a form of wealth that spreads, grows and cannot be used up.

Indeed, the more widely and rapidly information is disseminated (as in sowing seed), the more wealth and useful new information it will generate as it reaches those best positioned to benefit. So in contrast to the limited biological carrying capacity of our biosphere, there is no apparent limit on the information carrying capacity of this new and separate reality

## *What can we learn from sensory deprivation?*

Each of us views a particular television program, pickup truck, graduation ceremony or meatloaf quite differently. Furthermore, the varied, biased and unstable internal reality displays within one peer group differ drastically from otherwise-skewed internal displays of those who are older, younger or from other lands. Every mind bears an uniquely biased lifetime collection of inaccurate renditions of unique interactions, relationships and experiences that contribute variously and often inconsistently to its interpretations of subsequent occurrences.

Yet while each of us creates and responds to a relatively unique, subjective and defective internal representation of the outside world, this flawed process still represents a great evolutionary advance. For it allows humans and other higher animals to experiment internally with attacks, deceptions (that bird dragging its "broken" wing to lure you away from its nest) and other stratagems until a more appropriate/less dangerous response can be devised to what seems to be going on. Clearly this dynamic, ongoing process needs uninterrupted input in order to confirm and coordinate the endless balancing act between past and future, real and unreal.

However, you can voluntarily enter a state of minimal sensory input in the awake state by floating totally relaxed in a dense salt solution at body temperature within a dark sound-proof box. At such times your mind (whatever that is) tends to lose its steady interpretive control over your ordinary stream of consciousness (flow of ideas and perceptions) so you will probably hallucinate.

Presumably such an intentional reversal of the normal signal-to-noise ratio leads to defective sampling of apparent sensory inputs and inappropriate pattern recognition, as random or low-level nerve cell discharges are no longer drowned out by the usual overwhelming sensory inflow. The mind is therefore left treating accidentally generated internal noise as a signal, trying to piece together the most plausible current reality from random and irrelevant inputs.

An occasional near-death experience or startlingly real "vision" encountered during an illness or other abnormal mental state - perhaps while fasting or in relation to epileptic seizures - could reflect comparable alterations of nerve cell function. Indeed, stressful low-oxygen or low-glucose states and abnormal nerve cell discharge patterns have generated innumerable religious experiences, as well as convincing illusions of aliens or ghosts. Extreme fatigue and many chemicals similarly alter sensory inputs and perceptions to the point of hallucination.

## *How about anesthesia?*

This term refers to an induced state of "not feeling", usually associated with a relatively complete interruption of processing, conscious memory and voluntary responses. Many people apparently enjoy entering such a state, or at least its early stages, judging from the number of potent anesthetic agents (nervous system blockers, stimulants or depressants) that are currently abused (e.g. nitrous oxide, ether, heroin, alcohol, marijuana, nicotine, cocaine and various solvents).

Sometimes, as too often seen with alcohol, illicit drugs and solvents, toxic or anoxic side-effects such as death occur soon after or even before full anesthetic levels are reached. The composition and impacts of abused drugs are especially unpredictable, but even standardized medicines may affect different brain areas in variable, conflicting and not always reproducible ways.

## *Mind and brain*

The real functional you depends totally upon your current input, processing and output - any of which could easily be disrupted. Perhaps a useful definition of mind should specify intact sensory and motor systems as well as brain, for changes anywhere along the line can significantly alter behavior. It is true that some extraordinary individuals are able to rise above (function effectively despite) severe disabilities, but it is also apparent that injuries which seriously alter input, processing or output do change a person.

Those who write about afterlife experiences or total brain transplants might keep such limitations in mind when discussing the out-of-body transferability of an intact persona - regardless of whether they devoutly hope to ensure endless torment for others and eternal rewards for themselves (promoting the former might seem to make one ineligible for the latter) or merely wish to maintain the unchanged and reliable function of an old brain in a new body (or bucket of sterile salt solution).

Furthermore, consciousness and the readiness to respond are apparently inseparable. For the uniqueness of your being cannot derive from ordinary, hence widely shared, sensory inputs and common perceptions. Rather the real you is defined by your individualized output or behavior.

Your entire body is surfaced and permeated by exquisitely sensitive, continuously interacting sensors tuned to important electromagnetic frequencies (heat, light), mechanical stimuli (sound and other vibrations, pressure, movement, position, muscle and tendon tension) and specific molecules (taste, smell, pain and all manner of other specialized chemoreceptors and immunoreceptors). Most of these sensors respond to specific signals by changing the electrical polarization of their cell membranes.

All information about the outside world reaches your brain via twelve paired cranial nerves or through your spinal cord. Incoming nerve cell depolarizations are then displayed internally in a very specific and complex manner for your ongoing amusement, interpretation and response.

## *Your internal display is subjective and defective*

So is my internal display of your internal display, but both seem truly amazing - at least that is how each of us appears to interpret our own subjective internal displays. Your internal display also undoubtedly differs considerably from that of others. In the first place, what was noticed and not noticed and incorrectly noticed will depend upon the condition of your sensors, your overall state of awareness and your preconceptions - all of which vary over time. How you process that input for display and then interpret that display are subject to further great variation.

Not surprisingly, what you do about all of your input is even more variable. A bit of this variability can be seen in the differing descriptions provided by each of several witnesses to a crime, or in disagreements between jurors at any trial, or in the divergent ways that various individuals describe the same town, building, acquaintance or fruitcake. And even your simplest observations are influenced by context and subjective introductory terms such as large, small, sweet, cute, fast, ugly, risky, good, right, bad, threatening, bright, dumb, rich, cuddly and so on.

As yet, comparatively little is known about how your nerve cells integrate their discharges to bring about that appearance of evaluating and reacting to input referred to as behavior. And at a time when no one really knows whether your skull encloses 50 or 100 billion nerve cells, it is hardly surprising that we also cannot provide detailed descriptions of the countless ways those neurons interact.

Nonetheless, we can categorize your nerve cells as sensory (input) neurons, interneurons (processing) and motor (output) neurons. Furthermore, we know that interneurons make up the vast majority of nerve cells in your brain and spinal cord, and that activity-dependent alterations in the impact of interneuronal connections are basic to the development of your neural networks, memory and learning.

An average interneuron interacts directly with perhaps ten thousand others. Some connections are incoming, often to tiny nerve cell extensions. Some are outgoing, often from tiny branches of larger nerve cell extensions. Certain nerve cells tend to discharge hundreds of times per second - others might depolarize just once in that time. But all nerve cell discharges either stimulate or inhibit their target cells. Thus a single interneuron can affect the output of many thousand others in an additive or subtractive, organized and exceedingly complex fashion.

Apparently your behavior arises from a basic inherited pattern of neuronal distribution and interconnection that has been modified endlessly in response to random organizational events and individual life experiences. Your inheritance is unique. So are your experiences. And so is your behavior - within limitations set by those ancestral factors and chance events. That does not mean your behavior is necessarily unpredictable, however, or that it cannot be modified.

Your behavior is unique, just as a fingerprint or artist’s sketch is unique, but each is an ordinary output based upon certain rules and tools. Even repeated sketches on the same subject will be different every time, based upon experience, skill, time constraints and variable inputs such as lighting, materials, movements and moods. On the other hand, your fingerprints can only be altered by damage. Their hard-wired design differs from the fingerprint designs of your friends, but those differences mostly involve minor details.

Humans are very similar in their behavioral limits and responses as well. To a considerable degree, each of us shares not only the potential for a great many skills and abilities but also the potential for criminal or destructive behavior. Nature (your DNA), nurture (your life experience) and chance interact endlessly to determine the course of your life.

Within those limits, your ordinary behavior is based upon upon normal sensory input, normal processing and normal motor functions. Of course, the processing part may accompany or even follow a behavior or output, especially in the case of certain involuntary reflexes where sensory input directly activates motor output while also sending signals centrally for processing.

Thus your eye blinks at an approaching insect or baby's finger before you can even consider swatting the fly or praising baby's obvious intelligence and curiosity. Similarly, you swiftly withdraw your hand from a hot stove prior to any review of the potential for tissue damage by directly conducted electromagnetic energy in the infra-red wave band.

## *An evolutionary explanation for human consciousness*

Human consciousness is hard to define, but we know it when we experience it. Conscious verbal self-awareness seems uniquely vested in humans. Indeed, it is the defining characteristic of our species. Yet those who study prehuman or ancient human cultural artifacts - tools, weapons, shelters, clothing, cave paintings, burial sites and so on - generally agree that human consciousness only became manifest "relatively recently", in close association with the fluent speech and technological advances that allowed humans to organize large groups, develop specialized functions and take over the Earth.

Your remote mammalian ancestors survived by responding quickly and more or less appropriately to a variety of environmental and social challenges or opportunities. Their intelligent behavior was well-entrenched long before humans or consciousness arrived on the scene. But somehow the blossoming of conscious verbal self-awareness brought humans an unbeatable advantage over other intelligent creatures. So what do we know about human consciousness?

Well, repeated measurements regularly confirm that the conscious decision to undertake a "voluntary" movement arises one-third of a second after the complex neuronal interactions for initiating that movement first get under way. This seemingly reversed sequence - whereby conscious intent (the apparent cause) follows initiation of action (the apparent effect) - strongly suggests that conscious decisions merely rationalize, but do not instigate or control, your ordinary activities.

The amusingly inaccurate post hoc explanations of their own urgent behaviors - provided without hesitation in all seriousness by individuals as they carry out subliminal or hypnotic suggestions - bear a similar message. And because such a wide range of upstanding citizens unblushingly resort to these obvious prevarications, it must be very important - in other words, reproductively advantageous - to routinely assume or pretend that your rational inner entity or conscious mind is in charge of what you do, though this clearly is untrue. So how did such a muddle come about, and why would it persist?

Early animal brains evolved out of small neuronal collections dedicated to various inputs and outputs. Only the most competitive of these nerve cell clumps grew and interacted well enough so their owners survived to reproduce. But by several hundred million years ago, the basic connections between neuronal modules that permitted primitive brains to learn and make prompt, appropriate decisions in response to an expanding array of inputs, were fully in place, working well and no longer amenable to major revision .

However, it would have been fatally disruptive to radically revise those long-established inter-modular communication pathways, even in order to optimally integrate the increasingly dominant human language function as it developed. For only the most advantageous incremental improvements - or immediately profitable recombinations of independent well-established organizations - reappear in subsequent generations.

In other words, those who became our ancestors had no way to seamlessly meld their usual rapid and more or less appropriate responses, with those revolutionary new language functions, so they didn't. Hence your critically important language facilities remain awkwardly balanced upon the well-integrated functions of earlier module networks - which still allows human behavior to function effectively at several levels.

For example, wordless mimicry remains a highly effective mode of instruction for many advanced skills - from flint knapping and shelter construction to fire-making and bicycling - and verbal fluency clearly underlies the invention and spread of complex conceptual advances such as Atomic Theory, General Relativity or Evolution Theory.

Perhaps long-time, well-entrenched human groups such as the large-brained and physically imposing Neandertals finally faded away simply because their verbal skills never reached fully competitive levels. But where did that silent majority of those with less advanced verbal skills go wrong? Why should the most stable and secure be the ones displaced?

As the most successful, hence conservative, humans of their day, the Neandertals presumably felt the least pressure to enhance whatever language skills they possessed - before their stable environment finally started changing too rapidly, and their population numbers fell too far for further adaptations to evolve and become widespread.

In contrast, your immigrant ancestors already were struggling to survive, adapt, economize, communicate and organize more effectively. Hence their undoubtedly high birth and mortality rates selectively and persistently pushed them to gain greater verbal skills that always again had to be integrated with the smoothly functioning, preexisting brain structure.

So as your ancestors competitively extended the revolutionary capabilities of their new linguistic talents, those powerful new verbal skills interacted variously with previously perfected and jointly independent brain routines. Similar problems might face mechanics who randomly began imposing a variety of increasingly intrusive electronic probes and controls upon countless smoothly running, self-sustaining old jalopies. One presumes that the few vehicles flourishing after such revolutionary modifications would provide a useful beginning point for further modifications of the next generation.

One way or another, the internal stresses created in your surviving ancestors by their developing language facility, finally gave rise to the emergent outcome we now refer to as human consciousness. Of course, your ancestors would never have endured the advent of verbal consciousness and self-awareness if that additional administrative layer of verbal oversight had even slightly delayed critically important immediate responses while each problem was carefully evaluated and the best course plotted.

So like good administrators everywhere, your consciousness simply tries to identify relevant information, cope with the big picture and take credit for any positive outcomes, assuming all the while that the preexisting modular organization - although mostly ignored - would continue to utilize previously proven diagnostic rules and stereotypical responses to deal effectively with the here-and-now.

Presumably, the actual sensation of internal verbal oversight that we refer to as human conscious self-awareness arises from the uncomfortable interface between those two dissimilar agencies that a) developed independently and b) remain separately organized although c) they interact continuously and d) frequently work at cross purposes - as in “Do as I say, not as I do” or “I am not being emotional!” or “You can’t tell me what to do! (after all, I can’t even tell myself what to do.”).

So the consistent pretense by your language modules that they are in charge of routine decision-making seems to be an unavoidable side-effect of the superposition of intrusive, often abusively insightful language modules upon a smoothly functioning underlying organization. And the fate of that internally discordant amalgamation is ultimately measured by its ability to keep you in the race to reproduce.

Overall, the evolutionarily favored neuronal reorganization always limited intelligent oversight of important activities to avoid delayed responses or the need for a costly expansion of the brain.

So when we practice regularly, we are trying to outgrow the need for detailed real-time verbal oversight of our many routinely required athletic or professional skills - shooting baskets, driving an automobile or preparing sushi - since common experience suggests that with enough practice you can successfully delegate the responsibility for such new skills to your ancient pre-verbal centers - thereby gaining the improved performance that comes as skills are increasingly automated.

Language began as a new way to identify and deal with life's important externalities. Once it proved successful, it was extended to provide internal oversight or verbal self-awareness as our progressively more social ancestors found that complex internally cooperative behaviors brought the group additional advantages over comparable groups or wild, basically non-verbal beasts.

The analytical advantages of internal verbal oversight made consciousness an increasingly important aspect of intelligence as humans began to verbally dissect and develop motives, behaviors, concepts and programs. Yet there are times when your basic reproductive interests are better served by temporary cessation of close verbal oversight - for example, when confronted by a "stunning" reproductive opportunity.

Under such circumstances, your more primitive modules may temporarily realign your priorities while your verbal consciousness fades - leaving you to deal with the current physical emergency non-verbally. Thus there may be truth in apparently lame excuses such as "I really don't know how it happened!"

Ordinarily, however, the human verbal self-awareness that permits you to painfully dredge through, identify and revise your own internal assumptions, inconsistencies, experiences and confusions - also helps you to gain and sustain the functionally important moral pretense that you are another consciously responsible, rational human being.

However, the complex prejudices, beliefs and behaviors acquired over a lifetime continue to guide the subconscious or automatic interactions of ancient modules that sustain your being, emotions and behavior. And these often-limiting or misguided stereotypical responses rest upon many misinterpreted or long-ago-and-now-irrelevant experiences that are basically inaccessible and therefore exempt from rational modification unless they can laboriously be dredged up, verbalized and understood.

In other words, rewarding insights and increased efficiencies may be expected as humans verbally monitor and try to explain their own behavior. And careful repetitive verbalization appears to underlie the successful insights and explanations of psychotherapy. Nonetheless, you may still be wrong, even when sure you are right.

We all have experienced the embarrassment of having an initially confident verbal explanation to an attentive audience suddenly falter as previously unrecognized gaps in our understanding became glaringly obvious. More generally, you can never know which of your ideas or behaviors really make sense until you have tried to explain them clearly and logically.

Many humans experience life as “One damn thing after another.” And those whose basic needs for physical sustenance and love are unmet, often have insufficient time or inclination for developing a verbal conscious self-awareness that advances much beyond “shit happens”. But thereby they also miss out on many personally meaningful rewards, as hinted at by the startling claim that “an unexamined life is not worth living.”

In any case, great rewards - more insight, better relationships, increased productivity of a higher quality product - await many of those who work to achieve increased awareness and control over the stereotyped responses and emotions that were the characteristic responsibilities of their lower brain centers long before verbal oversight was added. Perhaps my awkward explanation of your awkward mental organization again illustrates why true insight is so laboriously achieved and never fully realized.

Summary: An ongoing process of verbal self-description that is functionally separate from your automated subconscious self is what underlies the phenomenon known as human consciousness. This process permits internal verbal oversight of your own activities on a nearly real-time basis. And the descriptive distance thereby established permits you to monitor or modify your own activities in a more coherent, effective, adaptive fashion - which allows you to lead a more rational, enjoyable and meaningful life.

## *Your behavior is often weird*

Mental states may greatly affect perceptions. Depressed and angry individuals, and those who have been abused, tend to misinterpret and respond furiously or fearfully to challenges or perceived threats that others might be willing to ignore or discuss. Males with higher testosterone levels often exhibit more aggressive behavior, and the intake of alcohol or other mind-altering drugs is frequently associated with poor judgment and violent behavior.

In any case, your sensory input is broken down and distributed to various sites within the brain for analysis in many different ways. This distributed information is then coordinated in some fashion between those separate sites so that you can consider what is occurring and where. Concurrently, you also reconstruct and maintain relevant pre-existing memories (including an entire medley of your own past responses) so that you can deal more or less rationally with the reality currently on display.

Interestingly, no single nerve cell or group of cells is in charge of integrating such group/school/herd/flock sorts of neuronal interactions - nor could one be, given the endless combinations of neurons that represent your unlimited experiences, thoughts and responses. While a great deal of input is routinely deleted at every level of integration, much of that passing information stream can still be sampled at the time if attention is directed to it - what your right index finger is feeling just now, for example. This sort of hierarchical organization makes it possible for small modules of nerve cells in your brain to collate and respond more or less sensibly to enormous flows of information from huge numbers of sensory nerve cells.

## *And even ambivalent*

The two largest parts of your brain are the right and left cerebral hemispheres. If you are right-handed, it is usual for the left cerebral hemisphere to dominate. That left hemisphere apparently interprets the world more or less by sequential processing, while the right seems rather a parallel-processing "Big picture, forget the details" side. Fortunately your left hemisphere dominates your language functions, vocabulary, speech and manual control, leaving the right to rule over spatial reasoning, face recognition and perception of emotions (tone of voice, gestures and attitudes).

The right hemisphere also dominates your left facial expressions of emotions, although the left will often cut in if the right brain is surprised and your face too truthfully expresses distaste for someone or something (that brief, especially left-sided flicker of distaste before the hearty greeting). Having the left side of the face dominant in expressing emotions leads some individuals (such as the first President Bush) to unbalanced emotional expressions that suggest the right hemisphere feels one way while the left thinks and says the opposite (a subconscious public recognition of this lack of commitment or insincerity might explain his wide but shallow electoral support, with many preferring the message but not the man).

During such times of internal conflict, your speechless right brain may still express its subconscious mind through the musical talent department, if your left brain is willing to listen. Say you suddenly encounter your boss who is not really such a fine person, although perhaps a legend in her or his own mind. You decide it would be reproductively advantageous to smile and say "Hello" and pretend to be very busy and enjoying your work. So far you have been successfully guided and controlled by your analytical left brain.

But for a second opinion from the right brain, you might identify the catchy tune you started to hum as boss and retinue marched off. That absent-minded melody could otherwise play on unnoticed until suddenly you found yourself mouthing a relevant verse such as, "You can take this job and shove it!" Apparently, speaking your right mind would be risky, so the right is properly speechless, which helps you to act and speak decisively as if of one mind.

However, the ongoing urge to sing your otherwise silent and often frustrated right mind might explain the public frenzy and huge incomes achieved by minimal musical talents who happen to tap into (speak to or for) your right brain. Perhaps the supreme relief that follows really successful communication represents the mute right brain saying "Well, it's about time that was said!"

Maybe listening to music while studying simply distracts the right brain so your left brain can learn more effectively. Some of the rare individuals born with only one cerebral hemisphere seem quite normal, but one might expect them to be unusually decisive - just as Harry Truman once told his staff to find him a one-armed economist - someone who wouldn't end every consultation with "Of course, on the other hand…"

Such speculation aside, your two large cerebral hemispheres are interconnected by great bundles of nerve cell extensions that keep them in close touch. And your complex human behavior is finally determined in this highest part of your brain - the so-called neocortex.

Ultimately it is the incomparable information processing powers of those two cerebral hemispheres that ensures your access to the solar energy stored within other life forms rather than vice versa. For humanity's future no longer depends upon your ability to run, jump or hit - important as those skills may seem. Rather, civilization relies upon your ability to utilize ever larger quantities of new or newly relevant information.

# Chapter nine

# Your Nervous System

Brain size increases with nerve cell count. Brain processing capacity depends upon the total number of neuronal interconnections. Opportunities for useful interconnections rise far more rapidly than nerve cell count, so larger vertebrate species get by with proportionately smaller brains.

## *Complex interconnections permit great thoughts*

Your tiny nervous system originated as a midline infolding of your embryo's posterior surface. Those first pioneer nerve cells had little chance to get lost as they moved or grew along underlying surfaces and followed faint chemical trails - abilities that they inherited from their unicellular ancestors. Many neurons elongated as your nervous system grew, and then provided signals and pathways for other nerve cells to follow.

Early neurons organized and oriented themselves through contacts with specific cell surface molecules. Their travels were guided by attractive or repulsive gradients of particular cell products as well as by more widely diffused organizer and growth factors. Each type of nerve cell was strictly limited in location and number. Sometimes several cell divisions used up essential intracellular instructions. In other cases, repeated replications affected vital genes.

Enlarging neurons sent out thousands of exploratory branches and twigs in all directions - many times more than would ultimately endure. Regional and local chemical gradients guided nerve cell branches to suitable targets. A single muscle fiber might initially receive extensions from several motor neurons. Appropriate muscle responses were worked out during random intrauterine movements. Any motor nerve cell that simultaneously activated several adjacent muscle fibers thereby strengthened its control over those fibers, while underutilized connections from competing neurons faded away.

Cerebral nerve cells traveling outward from their sites of origin, formed distinct columns as well as layers reminiscent of their surface cell origins. In the brain, however, the newest cerebral neurons had to migrate past previously positioned nerve cells to reach their outer-brain-cortex position. En route, each gave rise to and intercepted thousands of potential interconnections, many of which were then dragged along to produce an uniquely individualized, preliminary version of your incredibly complex cerebral wiring diagram.

Your cerebral neurons grew and became functional within electrically interconnected processing units of a few dozen neurons. There they blindly activated ancient instructions and sorted out new relationships through repeated group depolarizations. Gradually each neuron became dedicated to its own regularly required, locally coordinated, chemically appropriate connections and duties as it cooperatively developed important parallel contacts with a great many neurons outside of the local module. Enormous numbers of inappropriate connections disappeared in response to disuse, competition or suppression.

## *A single neuron can process a great many inputs and participate in an endless variety of responses*

A cerebral nerve cell (and its branches) attracts thousands of chemically directed connections from neurons throughout the body. One nerve cell may respond in various ways to dozens of different neurotransmitters and utilize a variety of its own chemicals for signaling as well. Furthermore, individual nerve cell branches can play distinctly different roles in many different circuits. Thus the extraneous daydreams or irrelevant scenes that occasionally flash through your mind may represent accidental activations of mental images previously stored on an overlapping neuronal circuit.

Neurotransmitters vary widely in mode and duration of action. Their repetitive impacts and cumulative interactions routinely enhance or inhibit countless different possibilities in different ways at different sites. The activity of each nerve cell is further modulated by millions of specific membrane receptors and ion channels. Consequently, most nerve cell interactions are far more complex than the better-known nerve-cell-tells-muscle-fiber-to-jump type of depolarization about which we still have much to learn.

Neurochemicals and their receptors often have entirely different duties in non-nerve cells located elsewhere about your body. That is properly frugal. After all, there is no need to design a new doorbell mechanism for every home, store or office. Nor does one expect the same response when ringing up a flower shop as a prison. Many mechanisms exist by which certain receptors can affect a variety of ion channels - some act directly while others employ secondary messengers of appropriate strength and duration to move the message along.

By exploiting the most suitable of those endlessly varying combinations to inform, contemplate and coordinate their naturally selected responses, your ancestors managed to attack, outsmart and endure until they could forward their DNA to you. Hence you have inherited a great many signal and receptor mechanisms. And a lot of those are modified in various ways at different locations to produce different impacts or play different roles.

Of course, we still do not understand all of the experimental evidence relevant to single nerve cells. And there is little doubt that we lack the brainpower to envision every possible interaction of your 100 billion intracranial cells, let alone figure out much of what is occurring in the world outside. Furthermore, life's trials and tribulations have a way of changing a person. Every day leaves its mark.

In fact, your brain has been altered by reading this chapter. For you create or modify relevant neuronal interconnections in order to evaluate and record life's incoming flood of new information. And it is reproductively advantageous that certain of your neurons alter their sensitivity to different signals during different phases of your development, while certain neuronal interconnections become more dominant and durable as you grow older.

Some lessons and skills are more easily acquired at certain ages. Old dogs often resist learning new tricks. Experience suggests that a one year old child cannot usefully be toilet trained while three-year olds toilet train themselves. It also appears that language sounds and then meanings are easier to grasp at some ages than others. But as long as those neuronal interconnections remain capable of change, you can continue to acquire new information and skills. So keep reading.

A nerve cell may last a lifetime if it continues to receive and transmit many messages, but it eventually kills itself if ignored. Your ongoing loss of unnecessary interconnections and useless neurons may explain the increasingly focused, often narrow-minded behavior that you display as you continue to improve your skills and acquire new information.

Naturally, your options also decrease with each trimming of redundant or neglected circuits. However, your regularly called upon interests and skills - and the designated processors (neuronal modules) that underlie many of your inherited abilities - are functionally enhanced by connectional adjustments associated with each use.

Individual brain cells that are ignored or depleted can be disposed of with little fuss. As is true elsewhere in your body, this orderly process depends upon the doomed cell activating additional genes and quietly destroying itself in a way that minimizes inconvenience to its neighbors. In contrast, when healthy neurons are severely damaged, their entire store of neuro-active signal molecules may leak out. The excessive local stimulation that results can injure or destroy nearby neurons tuned to those specific excitatory molecular signals, and those secondarily damaged neurons may adversely affect still others.

The repeated minor blood vessel and nerve cell injuries suffered by professional boxers are often enhanced by the area-wide or mass depolarizations associated with each concussion (knock-out). Many boxers eventually develop dementia pugilistica - a condition somewhat resembling Alzheimer's Disease - with shrunken brain tissues showing extensive damage. But while low-income boxers legally exchange brain cells for bucks, any sale of their other body parts would likely be considered an ethically dubious proposition.

## *Fatigue and sleep*

No biological mechanism can operate continuously. All living systems tire and wear out unless regularly rested, restored and repaired. Even your most uninterruptible functions like nerve cell depolarization, heart muscle contraction and breathing, rely upon intermittent activations separated by intervals that allow rest and recovery.

As yet, fatigue is not fully understood. Acute muscle fatigue probably reflects many factors including ATP depletion, the local exhaustion of oxygen and essential nutrients, adverse ion shifts, a temporary accumulation of waste products and possibly, structural fatigue. Muscles regularly tire and malfunction when exercised beyond their circulatory and other limits, but physical rest ordinarily allows full recovery - often with an appropriate enhancement of function.

All higher animals require mental rest or sleep. Even fruit flies nap. Your concentrated mental efforts become decreasingly productive as heavily used nerve cell modules tire and tune out, even though other parts of the brain remain available for useful work. Thus a student who has studied one subject to the point of exhaustion may still find enough energy to pursue some other interest, go running or take in a movie.

You probably don't view nightmares as restful. However, sleeping and dreaming serve numerous important functions. And a nap or good night's sleep often allows you to integrate recently acquired information and return to the task with capacity renewed.

Indeed, "Let's sleep on it" is the traditional indirect pathway to a better solution for some difficult problem. And ordinary experience confirms that complex tasks are more easily completed when their careful consideration is followed by repeated mental rehearsal until the sequence flows flawlessly - and then a good night's rest.

The daily sleep requirement is just one of many reproductively advantageous cyclical changes that together define life's circadian (about-one-day) rhythm. This rhythm is everywhere evident because it synchronizes life's activities - and the down-time needed for important maintenance and restorative functions - with Earth's daily rotation . By coordinating the daily ebb and flow of your body cycles and functions with the natural day/night rhythm, you save energy, minimize stress and rebuild cellular reserves on the most convenient and economical schedule.

Hence regardless of its original purpose, sleep now allows you to run through items of recent interest or emotional impact for collation and disposal. In similar fashion, bears, wolves and dogs have converted their need to urinate into an elaborate message system that includes information on identity, size, diet, sexual condition, time of discharge, territorial claims and much else.

Your vivid and disconnected night-time dreams may represent momentary extrapolations of images that flash by as you examine and clear your circuits with the recording function turned off. Dreams may also help you to collate the new and refresh the old memories that might otherwise fade through disuse of their neuronal connections. And some dreams - e.g. those examination dreams where "totally unprepared you" never even finds the classroom until test papers are about to be collected - may let you shield but still ruminate about your possible inadequacies.

Sleep interrupts a train of thought, thereby reducing the risk of obsession and perseveration in particular circuits - just as a computer or VCR avoids holding one display long enough to permanently mark the screen. Furthermore, sleep disorients, thereby forcing you to reorient yourself regularly amidst surroundings that might otherwise be increasingly misperceived as they are more and more taken for granted.

And sleep permits the general testing and revitalization of circuits at a time when these can safely be disconnected from most motor functions by the blockade of specific intervening neurons. That disconnect may be defective in sleep-walkers.

In contrast, narcolepsy is a sleep disturbance associated with unanticipated daytime attacks of sleepiness, sometimes with other symptoms such as cataplexy - a sudden loss of motor tone associated with excitement or emotion - which may possibly reflect inappropriate activation or inadequate suppression of the inhibitory interneurons that keep you from injuring yourself or others during your nightmares.

Sleep provides a quiet time for routine drills that maintain the integrity of critically important but less-utilized neuronal connections and body-wide reflexes. Your potentially life-saving fight-or-flight responses - and your inherent life-giving reproductive functions - are therefore checked and rechecked during several periods of rapid eye movement (REM) sleep each night. Indeed, those penile and clitoral erections must be run far more regularly than fire drills to ensure that your circuits and tissues are ready, willing and able when an urgent reproductive opportunity arises.

Active REM-like sleep occupies about eight hours per day of an infant's much longer sleep time. Apparently the developing infant brain needs a great deal more circuit testing and electrical stimulation than the well-established circuitry of an adult brain. Whales and dolphins sleep one cerebral hemisphere at a time to reduce risk of drowning.

## *Overview of your nervous system*

Your delicate, symmetrical, 1.5 liter brain and its spinal cord extension are weightlessly submerged in nourishing cerebrospinal fluid - then stabilized and supported within three concentric fluid-filled membranous wrappings of increasing strength. In addition, your brain is firmly crated inside the skull while your spinal cord is insulated by overlying fatty tissues and sheltered beneath bony vertebral arches.

From that warm, dark, quiet, least-disturbed location of your entire body, your central nervous system sends out the symmetrically paired bundles of neuronal extensions known as nerves. You may be most familiar with the ulnar nerve as it passes behind the inner aspect of your elbow, for bumping that "funny bone" sends quite a jolt down the ulna bone side of your forearm and hand into your little finger.

Individual nerves enclose multiple nerve cell extensions headed in roughly the same direction. Those nerve cell axons or fibers often separate from one nerve bundle to join another as they connect your central nervous system with a target tissue. The apparently haphazard ways that various body structures draw their nerve and blood supplies from high and low often indicate where these structures were initially located or how they were reorganized during your embryonic and fetal days - or they may hint at the level from which comparable tissues originated in your remote ancestors.

## *Physics has Laws - Biology has Exceptions*

The immutable laws of physics and chemistry were established at the time of the Big Bang. Those laws cannot change. Once understood, they allow reliable deductions and predictions to be made about many past and future events or conditions. In marked contrast, human anatomy and physiology usually cannot be described by any rule less complex than the number of structures and processes (elements and interconnections) being described.

In other words, life has little algorithmic compressibility since each human structure and function could as easily have come about by countless other, often more practical routes, at least from a designer's perspective. But, of course, there was no designer. Biological unpredictability is an inevitable consequence of life's endless modifications and revisions over billions of years

- especially as the only justification each successive change order ever needed was that it brought reproductive advantage at the time.

The otherwise incomprehensible layout of plumbing and electrical circuits in frequently remodeled business or professional buildings reflects similar historical contingencies. As a result, it is usually simpler to memorize human anatomy and physiology than figure it out - for the particular way things evolved under long-forgotten circumstance leaves biology with few hard-and-fast rules and many exceptions.

So we are not surprised that your important phrenic nerves consist of nerve branches from your neck, or that they descend through the chest alongside the heart to innervate their respective halves of the flat diaphragm muscle. Or that the diaphragm muscle separating your heart and lungs from your abdominal viscera, also migrated downward from your neck region during embryonic life.

## *Most nerve cells depend upon many support cells*

Every computer designer lusts for the improved performance that can be achieved by successfully packaging more processing units onto a smaller chip. For similar reasons, the extreme close-packing of your neurons enhances the efficiency of your brain. However, such a concentration of nerve cells would be impossible if your brain and spinal cord were to swell and shrink with your state of hydration, as other tissues do.

Therefore, a very important task of your many neuron-support cells is to regulate the movement of fluid and dissolved substances to and from the central nervous system. This functional separation of your brain cells from your circulation also allows brain neurons to utilize preexisting cell signals and receptors in a variety of new ways.

In fact, many dozen ordinary ions and molecules have critical signaling duties in the brain. The majority of those molecules - simple amino acids, modified amino acids and short sequences of amino acids - are common components of other life forms upon which you prey. Consequently, those neuron-support cells keep your thoughts from being scrambled by the eggs that you eat, or by the hormones with which you regulate your gall bladder and pancreas.

## *From thoughtless embryo to thoughtful human adult*

Your brain selectively acquires, stores, integrates and responds to information. That is all it does. That is all it can do. Furthermore, the advanced language-based cognitive activities of your brain are what define you as a living human.

Remarkable as they are, each of the innumerable eggs and sperm scattered about by adult humans includes only one half of the information needed to produce a human. Incapable of living on their own, sperm and eggs are therefore the moral equivalent of an ineffective virus.

In contrast, the several hundred pounds of hair and surface cells you eventually shed into the environment include countless complete versions of your invaluable human information. Yet those cast-off cells simply become house dust and insect bait.

Nonetheless, the unique combination of information created when mother's egg combined with father's sperm was critically important to the success of your embryo as it developed and grew in strict accordance with the ancient DNA program of all animals. And even when electrical activity began to flicker and then pulse through your fetal neurons - helping them to grow, develop and organize - you still followed those instructions mindlessly.

Although it included only generic content at birth, your mind soon began acquiring information from that new and ever-challenging outside environment - and you have been submerged in a flood of information ever since. As an infant, your limited circuits dealt mainly with immediate needs. Slowly you learned to interact, to listen for meaning as well as sound sequences and rhythms, and to express yourself - trying always to help others serve you more efficiently.

So you experimented, investigated, cooperated, defied and tested. Gradually you acquired skills. Progressively you sought to impose your will. Inevitably you were socialized. Eventually you defied traditional authority, declared your independence and entered relationships outside of the family - only to fall prey once again to your inherited instructions and their hormone enforcers.

As a result, you now feel controlled by your spouse and children (not to mention aging relatives, bankers, coworkers, credit card companies, customers, employers, HMO's, lawyers, politicians, repair persons, supervisors, suppliers, tax people, teachers, utilities and undertakers) when all you really want to do is play golf, go fishing, or take a weekend off.

So rather than finally becoming ruler of all you survey, you now compete madly just to stay even - and that is probably the best possible outcome for both you and the world you intended to redesign, since radical redesigns rarely improve upon what has evolved over time in a more or less free and competitive fashion.

Just as human anatomy could be much simpler, so could human social systems. Neither was meant to be this way, they just happened. And the endlessly interacting, stabilizing and destabilizing influences at every level make those social systems far more difficult to understand, untangle and improve than you would expect.

## *Memories are made of this?*

The present is a moving knife-edge that separates past from future. The significance of each moment lies buried in the past. The outcome of that moment depends upon processes already in motion. Without memory you could not learn from experience.

You rely upon your visual-spatial memory to find your bedroom or a handkerchief in the dark. Your short-term recall of visual and auditory events remains essential for the acquisition of vocabulary, for reading, writing and verbal language skills, and for understanding what was just heard as well as checking back to see whether you said what you meant to say while those recent sentences still resonate in your mind.

Your warmest memories of unforgettable moments and the ongoing function of your brain both depend upon processes that are very complex and very unstable. Somehow the input from a chaotic world is superimposed upon the steadier spontaneous rhythms of your basic circuits to modify the excitability and maintain the appropriateness of specific nerve cell connections.

Furthermore, your uniquely encoded version of "what was" must constantly be compared with your currently displayed version of "what is", in order to detect novel inputs in a timely fashion. Hence you must maintain a whole library of familiar inputs at a meaningful (above spontaneous nerve discharge) level for comparison.

But why should a glance or smile from your classmate be so memorable - and new hit tunes so easy to recall - when the subjects taught in your classes have totally escaped from memory? Perhaps one day it will be possible to enhance learning chemically. In the meanwhile, it is surely significant that carrot cake provides more immediate pleasure than studying Socrates.

Presumably smiles, hit tunes and cake interest you more than some annoying old Greek because the modular brain circuits that you have inherited are tuned to reproductively useful information. More specifically, your specialized brain modules are organized to help you evaluate risk and movement, deal with allies and competitors, locate and acquire food and engage in sexual and child-rearing activities.

Perhaps the unusual mathematical skills of an occasional idiot savant reflect an extremely skewed neuronal wiring diagram that happens to simplify certain calculations at the expense of many other skills. But we all differ. So regardless of prior exposure, student effort or appropriate instruction, students generally find some subjects more interesting and easier to learn than others.

Some of this variability may simply reflect how much particular brain modules - originally dedicated to deciphering odors or comprehending language - must modify their connections in order to manipulate the concepts of chemistry or philosophy. In any case, we instantly understand our relationship to cake and never forget it, while school lessons often vanish despite our most valiant, though too often last-minute, efforts.

Yet if we persist there comes a point (usually in association with an outstanding teacher) where we begin to develop a more abstract value and reward system. Or perhaps we simply rediscover the inborn curiosity that was stifled by boredom, irrelevancies, authoritarian instructors and adolescent peer pressures to be cool.

As we then learn how this interesting and new-to-us information can indirectly bring competitive and reproductive advantage, we find pleasure and reward enhancing our ability to learn, until eventually a new fact or idea becomes more welcome than extra-rich cream cheese frosting.

Nonetheless, new facts or ideas must fit in. Onions have their place, but not in carrot cake. And information that is appropriate and rewarding is easier to learn than information based upon foreign concepts or beliefs. Furthermore, punishment rarely teaches the lesson intended - it is far more likely to instill an ongoing distaste for learning as well as for those in charge.

But just imagine how easy life would be if one could unforgettably imprint all of mathematics or all of economics or all of art upon anyone's neuronal circuits as they slept. Surprisingly, that might be no great favor to a person who values her or his integrity. For surely it would be the ultimate rape to have the always questionable and often outdated values, belief systems, concepts and approaches of another inserted along with the tortuous information gathering and reward system that made it all possible.

It seems far better to avoid cluttering your unique brain with the dated illogicalities of others, and simply keep their useful information nearby in a book or machine where it can be consulted, evaluated and accepted or rejected in whole or in part as seems appropriate.

So if at first the effort required for learning seems all out of proportion to the gain, just keep looking at the big picture and remember that (for better or for worse) you are building the only mental house you will ever inhabit. And in the long run, your success - meaning your worth to yourself and others - is likely to rest upon what you understand and therefore can contribute.

## *And don't you ever forget it*

Their neuron-like membrane receptors suggest that some of your uncounted trillions of neuron-support cells might play a direct role in neural function and thinking. And if those cells do participate in processing information, that would tremendously expand the already impressive estimates of your total brain capacity. But even without such a huge boost, you probably have about 100 billion neurons that may average ten thousand connections each.

And if we conservatively disregard the fact that some connections stimulate while others inhibit, we still have those ten thousand connections raised to the hundred billionth power as your potential number of possible brain states - which is more than the likely number of atoms in the universe. And if neuron-like support cells also contribute, the computing potential of your brain becomes even less comprehensible to our limited brains. So how is all that brainpower tied up?

Well, what did you have for lunch last Tuesday? Were you sleepy after lunch? Was the traffic noisy? Dogs barking? What program was on TV when you stopped by your aunt's house? How many steps on her porch? About how many boards? What color was your first bicycle? How was the weather on your last vacation? The food and the company? The season? The flowers? Was the big lamp over the table? What did you discuss?

How many songs do you know? How many cartoons or jokes or stories have you recalled over the years? How many roads and trails and buildings can you remember? How good are you at geography? How many faces do you recognize? What was the name of that cute girl in first grade? Where did you see that tall chimney? That huge tree? That spectacular sunset?

What was your most interesting class? How many books have you read? Where did you leave those insurance papers? When? How many ball games, movies and television programs can you recall? How many street lights between here and there? How often have you worried about your children or yelled at them? Does Grandmother have a little bump on her nose?

It is possible that a single neuron has major responsibility for recognizing grandmother. But in addition, your grandmother is taken apart and analyzed in separate areas according to color, form, movement (if any), voice and her many other delightful qualities. These various circuits then recombine in some fashion to create an active internal display in real time - while it is still happening.

Of course, all of that information is not needed in order to recognize either grandmother or Beethoven's Fifth Symphony. Just a few lines on a clever sketch, that familiar voice on the phone, a few notes of a well-loved theme and your previously imprinted memory circuits fire up to fill in the blanks. A great many such modular processes may go on simultaneously, often involving some of the same or mostly different neurons.

That is how you come to your often-incorrect conclusions. That is what accounts for your not-always-perfect behavior. For you are so overburdened by ordinary day-to-day information that even your superb sensors and processors cannot hope to handle it all. And despite the fact that you regularly lose thousands of nerve cells and constantly forget a great many details, almost surely you will still recognize Grandma.

Similarly, you could spend days painting a lovely landscape or sketching a detailed map of your home-town or city. A finely detailed photograph of the same information might take but a moment, yet that photo would also include too much information for instant perusal, analysis and internal replication. To be useful, our brains must continually cut corners, conjecture and consolidate. So deer hunters are sometimes mistaken for deer, and an understanding jury of his peers acquitted the man who shot his mother-in-law after allegedly mistaking her for a raccoon.

## *All creatures offer evidence about you*

Early insights into human nerve cell conduction were derived from careful studies of squid neurons. The simple neural networks that keep your distant worm and jellyfish relatives moving provided additional useful information. Our understanding of how various portions of the human brain function and interact remains rather primitive but it is growing rapidly.

Until quite recently, the situation rather resembled someone investigating how an automobile works by shooting a rifle into various sectors and observing what went wrong. As late as 1966, for example, some Russian scientists operated upon a cat, dividing its nervous system at the midbrain level. But despite leaving no connections between the upper and lower parts of its central nervous system, they discovered that regular electrical stimulation of the cut midbrain surface allowed that cat in the neurosurgical hat to run on a treadmill - admittedly in an absent-minded fashion.

But even when running on a flat surface at a steady rate, an endless variety of positions and tensions still had to be computed in order to detect and correct errors and smooth out instabilities of movement - while locally acting learning rules continuously reported back and strengthened best efforts through trial and error. All of which allowed that cat (undoubtedly an experienced runner) to maintain balance and coordination using proprioceptive (position, muscle and tendon tension, and other internally generated) feedbacks from lower nerve centers that could only go as high as the cut midbrain.

Many subsequent studies of other similar-to-human animal brains have revealed how extensively higher and lower brain centers interact. But the lower non-conscious modalities clearly can handle routine body operations without detailed instructions from above - which is hardly surprising since higher centers could only evolve after such housekeeping matters were efficiently coordinated.

Surely, countless preliminary versions of those underlying brain centers were tried and trashed before ancestors bearing your particular smoothly functioning version were naturally selected. So it would have been foolhardy to even consider redesigning the entire ancestral brain each time some new function was thereafter added. So you daydream about last night's date as you drive and sing along with the radio, chew gum and scratch, but watch out for that driver talking on the phone, and that gal applying her make-up.

## *You think, therefore you are - or so you seem to think*

Two cerebral hemispheres account for 7/8 of your brain volume. But unlike the overlying, smoothly domed skull, your soft, grayish, highly cellular cerebral surfaces are markedly expanded over many rounded ridges and intervening deep grooves. The consistent location of these external folds allows anatomists to descriptively subdivide each hemisphere into a frontal lobe up forward, an occipital lobe posteriorly, a parietal lobe in between, and a temporal lobe on the side.

Your thin cerebral surface layer of heat-producing neurons is economically cooled (or warmed) by copious flows of blood through the adjacent skull, scalp, face and nose. The trillions of tiny nerve cell branches that pass to, from and between those surface neurons, contribute an off-white color and slightly striated appearance to the interior of your brain.

The length of all those white-matter nerve cell extensions is minimized by their placement inside the brain's cellular gray matter. Similar savings in materials and conduction times are achieved by running the extensive white matter tracts that connect your brain and periphery, outside of the small nerve cell collections that serve various levels of your spinal cord.

Although the gray matter surface of your cerebral cortex provides the vast majority of your cerebral nerve cells, several deeper collections of nerve cells also contribute to the planning, generation and automatic execution of voluntary movements, or the development and retention of motor skills such as playing basketball, flossing your teeth, driving an auto, and so on. .

A deep groove between your parietal and frontal lobes separates the site where body sensations are displayed from the frontal motor area in which you decide what to do about it. But as usual, things are not nearly that simple. For many nearby and distant areas subtly send, receive and interact with numerous side branches of various other neurons en route to their principal functional area.

After localized damage to a primary area, such preexisting ancillary connections can often be unmasked and strengthened if diligent early retraining efforts are undertaken before those secondary branches melt away from disuse. Good recovery from a small stroke is allegedly more common among human females, who seem to have less dedicated and specialized neural circuitry than males.

The right cerebral hemisphere receives information primarily from and also controls the major musculature of the right side of your head and left side of your body. The left cerebral hemisphere is correspondingly in charge of left head, right body. This pattern is due to large bundles of axons crossing the midline in the brain stem.

The reproductive advantage in having right brain control the left arm and leg while left brain controls right arm and leg is uncertain. Such an arrangement may simply help the two cerebral hemispheres coordinate their activities. Or perhaps this is another leftover from the days when your fishy ancestor barely escaped some threatening sensory input by first contracting trunk muscles on the opposite side to pull away more quickly.

Your midbrain is about an inch in length. Eye and ear input and reflex eye movements are coordinated at this level. Loss of cells in the midbrain structure known as the substantia nigra ("dark substance") can lead to progressive tremor and other difficulties of Parkinson's disease.

## *The thalamus and hypothalamus ("under thalamus")*

The thalamic area is a reflex center that accepts all sensory inputs except smell - which goes through your olfactory bulbs directly into the cerebrum. Some sensory input is interpreted in the thalamus, including temperature, pain, light touch and pressure. And once those thalamic control systems were perfected by your remote vertebrate ancestors, they were incorporated with minimal change in all later models.

Certain basic emotions also seem to spring from this level, which is hardly surprising, given that most mammals have quite similar lower brains and basic emotions. In fact, the many obvious differences between mammalian species tend to obscure their basic functional similarities.

Distinctive variations amongst mammalian brains reflect the extent to which various species depend upon inputs such as smell (dog, wolf or bear) or sound (bat or dolphin), or outputs such as speech. As previously mentioned, relatively recent upgrades of the consciously dominant brain modules involved in human language and logic, still demonstrate awkward and even competitive interactions with brain areas perfected long ago.

Presumably, this is why repetitive verbalization often helps you get in touch with and develop the logical consistency of - as well as enhance your control over - your own basic emotions. Indeed, it seems that frank verbalization and persistence in examining what seems to be bothering you, are essential steps toward the development of useful insights.

Such insights may arise as you tape-record a diary, or while you write and rewrite an important-to-you novel that no one else need ever read, or during gossip with a close coffee-buddy, or through formal counseling or psychotherapy sessions with a skilled professional who can help you to express and understand your internal and external conflicts and disparities.

Memories form at this thalamic level - and in medial temporal and other nearby nuclei such as the hippocampus - as well as in higher brain centers. The hypothalamus is in charge of keeping your body stable and healthy. It coordinates hormonal advice distributed through your circulation with information flows via your involuntary or vegetative nerves.

In the hypothalamus we find some aspects of aggression and the uncontrollable rage of rabies - also temperature controls, the regulation of your carbohydrate and fat metabolism, blood pressure, hunger and thirst, excretion, sleep, sexual reflexes and biological rhythms - the basic functions that you share with all mammals. While some of these modalities have highly localized trigger areas, their overall functions often involve body-wide feedbacks.

For example, rage or fright release adrenalin (a hormone also known as epinephrine) which causes red cells to be squeezed from the spleen into the circulation while your skin and gut blood vessels also constrict and your heart rate and blood pressure rise. These responses divert blood to your skeletal muscles, whose contractions are simultaneously brought to a peak as if through strenuous warm-up exercises. Other direct effects of epinephrine include dilated pupils, widened airways, an increased availability of glucose in the blood and maximal enhancement of various brain and sensory functions.

Your cerebellum attends to many complex inputs as well as the training and coordination of complex movements. Note that as we move from higher (cerebral hemispheres) to lower (cerebellum and brain stem) brain structures, the functions become less voluntary or conscious, more automatic, primitive, generic and efficient.

Below the cerebrum your brain works about the same as the brain of any other primate. Yet even when using your cerebrum, you have been known to make a monkey of yourself - which is hardly surprising, given that your obvious resemblance to great apes derives from the ape-like ancestors you both shared 7 million years ago. But while your proteins differ from chimpanzee proteins by less than 1%, your behavior usually differs from theirs by rather more - which again suggests that you do not need another new gene for every structural or behavioral modification.

Indeed, it is easy to imagine how a very slight modification of one gene might have allowed your ancestor's cerebral cells to divide an extra time - thereby increasing her cerebral neuron count by 1/6 and her neuronal interconnections by very much more. One can also understand how major anatomical enhancements might result from apparently minor genetic changes whose principal impact came early in development.

Of course, any single change opens the way for numerous compensatory alterations elsewhere, so its full benefit may only gradually become evident. Nevertheless, even a sudden increase in total neuron count could have been integrated quite easily if it brought any immediate reproductive advantage. After all, incoming nerve cell messages already compete for cortical space and help the cortex organize into functional units, and many nerve cell branches are routinely discarded due to disuse or misconnection.

Quite obviously, there is far more to brain function than any possible description of the complex cellular mechanisms within your skull could ever imply. Furthermore, your own peculiar behavior depends directly upon the interplay of your current chemical and hormonal state with that enormous number of neuronal connections.

So while some chemicals temporarily enhance the sensitivity of your nerve cells to a highly responsive but stressful level, others might sufficiently decrease your sensory signal-to-noise ratio to make your behavior repetitive and unsure. But whether tuned in or toned down, your individual activities, survival and reproduction finally depend upon how well those 100 billion neurons function and interact. For what you detect, how you process it, and the way that you respond to those particular inputs is what eventually defines the real you - which brings us to your senses.

# Chapter ten

# Special senses

## *The input is overwhelming*

Day and night, wherever you go, you are immersed in electromagnetic waves of all possible frequencies and energies. Some arrive directly from the sun and stars - others reflect from the moon in June or your cow in heat - still others are emitted by radon, molten lava, your warm spouse or the street light at midnight.

Furthermore, this is a disturbed world of avalanches, earthquakes, creaking doors, gunshots, approaching footsteps, frightened screams, howling dogs, pounding surf, quaking aspens, shrill ice cream trucks and children singing. And it is a chemical world of factory chimneys, internal combustion engines, burnt toast, roasting coffee, sewer gas, forest fires, roses in bloom, fresh baked bread and bacon frying.

You cannot possibly keep track of it all, and fortunately, you don't need to. For in their incessant struggles to survive and reproduce, your long-suffering ancestors were similarly inundated by information. They too tried desperately to identify and amplify personally important signals buried within that overwhelming noise. And of all the solutions they tested, intense emotions proved the most effective - hence the most rational - way to identify, and focus attention upon, urgent threats and opportunities.

Therefore, information relevant to your own survival and reproduction elicits anxiety, misery, distaste, fear, anger, hate, pain, pleasure, love, jealousy, passion, disgust or rapture. For these strong emotions bypass your normally methodical reasoning processes to induce a body-wide state of emergency that focuses attention upon urgent matters like hunger, thirst, danger, competitive threats, tissue damage or an exciting reproductive opportunity.

## *You can run but you can't hide, for you never stop signaling*

All living things disrupt and pollute their environment. The context of those inadvertent "Danger!" or "Opportunity!" signals may be as significant as the content. Your ancestors survived by paying attention to both, so your naturally selected sensors and nervous system processors extract and extrapolate a great deal of useful information from the countless signals that they detect. But before we examine those remarkable receptors, let us review how various disturbances spread.

Ordinary light and sound move outward from their source in all directions at top speed, with light traveling a million times faster than sound. And even after the momentary light-and-then-sound frontal disturbances of a nearby firecracker explosion pass you by, they may still startle fine folk farther off while you again enjoy the dark and quiet. Apparently, your eyes and ears excel at sampling rapidly expanding, energetic disturbances.

On the other hand, your sense of smell extracts useful information from odorant molecules intermittently drawn up your nose by each breath. And even on a calm day, innumerable collisions with atmospheric gas molecules will slowly dilute and disperse the airborne signals of an annoyed skunk as disorder increases in accordance with the Second Law of Thermodynamics.

When an isolated, uniformly smelly patch of air doubles in diameter, its odor molecule concentration should decline eightfold, for the volume of a sphere is proportional to its radius cubed. But near-ground temperature gradients distribute expanding smells unevenly, so odors tend to fade unpredictably as you leave their current center of concentration.

## *We are all submerged in the same sensory soup*

Earth's surface is ceaselessly vibrated and illuminated by expanding mechanical and electromagnetic disturbances on every scale, from all directions and times. Countless molecules diffuse or interact throughout land, sea and sky. Nonetheless, the glare, clamor and stink of trivial local events will usually overwhelm any faint glimmers of unimaginable cataclysms that occurred long ago and far away.

As your multicellular ancestors enlarged and developed specialized tissues, their increasing metabolic investment made it reproductively advantageous to detect and utilize more information. Your modern, naturally selected senses were developed over billions of years through countless minor modifications and recombinations of preexisting receptor molecules, cellular structures and processes.

Throughout that arduous but undirected design and engineering process, the grading system remained strict but fair, though a bit sloppy. "Pass" meant your ancestor may have come up with something useful - "Fail!" suggested a potential ancestor was unfortunate or critically deficient under certain circumstances. But whatever the reason, any modification that was eaten before it could reproduce, left no descendants.

Such an aimless, incremental, self-scoring design system might seem hopelessly inefficient, but its overwhelming advantage lay in being able to sort through and recycle trillions of contestants simultaneously. So despite having no guidelines or goals other than reproductive success, natural selection managed to come up with amazingly effective special senses for the duck-billed platypus, the hammer-head shark and you.

Delicate electrical sensors that border the eye wings of a hammer-head shark, or the bill of a duck-billed platypus, are able to detect tiny electrical depolarizations of bottom-dwelling life forms as those creatures rest or move innocently about in the muck, seeking food or romance. This sense therefore provides shark and platypus with efficient access to otherwise underutilized resources cowering beneath muddy waters.

Larger animals are usually more interested in or threatened by creatures of comparable size that may disturb their environment mechanically, electromagnetically or chemically. So grazers and browsers have tall, steerable sound collectors at the very back of their skulls where they remain high to provide good reception with minimal interference from self-generated noises caused by moving about and chewing.

Grazers and browsers also have outward directed eyes and nostrils, as well as extended jaws to support their long grinding teeth. This permits the widest possible field of vision and smell while feeding, yet minimizes the disturbance of dust, grass and leaves during expiration.

In contrast, pouncers generally direct both eyes forward since binocular vision permits more precise three-dimensional pouncing. Overlapping visual fields also make possible the stereoscopic vision needed to see a striped tiger in tall grass. And both pouncers and grazers have very sensitive detectors for molecules of plant or animal scent that waft by on the breeze.

Perhaps you view yourself as part-pouncer and part-grazer but your visual fields overlap and you cannot even wiggle your ears. Furthermore, despite having comparatively few odor receptors, you possess one of the finest processors on Earth for evaluating what you do detect.

So you watch, sniff and taste your victims before swallowing. And if unsuitable food should get past your primary mechanical, electromagnetic and chemical input sensors, that food can still be rejected from either end of your gastrointestinal tract.

## *How you taste*

Your various sensory cells convert chemical inputs, light, sound and other mechanical signals into altered trans-membrane potentials for your brain to interpret. Even exquisitely faint tastes and smells (a few molecules), visual signals (one photon) and sounds that displace one hair cell by less than 0.1

nanometer or billionth of a meter (which is close to thermal vibration levels) may be detected and then amplified for your evaluation and response.

Your more or less standard-issue mammalian olfactory system can distinguish over ten thousand different airborne odorant molecules. In contrast, taste chemoreceptors in the crevices of your tongue report on just five critically important non-volatile food flavors.

Of these, *Sweet* identifies easily utilized food energy. So sensory cells bearing sugar receptors are located near the tip of your tongue - which allows you to test a possibly edible food or fluid without taking it into your mouth. Non-sugar no-calorie sweeteners fool some peoples' taste buds some of the time, but the per-person consumption of sugar and other high-calorie sweeteners has gone up in the United States since no-calorie sweeteners were introduced. Hence no-calorie sweeteners may simply reset the average preference to a sweeter flavor.

Even lead acetate ("sugar of lead") tastes sweet. The Romans valued that flavor in the slightly vinegared wine drawn through their lead pipes. So while wine exports remained important to the Roman economy, and helped befuddle Celtic barbarians, lead poisoning also contributed to the decline and fall of the Roman Empire.

*Salty* receptors also are located at the front of your tongue where they can detect unexpectedly salty water or monitor the replacement of salt lost through your urine and sweat. Both sodium chloride (table salt) and potassium chloride stimulate those salt-sensitive receptors while calcium ions leave a salty/bitter flavor.

The *Sour* receptors on both sides of your tongue, help to regulate your intake of acid foods. And *Bitter* receptors near the back of your tongue analyze moist well-chewed food just before you swallow it. You rightly tend to avoid bitter foods, as toxic plant alkaloids are often very bitter.

A fifth flavor - recently identified as a glutamate receptor - is *Umami* (meaning "yummy" in Japanese). Your umami receptors are stimulated by monosodium glutamate or MSG, as well as by the high glutamate levels in meat, parmesan cheese, mushrooms and many Asian foods. So while umami usually announces nutritious food, it can be fooled by MSG or mushrooms.

Your perception of flavors varies according to your needs. Hence a huge piece of cake with plenty of frosting (lots of sugar and fat) may seem delightfully sweet and satisfying until you have had rather more than enough - then it might acquire a somewhat sickening taste. And after vigorous physical activities on a warm day, extra salt may improve the flavor of salty snack foods. Your tolerance for sour fruit or juices is similarly dose and need related.

Pain, too, may add “flavor” through separate receptors. But a simple tooth-ache or biting the tongue doesn’t contribute flavorful pain. Rather this sensation results from a careful titration of chilies and other spicy foods that may stimulate pain fibers sufficiently to make your face perspire and nose run by reflex - as if to wash the irritant away.

Pain of the sort induced by “hot” foods from India, Korea or Mexico is an acquired taste that in mild doses accentuates the gustatory process. However, Mexican children must reach 3 to 4 years of age before they can appreciate this flavor. And subjective factors can alter your enjoyment of food and beverages. For example, shared food and drink usually taste better. And significant temperature gradients associated with heated or icy foods may additionally stimulate some flavor receptors.

## *How you smell*

Located well beyond the reach of your exploring fingertip and somewhat aside from the direct flow of air into your lungs, a dime-sized area at the top of each nasal cavity exposes about three million olfactory neurons under a thin sheet of specialized mucus. These sensory nerve cells die and are replaced regularly by new neurons that extend a branch onto the nearest of two symmetrically placed olfactory bulbs inside your skull.

Although other sensory inputs are preprocessed at lower levels, the information received by each olfactory bulb goes directly to the adjacent cerebral hemisphere - so smells (but not sights or sounds) frequently activate relevant memory/nostalgia pattern-recognition circuits. And that recalled ambience can contribute to your safety or dining pleasure, for in our world of many different smells, any person, animal, plant or food closely associated with a smell on one occasion is likely to be so again.

Since breathing never stops, the direct cerebral olfactory connection (along with your hearing) helps you keep track of nearby matters at night, even when asleep. These advantages explain why that ancestral olfactory-cerebral connection persisted as the tremendously expanded and modified forebrain evolved out of two small nerve cell clusters dedicated to analyzing odors.

Some scents stimulate your memory or affect your behavior without entering your awareness. We know that female moth scent can drive a male moth mad with passion, sight unseen and a mile downwind. Similarly, the perfume industry thrives by misleading non-allergic humans through unrelated nostalgia circuits. And one human female pheromone (scent with hormonal effects) causes the menstrual cycles of women who room together to coincide.

Presumably this chemical version of peer pressure is based upon some scent emitted by the dominant female. Perhaps menstrual synchronization formerly enhanced reproductive success by encouraging simultaneous births at a time when seasonal variations in resources, predators or parasites necessitated group travel that could affect newborn survival.

The truffle - a fungus that grows underground on oak tree roots, most notably in France - also produces a male pheromone. Apparently that pheromone explains why truffles have long been valued for their flavor and possible aphrodisiac effects (honoring Aphrodite, the Greek Goddess of Love). Indeed, the complex flavor of a truffle reportedly mimics the scent of a "freshly screwed-in bed" (another acquired taste, perhaps).

This same pheromone is produced in the testes and released through the sweat of adult human males. Boar pigs are another source, so female pigs are tireless truffle snufflers. And interestingly enough, when repeatedly judging a long series of photographs, both male and female humans rated a particular female as more attractive while those viewers were under the influence of that male pheromone.

So how does natural selection develop such useful signal-molecule-to-receptor-molecule interactions? Well, any female (human or sow) that found certain male scents attractive (or even tolerable) might thereby gain reproductive advantage. But ordinarily, the pheromone of an undisturbed truffle attracts burrowing rodents to eat the fungus and distribute its spores in their stools.

Hence the current high cost and demand for truffles might be viewed as a possibly lethal (for the truffle) side-effect. However, if the French and others learn to farm them successfully, truffles might thereby additionally promote their own reproductive fitness through that pheromonally induced process of selection.

Even without perfumes containing pheromones (should they be illegal?), we respond to the odors of others from the time of our birth. Indeed, body odor is an important part of the bonding process - and of unbonding as well. And new parents can probably enhance early bonding with their infant by avoiding the use of perfumes and scented toiletries.

## *What you smell*

With the entire mechanism of smell still under investigation, we might view each additional sort of odor receptor as yet another in a long series of piano keys upon which an almost endless variety of chords or single notes can be played with varying intensities. Naturally some of these effects are far more pleasant than others. So while horsemen wax nostalgic about the scent of horse manure - and cow manure signals prosperity in certain cultures - few humans seek out the smell of human feces.

Nevertheless, I have encountered individuals who were truly convinced that their own stools did not stink. And others who feared that every fecal odor represented an airborne escape of tiny stool samples from their turd-of-origin, with those particles then cruising freely on the breeze until firmly lodged in some innocent smellee's nose or toothbrush.

These ideas are understandable misinterpretations of ordinary experience. But those taking undue pride in their own unscented stools might be dismayed to learn that odors often become undetectable when they exceed the maximum signal strength of relevant olfactory receptors.

For while the initial impression made by an intense chemical signal often seems unpleasant, your nasal and other chemical sensors thereafter report only changes (just increases, actually) in concentration rather than absolute values. So those who swiftly desensitize relevant nasal receptors in their own bathroom or outhouse will thereafter remain untroubled. And wherever they may subsequently wander, they will initially be moving from greater to lesser concentrations of stink.

However, there is no sensory signal for "things are getting less bad" other than the absence of a sensory signal. And upon leaving and soon returning to a smelly, unvented bathroom, the source individual may remain at least partially desensitized by the recent severe exposure. Thus he or she may judge self-generated odors with unwarranted favor, especially in comparison to those equally noxious but other-generated. For when the latter already seem troublesome at a distance, they can only become worse as you approach.

During a winter visit to a small Alaskan community, I inquired where the creaky old sewage truck got rid of its "honey-bucket" contents after these were picked up in house-to-house collections. An observant bystander pointed out that the major ongoing leak from the old truck's rusted tank seemed to make formal disposal unnecessary.

While I tried unsuccessfully not to breathe thereafter, I detected no odor out there in the cold. And those delicate souls who complained about the dusty roads of this town in summer also detected none - despite the fact that on dry summer days, each passing vehicle stirred up an impressive cloud of partly-fecal dust.

So when oxidized dry stool does get up your nose, it may deliver no detectable odor - which is not too surprising, given that each exposure to oxygen allows bacteria to recover more of the food value in stool. In contrast, archeologists have collected and analyzed 800-year-old air-dried human feces from old Chinese fortresses in the Gobi desert. Those stools had lasted many centuries in mint (fine) condition because bacteria also require moisture for their metabolism.

It is reported that by heating these ancient stools - and directing their fumes into the nose of a dedicated and highly trained investigator - these scientists could determine important details of that long-dead soldier's diet. That information then helped archeologists clarify historical trade routes since the origin of partially digested foodstuffs identified by the investigator could often be determined.

Chemists who study and replicate odors have found that the different chords played upon your nasal sensor "piano keys" usually consist of just a few volatile (easily vaporized) molecules. Hence stool smells ought to be viewed as chemical signals rather than feces up the nose. Even rocks emit an odor when struck sharply together, for that strike momentarily creates a great deal of heat, causing some rocky constituents to vaporize and thereby activate a "rock" tune in your nose. Similarly, a cinnamon roll emits specific molecules into the air that play "roll" messages.

Interestingly, not every nose gets the same crappy rock and roll message, for some individuals lack certain receptors and all individuals differ in their sensitivities and abilities to discriminate between odors. Such variations between individuals may help to account for different "tastes" (smells actually) in coffee and wildflowers as well as barnyards. And what one observer might identify as "either lilac or clover" can often be classified more accurately by another whose receptors are sensitive to less dominant secondary scents.

Skunk cabbages heat their florets to increase the number of scent molecules being vaporized. Newborn animals commonly remain odor-free for some hours until bacteria colonize their skin and begin to break exposed organic materials into smaller, more volatile molecules.

Perhaps noses make their greatest contribution when they decipher very faint chemical messages. At such times, the odorant molecule is quickly detected and rapidly deactivated, so its effect can be both prompt and brief - another good reason for locating your nose as far from your anus as possible.

But regardless of how sensitive your nose may be, or how many more working receptors you may have than someone else, from the time you first encounter an undisturbed expanding sphere of smell, you will usually be moving against a rising concentration gradient.

And if you move on through very slowly you may not notice much - since “no gradient” transmits “no message”. However, going through more swiftly can greatly increase the gradient and thereby send a stronger message. So while walking past an apple orchard at blossom time is pleasant, biking through is really nice and motorcycling past (with no windshield or helmet visor to stir the humid evening or morning air before it enters your nose) can be memorable.

On the other hand, auto exhaust is both unpleasant to smell and dangerous to breathe. Yet if you mix auto exhaust with lots of other chemicals including lovely flower scents, you may detect very little, even when visibility becomes markedly reduced by the dense smog of odorant molecules.

Similarly, if you over-stimulate most or all nasal receptors - as those obnoxious and possibly dangerous bathroom deodorizers do - your brain may perceive only noise to ignore rather than information. Indeed, very strong smells can temporarily or permanently disable your nasal receptors, thereby rendering you anosmic.

Which is how a criminal lawyer (aren’t they all?) discredited an apparently reliable witness who had recognized a particularly incriminating odor at the scene of a crime. Asking him to first confirm his nasal expertise for the jury by identifying a few common odors, the lawyer gave this witness gasoline as his initial test odor, thereby rendering him temporarily anosmic. At the same time, even heavy smokers on the jury were able to recognize the other odor in question.

You may lose your sense of smell for three or four days after heavy exposure to wood smoke around an open campfire. For as you have surely noticed, if you come close enough to be warmed, the smoke tends to be drawn toward you even if you are directly upwind, since your wind shadow reduces air pressure between you and the fire.

Strongly reactive, odorous chemicals such as formaldehyde (formalin), and other chemical fumes or smokes, can induce anosmia that lasts for a couple of years. Although they often seemed indifferent to that loss, many older chemists and pathologists were chronically anosmic from repeated occupational exposures to strong-smelling volatile chemicals.

Thus while the regular replacement of old olfactory nerve cells ordinarily keeps your nose up to snuff, a severe chemical exposure, infection, tumor, nearby skull fracture, or other known or unknown agent can render an individual chronically or even permanently anosmic.

Anosmia can be quite distressing, for it means losing the nostalgic smells that so enrich an ordinary existence. On the other hand, an anosmic individual remains blissfully unaware of annoyances such as a freshly tarred roof or poorly ventilated bathroom, or the many city smells that make country living seem so sweet.

Among disadvantages of the anosmic state are the inability to detect hazardous gas leaks, pesticides, smoke and rotten food, as well as the loss of pleasurable overtones when smelling the flowers or eating. After all, the enjoyment of fine food and wine is mostly in the volatiles.

Indeed, that is why the temperature at which food is served makes such a difference, and why oenophiles (lovers of the fermented grape) are so fussy about using properly shaped wine glasses and cooling their wine just so. But science marches on, and recent computer simulations suggest that the standard champagne glass - which allegedly was modeled on the breasts of Marie "let them eat cake" Antoinette - would work better if reshaped (proving once again that computers have no feelings).

## *The purpose of pleasure*

On this approach to your special senses, we have not yet explored beauty and pleasure, nor ugliness and disgust. But those commonplace interpretations of your ongoing sensory input are what eventually guide your behavior. Thus an enjoyable taste, smell, sight, sound or touch whets your appetite for more of the same. And it shouldn't surprise you that those sensory inputs most likely to give pleasure also tend to involve you in reproductively advantageous behavior. Such behavior may include anything from better nutrition to improved socialization with the group to actual sexual and reproductive activities.

The generally favorable relationship between beauty, pleasure, survival and reproduction only breaks down under conditions that your ancestors were unlikely to encounter - e.g., neuro-active drugs that bypass sensory input to alter brain function directly, or technologically created situations involving sensory deprivation or sensory overload (a rock concert, perhaps). So while such chemicals or conditions are sometimes associated with pleasure, they need not improve survival or bring consistent reproductive advantage.

Certainly you tend to avoid the ugly, scary and annoying, such as food that tastes bad, or excrement, or decaying flesh or volcanic gases. You probably find the sight of open wounds and bleeding very distasteful as well, especially when the injured is nearby or happens to be a relative or friend or even yourself.

And loud noises over which you have no control can be extremely irritating, as can excessively hot, cold or even continuously wet skin. Yet no matter how much you might wish to shut out that sort of obnoxious sensory input, you cannot. For it is unsafe to be out of touch, even when the input becomes strong enough to damage your special senses.

Ordinarily the wide gap between barely detectable and potentially damaging inputs allows you sufficient time to flee. Interestingly, the perceived intensity of a sensation often varies with some power function of the actual stimulus intensity. For example, the apparent loudness of a sound increases more slowly than its actual signal intensity, while the apparent strength of an electrical shock rises very rapidly (with the square or even cube of actual intensity).

It is also important that many benign sensory inputs invoke pleasure. For simple enjoyment encourages you to stay tuned and acquire additional useful information with less effort. After all, if you only activated specific receptors at times of obvious opportunity, trouble or danger, you would suffer adverse consequences due to missed signals or the inevitable delays involved when tuning in.

## *Tastes vary*

There are innumerable examples of beauty being in the eye, ear, nose or mouth of the beholder. People vary, tastes vary and the impressions created centrally by sensory inputs also remain subject to ongoing readjustment, based upon need and past experience. The resulting diversity may not provide survival advantage under ordinary circumstances, but at least it keeps most of us from being irresistibly attracted to the same special individual for a mate.

In that way too, variability tends to maintain itself and increase, even if its only advantage is to raise the fraction of available resources that a population is willing to utilize. Of course, without variability there would be no natural selection, no survival of the fittest, no evolution, and no you.

## *Some inputs are more important than others*

Your strongest visual response is to red, green and blue. Superman’s X-ray vision allegedly brought him great advantage. Infrared goggles allow soldiers to fight all night. Small bats echolocate during flight for object avoidance and to capture insects. Large bats and almost all birds rely mostly on vision rather than ultrasound to direct their flight and help procure food.

Nocturnal birds often have a better-developed sense of smell. Some flowers put out lots of scent. Other flowers, and even lizards, may appear bright in ultraviolet but not in visible light or vice versa. Why so much variety? Why don't creatures and plants simply do their best in normal ways and compete on that basis alone?

As usual, life is not that simple. Certain inputs or outputs only provide benefits under particular circumstances. Echolocation is energetically expensive except during flight when breathing already is forcefully coordinated with wing strokes. Furthermore, any terrestrial creature emitting strong echolocation pulses would generate confusing echoes from nearby surfaces while revealing its own location to others.

Although few of them echolocate usefully, birds and large bats do have good visual systems and effective central processing. By giving up some visual capacity, such birds and large bats could devote more of their central processing to echolocation. However, having intermediate levels of both skills might be an insurmountable reproductive disadvantage.

Clearly it is risky to switch away from something that works. For example, fetal bird brains are strictly constrained in size by the rate of gas diffusion through their egg-shell pores, since larger pores would allow intolerable water losses - yet another natural balancing act. And if certain flowers find seasonal success via the pollinators they attract, while those pollinators find such flowers the most rewarding, both may find themselves joined in an increasingly codependent relationship that excludes others with different skills, tastes and characteristics. Many sorts of wild berries are poisonous to you, but some creatures most likely gain reproductive advantage by spreading the seeds of those berries as well.

Your own color vision is not just a matter of esthetics either, for the survival of your ancestors was enhanced by photoreceptors sensitive to green - the main color reflected by chlorophyll and therefore the most universally present visible light frequency on the heavily inhabited lands of our plant-powered planet. So all rod cells - and about one-third of the cone cells in your eyes - detect green better than any other light frequency.

That a subset of your cone receptors is especially sensitive to red also makes sense, for red happens to be the color best absorbed by chlorophyll, as well as by Earth's seas - which are blue because, unlike chlorophyll, they absorb blue light very poorly. Fruits and berries often turn red when ripe, which heightens their contrast with surrounding leaves.

Having the best reception of your blue-sensitive cones located on the far side of green from red further reduces the opportunity for your predators and predatees to avoid detection among all the green grass and leaves. In other words, your particular photosensitivities optimize contrast in the visible light portion of the electromagnetic spectrum that best penetrates Earth's atmosphere from outer space.

A purely green background is uncommonly encountered by larger-than-leaf-sized creatures, so larger animals generally camouflage themselves with other colors - often using dominant patches and stripes that disrupt their outline at a distance.

As for infrared vision, that might not have helped your earlier ancestors underwater where all surfaces are uniformly cool, nor those who later emerged on land in the tropics where everything is hot (except at night when your primate ancestors mostly slept or huddled in fear rather than roaming).

With ultraviolet light mostly blocked by the ozone layer, any cone cells in your eye that detected ultraviolet light would not see nearly as well as cone cells sensitive to visible light frequencies. As noted above, flowers that are brightest at ultraviolet frequencies, probably became so in a codependent fashion with increasingly ultraviolet-sensitive insects. On the other hand, fish exhibiting colorful near-distance mating displays at ultraviolet frequencies, may thereby reduce risk of detection by distant predators.

All electromagnetic energy travels at the standard speed of light. But as the energy of an electromagnetic photon increases, its wave-length decreases. So higher energy electromagnetic waves have higher frequencies (more waves per second) as well, and the energy carried by gamma ray and X-ray photons is sufficient to damage atoms and molecules.

Fortunately, the short wave length of high-energy photons from outer space virtually ensures that they will be scattered and blocked by air molecules while passing through our thick atmosphere. Similarly, blue light is more likely to be scattered by air molecules than red light since longer waves are less affected by such small particles - just as a rowboat can block ripples while large ocean waves pass unaffected. So clear daytime skies appear blue because of scattered blue light, and higher frequency electromagnetic radiation had little relevance for your ancestors.

On the other hand, lower microwave (radar) and radio/TV frequencies were uncommon on Earth until recently. But even if radio waves had been encountered regularly since life began, they would not have been helpful frequencies for animals to detect. After all, a radio wave as long as a football field will not reflect from, or be usefully distorted by, a small object like a lion or a rhinoceros.

Hence if you could only see at radio frequencies, you might get the big picture but important small stuff (other animals, rocks, trees) would be invisible and more likely to get you. Furthermore, while visible light is conveniently subcellular in wave length, you might find it impractical to run about with antennae or satellite dishes sprouting from your forehead in the fashion popularized by (extinct) Irish Elk.

## *Picking up sound waves*

For similar life-and-death reasons, humans are most sensitive to air-conducted sound vibrations in the 1000–4000 hertz (1–4 kHz or 1–4 thousand cycles/second) range, although young adults can detect sounds to 15–24 kHz (and loud inputs at higher frequencies up to at least 90 kHz are detectable by some deaf adults via bone conduction - presumably through their effects on some inner ear structure).

Since sound travels at about 350 meters/second (1150 feet/second) in air, that means your best heard wave lengths are 1/10 to 1/3 of a meter or 3–12 inches long - a range that includes the distance between your ears. And the same close relationship between best-heard-wave-lengths and head-size apparently holds true for all mammals.

As a result, elephants, rhinos and whales converse at inaudibly low (to you) frequencies while mice chat about you and also listen at far higher frequencies than you can detect. Of course, owls and pussycats must hear up to 50 kHz in order to accept a mousy invitation to lunch. Furthermore, barn owl ears are asymmetrically mounted (left higher and pointing down, right lower than eye level and pointing up) in order to improve vertical correction for sound intensity when flying in total darkness.

But while mice and elephants hear best at wave-lengths comparable to their skull width, their squeaks or roars - and humpback whale songs - include frequencies that you too can hear. Similarly, breaking twigs or light footsteps put out a wide range of sound frequencies.

Thus the usual problem is not which frequency to monitor because it happens to carry critical information for you. Rather it is which wave-length provides the most information for your particular head size - or the most easily detected pressure changes in your swim bladder, if you happen to be a fish bearing one of those multi-purpose air-filled sacs.

Except for the very energetic and focused echolocation sounds emitted at up to 120 kHz by bats, the higher frequency calls generated by smaller creatures transmit poorly through air. But small animals pose less danger to larger creatures than to others of their size. Hence large animals need not monitor those higher frequencies for defensive purposes. Nonetheless, being able to hear a wide range of frequencies is clearly advantageous.

Bats and dolphins produce a concentrated beam of high-frequency sound with a wave-length well below target size for easy reflection. But sound wave lengths comparable to your head width are most helpful for locating the source in three dimensions, even if you and/or the source are in motion or out of sight. For when your head partially blocks incoming head-size or smaller sound waves, the resulting sound shadow provides important directional information about where that sound originated, especially if it was not significantly reflected to create misleading echoes.

Of course, before you can extract any useful information from sound, your immobile funnel-shaped external ears must gather and concentrate those passing waves of air compression and rarefaction. Even when a sound reaches both ears at once, the directional distortion caused by those asymmetrical (not round) external sound collectors usually allows you to determine whether the source is located in front, above or behind you.

While that sound persists, you can additionally confirm its origin by turning or tilting your head slightly in order to reduce sound pressure and delay reception on the farther away ear. For when you thereby modify sound intensities and arrival times at your two ears, you unavoidably alter sound-wave phase differences between the two sides as well.

Unlike visible surface waves moving across a body of water, sound waves cycle invisibly between higher and lower air pressures as they travel outward in all three dimensions. You convert those sound waves into useful information when your centrally located sound-detecting cells report on which ear first perceived the sound wave as well as how that incoming wave was distorted by your external ears. Since the size, shape and frequency of water waves or sound waves can be modulated endlessly, both can carry a great deal of information from and about their source.

Admittedly, all of this seems even more technical, complicated and amazing than your first bicycle ride. And your hearing skills actually developed much as you learned to ride a bike - by simple trial and error. Fortunately for you, your long-suffering, naturally selected ancestors already had evolved ears and bicycles. Your far simpler task was merely to figure out how to use them without (or despite) any instructions. And within weeks of your birth, the detectable differences in sound intensity and arrival times at your two ears were already helping you to visually locate the source of various cooing sounds as doting relatives tried to make you smile.

The internal comparison and evaluation of sounds received by each ear depends upon simultaneous analysis of a great many different inputs. Somehow that allows you to detect a few microseconds difference in sound arrival - which is far less time than even the fastest neuron requires for depolarization. Note that you need not respond within microseconds, you merely have to detect differences in sound wave arrival times on that scale. And this project is simplified by a whole matrix of coincidence-detecting brain neurons that respond specifically to matching phase inputs from both ears.

The most activated neuron therefore lies farther from the ear that first heard the sound, as determined by the ordinary conduction speed of nerve cell extensions carrying their report centrally. The great advantage of having an entire array of neurons ready to report coincident impulse arrivals at their location is that each neuron can then represent a position in space from which the signal seems to arise.

In other words, specific nerve cells respond to specific delays in the arrival of a detected sound - from the time it reaches one ear until it arrives at the other. And because the firing of a characteristic delay cell is most vigorous when the sound arises from a particular direction relative to the head, this creates an audio-spatial map within your brain that localizes the sound's source.

Visual disparity neurons serve a similar function in animals with binocular vision by reporting specific differences in viewing angle between the two eyes that again localize an object's position relative to your head. Because different nerve cells respond to different visual angles, binocular vision produces an internal, three-dimensional map comparable to that based upon binaural hearing.

Of course, there is no need for this entire finely tuned mechanism to have come about all at once. Indeed, it could far more easily have evolved through innumerable intermediate, individually advantageous stages to reach the present level of complexity and acuity about which we still have so much to learn.

## *It has always been harder to listen than to talk*

Quite obviously, talking and listening evolved together. And your early branch-swinging, or later cave-dwelling, ancestors clearly required increasing intelligence to determine the significance of each others' grunts and howls as these slowly became modulated by greater information content.

That prolonged progression surely involved a great deal of body language as well - with simultaneous visual signals supplementing and confirming verbal meanings. But while many people still say as much with hand and face movements - even when speaking over the car phone - as with their voices, that does not necessarily mean they are less evolved than you.

## *Your hearing machine*

Adult human males sprout varying numbers of hairs from their external ears. Women cannot compete on that trait as the hairy ears gene is located on the y (male) chromosome. Your flexible, cartilage-supported, immobile external ear concentrates sound waves onto a delicate eardrum.

This thin membrane stretches across and seals the narrow inner apex of your ear canal - well past a sharp bend in the tapering external ear canal. Wax-producing glands in the outer ear canal may immobilize or otherwise defend against inquisitive insects, while also helping the canal shed water and avoid fungal infections.

Each tiny air-containing middle-ear cavity is separated from its adjacent external ear canal by the eardrum. Your two middle-ear cavities open into the nasal part of your throat through separate eustachian tubes that drain secretions and equalize middle-ear air pressures with air pressure in the adjacent atmosphere.

Air travelers suffering from a cold or allergic sniffles may develop painful earache and partial hearing loss during descent due to obstruction of one or both eustachian tubes. These symptoms clear when the ear “pops” as air entry relaxes the ear drum - often when a yawn successfully reopens that eustachian tube.

Your middle ears routinely release air in little pops as you walk, drive or fly to higher elevations where surrounding air pressures are lower. The eustachian tube is short and straight during childhood, allowing throat infections easier access to the middle ear. Children regularly encounter new-to-them infectious organisms so they frequently have swollen adenoids (lymph tissue) compressing the entry of their eustachian tubes into the throat.

Having atmospheric pressure on each side allows the tightly stretched eardrum to move freely in response to incoming air compressions and rarefactions (sound waves). Every tiny displacement of the eardrum is amplified through a series of three little interconnected bony levers - the hammer, anvil and stirrup. The footplate of the stirrup finally vibrates a small membrane-covered oval window between your air-containing middle ear and your fluid-filled inner ear.

An eardrum’s surface area is about 25 times greater than that of the oval window. Consequently, the three little levers crossing your middle ear vibrate the oval window about twenty-five times harder than the incoming sounds, focused by your external ear, vibrated that eardrum. Two tiny skeletal muscles somewhat stabilize your middle-ear bones against anticipated strong noises but unexpected loud sounds exert their full impact on the delicate inner ear.

Ordinarily, the air-containing middle ear separates and insulates your fluid-filled inner ear from the outside world. And while (middle) earaches are painful, they are usually far less devastating than the deafness and dizziness that may follow apparently minor inner-ear injuries or infections.

## *Your inner ear*

The inner ear serves all vertebrates as an organ of balance and hearing. Both functions rely upon groups of specialized *hair cells* - so named because each of these cells is capped by a tuft of fibers that is narrowest at its cell-surface site of flexion. Movement of this hair bundle in specific directions distorts nearby ion channels, leading to changes in the hair cell's transmembrane voltage.

Thus every hair cell acts as a transducer - converting tiny mechanical hair bundle movements into electrical signals for your central neurons to interpret - just as electrical phonographs converted needle movements in the irregular tracks of a slowly spinning bakelite or vinyl record into electrical signals destined for the amplifier and speakers (the needle in an old mechanical phonograph vibrated a thin metal diaphragm directly).

## *Balance*

The inner ear includes three semicircular canals - each exquisitely set into skull bone at a right angle to the other two. As a result, the slightest acceleration of your head displaces fluid by inertia within at least one of those canals. And any fluid emerging from a semicircular canal stimulates hair cells near that opening by displacing a flame-shaped gelatinous mass in which the hairs are embedded.

Once your own movements have been sensed by this tiny inertial guidance system, copious neuronal connections to and within the brain stem swiftly redirect your eyes so that they remain centered upon the lady or the tiger. Because you must also take your own movements into account during square dancing or mortal combat, your voluntary motor nerve cell discharges are immediately reported to the sensory areas of your brain so that you may anticipate the effects of those pending muscle contractions and appropriately modify forthcoming movements of your eyes, arms and legs.

However, if ice water should happen to enter your external ear, it will cool nearby fluid in your semicircular canals. That cold dense inner ear fluid then sinks, displacing warmer fluid upward - just as cold milk initially settles through your hot coffee. The resulting stimulation of your semicircular-canal hair cells is therefore misinterpreted as a violent spinning acceleration. Hence you become dizzy and unable to maintain balance or direction, and your eyes move back and forth rapidly.

***If such a loss of orientation should occur to you while swimming with one ear dipped in very cold water*** (as when doing the sidestroke), simply dip the other ear until things stop spinning. Then keep your head out of that cold water until you are safely back in a boat or on shore. ***For that "caloric" response may explain why individuals who fall into cold water so often seem disoriented - swimming away from the dock or in aimless circles until they drown.***

In addition to the three bunches of hair cells associated with your three semicircular canals, you have two other clumps of inner-ear hair cell sensors, each embedded in a small gelatinous mass that is weighed down by many tiny calcium carbonate crystals. One of these masses lies horizontally, the other vertically. Thus those rocks in your head allow you to detect changes in position with respect to gravity.

Comparable structures in fish - known as otoliths - display microscopic daily-growth rings that retain information on chemical exposures, temperatures and nutrients encountered during that day. Each otolith therefore provides a valuable record of which pollutants were encountered where and when along the migration route.

## *Hearing*

The sixth and largest collection of hair cells in each inner ear is located within a tiny structure known as the cochlea that is shaped like a snail shell. Here 15,000 hair cells sit on top of one curving membrane with their hairs embedded in another. Each cell is tuned to a specific sound frequency by the length of its hair-like appendage as well as by the membrane's tension - which declines toward the cochlea's narrow upper end.

Consequently, hair cells farther from your oval window respond to progressively lower sound frequencies, just as loosened guitar strings vibrate more slowly. And the high-frequency-response hair cells nearest to your oval window, are first to die from the noisy input of rock concerts, gunfire and jet engines - while aborigines not exposed to the noises of our civilized world often retain acute hearing into old age.

A tiny membrane-covered round window bulges into your middle ear each time the stirrup pushes your oval window toward the inner ear. The resulting pressure relief expedites passage of each sound pressure wave through your incompressible inner ear fluid - from the oval window, up one side of the spiral structure, then down the other to that round window.

# Chapter eleven

# Vision

## *Seein' is believin'*

Your eyes may contribute grossly incorrect information to your internal displays of external reality but nevertheless, seein' is believin'. And where other senses are involved, you tend to rely more upon visual input than on smell, taste, touch or hearing. So when you are served a rich dark steak that smells and tastes like fish, you might wonder about local food storage facilities or conclude that today's entree was grilled seal rather than beef - yet despite the unexpected smell and flavor, this surely is meat and not fish.

Similarly, if it sounds like an elephant tumbling down the stairs but looks like your teen-aged son rushing off for a date, you will not be tempted to shoot. For vision ordinarily brings in such a flood of detailed information about external reality that other senses merely add feeling, flavor, tone or smell.

But should you become lost in an unfamiliar forest on a dark summer's night - with no flashlight or campfire to elicit nearby details - a few vague shadows might easily morph into terrifying threats as you try to recreate a coherent big picture out of buzzing insects, breaking twigs, animal calls and other ill-defined sounds that compete with moist, sticky, crawling or biting skin sensations and ambiguous odors - while thorns grasp your arms as you shield your temporarily useless eyes and stumble into wet holes, brush by creepy ill-defined things and crawl over or under fallen trees - hoping for dawn and a return of that wonderful visual input.

## *Two eyes are faster than one*

The speed and accuracy with which you evaluate a scene is ordinarily enhanced by the major overlap of your two visual fields. Thus an early comparison of left and right eye inputs allows you to interpret a scene and develop an appropriate response more rapidly than when one eye is covered.

Furthermore, each eye performs a considerable amount of preliminary processing. And by filtering out or enhancing a great deal of that raw data - arriving at 100 megabytes per second - an eye eliminates much noise and redundancy before referring its more relevant input centrally.

Upon reaching your brain, this information stream then diverges to allow separate analyses of positions, outlines, movements and colors. The outcome of that intermediate evaluation turns into the *what and where* of your next fleeting moment of visually defined internal reality. But before looking deeply into your eyes, let us review how a pinhole camera works and how light can be focused, as this may help us to see how eyes evolved.

## *A pinhole camera makes sharp images*

The pinhole camera is an internally blackened (to avoid reflections), light-tight box. A light-sensitive film is held against the back wall inside. There is no glass or plastic lens, just a covered needle-sized opening about 0.4 mm in diameter that passes centrally through the camera's front surface. If that pinhole is momentarily uncovered and all goes well, both the rich man and his camel will pass easily through that eye of a needle to expose the film, leaving a clear upside-down left-right-reversed likeness of themselves.

When a baseball player faces the camera with ball in right hand and glove on left, his image too will reach that film upside down. Fortunately, the ball and glove remain attached to their same (correct) hands - simply turn the exposed and developed film right side up and view it from the exposed side (but not through the back of a transparent negative film, for that would reverse left and right as in a mirror image). Apparently ball and glove have traded places in the same fashion as head and feet. How is this possible?

## *Pinhole dynamics depend upon slivers of bright light*

In order to expose the film and thus be visible, every tiny part of the scene (which happens to contain no lights or mirrors) and ballplayer must be illuminated sufficiently to become an independent source of reflected light. One can therefore view light reaching the camera as tiny segments taken from sequentially expanding spherical surfaces of light, reflected from each point of the scene.

Because the surface area of any sphere increases with its radius squared (here radius equals the distance between source object and camera), and the total amount of light emitted or reflected from an object is unaffected by the distance from which it is viewed, a camera twice as far away from an object will receive only one-fourth as much of its reflected light. A more distant object also occupies a smaller percentage (or angular dominance) of the camera's field of view, so that distant snow-covered mountain peak may appear smaller and less bright than a shiny new baseball nearby.

As mentioned, the baseball in the player's right hand reflects light in every direction, even toward the cheapest seats in the bleachers. So almost all of the baseball-reflected light misses the camera - only the tiniest bit of it is properly aligned to pass through that pinhole. And with the player centered in the scene, that sliver of light from the player's right hand will pass through the pinhole heading toward the player's left. Similarly, a tiny bit of all light reflected from the left-hand glove passes through the pinhole toward the player's right. And those shiny white teeth (this player does not chew tobacco) send slivers of light angling downward into the camera, while his once-white socks send their light slivers through the pinhole toward the top of the film.

If there is sufficient light and nothing moves, both the nearby scene and its distant background will remain in focus no matter how far back from the pinhole the film has been placed. But the farther back the film, the more those light slivers spread to form a larger but less clear and intense image. Of course, total light entry depends only upon brightness of the scene and how long the pinhole remains uncovered, regardless of film position.

That illumination can be increased by waiting for the sun to come up, or by turning on more lights, or by discharging well-timed flash bulbs somewhere behind the pinhole (in order to illuminate the near surface of nearby objects) while the pinhole is uncovered. Flash bulbs are especially helpful when an image would otherwise be too faint, or where the pinhole can only be uncovered briefly. For example, during a longer exposure, the moving ballplayer might travel across the scene, thereby blurring his image.

It seems logical that "not enough light for a good picture" could also be overcome by enlarging the pinhole to something more generous - say a circular opening 10 millimeters in diameter. Indeed, when it is really important to capture some dimly lit scene, why not momentarily uncover the entire front of the film? After all, a much larger camera opening intercepts far more of each expanding sphere of light, which should brighten the image in the same fashion as moving the pinhole camera much closer to the action.

Unfortunately, a film exposed through a simple larger-than-pinhole opening develops as a total smear. This occurs because light from each spot in the scene - baseball, teeth, socks, grass - passing through such an enlarged hole, now overlaps across much of the film, thereby exposing the entire film more or less uniformly. So the film exposed through a 10 mm finger-hole, or a film momentarily uncovered while facing the scene, will be relatively uniform in shade or color, recording no identifiable objects or details.

Even so, every part of that film did receive far more light than would have passed in the same time through a similarly placed pinhole. And that increase in light represents a much larger (though still tiny) fraction of all light reflected from every object in the scene. It seems that finger-hole camera pictures might become useful if we could somehow sort out the additional light slivers entering that finger-hole and redirect them to where each tiny sliver of advancing wave front would have hit the film in our pinhole camera. That apparently complex task can be simplified if the finger-hole is round, but before considering how light is focused by a circular glass lens, we might think about ways to bend and redirect light.

## *Refraction of light*

To simplify this exercise, let us assume that all objects to be imaged are more than 20 feet from the camera opening. That means photons reflected from the target area will approach in essentially parallel fashion - or you could view those incoming spherical wave-fronts of light as almost flat surfaces more or less parallel to the camera front. But regardless of whether you prefer to view approaching photons as parallel rays or arrows or as a series of flat wave fronts, all light penetrates clear glass or water more slowly than it travels through air.

Visible light that does not enter a glass or water surface perpendicularly will therefore slow most on the side that first enters the denser medium. So light photons encountering a clear glass or water surface at other than a right angle are refracted - their direction of travel is altered. That is why a straight but partially submerged straw appears bent or displaced at the surface of your soda.

You experience a comparable diversion when your right front car wheel wanders off the paved road. As that right side is slowed by snow, sand, grass or water, it will pull the car to the right unless you skillfully overcome this unexpected deviation - but don't overcorrect, for that would send you across the road into opposing traffic and probably kill someone.

On the other hand, if your car were to strike a strong guard rail at a minimal glancing angle, it might simply be deflected back onto the street. Some of the photons approaching a smooth water or glass surface are similarly reflected (bounced away). A mirror is simply a super-strong guard rail that reflects almost all photons regardless of the angle at which they strike.

It is possible to curve a guard rail or mirror so that it will bounce all parallel, incoming, perfectly elastic cars or balls or photons back toward a single point where they can be collected. And even a small properly curved mirror can focus enough sunlight at one point to start a fire - another reminder of solar-driven life's precarious existence between fire and ice.

## Light can be focused by refraction

A transparent glass camera lens is curved in such a way that all light collected from a single small object (for example, the baseball) will be redirected by its passage through the lens to produce a sharp image of that object on the film. Such a refractive gathering of parallel (or even diverging) light rays is readily accomplished by a doubly convex lens (one that bulges on both surfaces). Let us now sample a few light rays from the target scene directly ahead as they pass through that glass lens.

In the simplest case, a light ray strikes the exact midpoint of the convex lens and proceeds perpendicularly through the glass. So with parallel incoming rays, the center point of the symmetrically curved front-of-lens surface becomes equivalent to the former pinhole, as light passing through it will not change direction. However, incoming photons from the target that strike our convex lens off-center must enter that glass at an angle other than 90°, since the center is the high point of that lens. And because those off-center photons are initially slowed on their first-to-touch central side, all off-center photons are redirected slightly toward the lens center.

Photons passing straight through centrally do not deviate as they escape from the symmetrically convex back surface of that lens into air. However, all light rays emerging at a non-perpendicular angle from the bulging back face of the glass camera lens will first enter air on their peripheral side. That extremely brief center-sided drag (longer glass path) again causes each off-center photon to deviate centrally as it speeds up on escaping from the glass lens. In this fashion, a lens with proper convex curvatures can concentrate all entering and essentially parallel rays of light from any part of the baseball onto the same spot of film that a mere sliver of that light would have hit after passing through an identically centered pinhole.

But a lot more light has passed through this larger glass lens so the image is much brighter - providing better detail with a far shorter exposure time. As with the pinhole, light passing through the lens from the right side of the scene exposes the left side of the film, and the image will be upside down as well. Unlike light passing through a pinhole, however, the light gathered through a lens creates a clear image only at the one point where it comes into focus. Before or behind that focal point, the projected image of an object remains blurred. Furthermore, by collecting more light from a narrower field of view, a lens focusing light from a distant object creates an image that seems much closer than it would appear within a wider-view pinhole camera at the same spot.

Once again, by doubling the diameter of the tiny pinhole and inserting a tiny lens, one can collect four times as much light during the same brief exposure - equivalent to locating the camera half-as-far from the object. Note that we have not considered the apparent size of the image on the film, as we can easily expand or shrink that sharp image by altering the lens focus - while moving the film away from or toward the lens to keep the film precisely at the focal point of the camera lens.

If we wish to make an enlargement for better evaluation of detail, or so some part of the image seems closer, the grain size of the film and the quality of the lens, as well as the original illumination, will determine how much magnification can be achieved without rendering the image indistinct.

Computer enhancement can un-blur an image and increase contrast by filling in what ought to have been there. Your own eyes continuously perform that same difficult trick on a real-time basis. For example, whatever dominates the adjacent image at any moment is routinely expanded to fill in for information not received from the blind spot of each retina (see below).

## *Focusing on nearby objects*

Rather than being almost parallel as in previous examples, light rays from nearby objects still diverge noticeably at your camera lens. To focus light from nearby objects with an ordinary lens, your film is moved back from that lens to provide those initially diverging light rays with a longer post-refraction path over which to reach a focus.

Of course, light rays from nearby objects may continue to diverge even after refraction by the usual camera lens if that lens was not strong (curved) enough to bend them back to a focus - the image of that nearby object then remains indistinct at every film location. On the other hand, a blurry background results when the camera has successfully focused onto a nearby baseball - for if diverging baseball rays are sufficiently bent to reach a focus at the film, all parallel light rays from the background will have come together and again spread out before encountering the film.

## *The rainbow is a sign that a flood of different light frequencies have been refracted*

A prism separates white light into its constituent colors. Of course, there really is no such thing as a color. Colors just happen to be the graphic and efficient way you visualize specific wave-lengths of visible light. And since your various photoreceptors are stimulated in accordance with their sensitivity to specific wave-lengths, any visible light frequency can be recognized and displayed internally as light of a particular color.

Most of us would insist that colors really exist, or at least that they provide real information about a real object that (like other attributes of such an object) might be subject to change. And most of us seem to experience colors in a relatively similar fashion. Or at least we have learned to label certain frequencies as red, green or blue and so forth, whenever those particular frequencies show up on our internal reality display.

Electromagnetic frequencies differ markedly in how readily they penetrate clear glass. Even within the narrow frequency range of visible light - which has a wavelength of 400 to 700 nanometers or billionths of a meter - the longer waves - that carry less energy and thus make fewer zigzags within a given distance - are refracted less than shorter light waves as they enter and leave clear glass. Therefore any spot of incoming light will spread into an orderly spectrum (consecutive display of its component frequencies) on passing through the non-parallel flat glass surfaces of a prism - just as sunlight passing through certain size water droplets (on the side of you away from the sun) is naturally spread into a rainbow projected onto other droplets behind them.

## *Darwin was initially perplexed by evolution of the eye*

Before we apply some of this optical information to the human eye, let us consider how a complex mechanism such as your eye could possibly have come about - other than by Divine design. Darwin puzzled a great deal over that. At first, he could not imagine that such a delicately adjusted optical system with so many critically interacting components could develop gradually. For had the eye evolved over a long time as he suspected, it would have passed through an endless number of intermediate stages. However, each of those many stages could only persist and spread if it brought immediate reproductive advantage.

Yet it seems intuitively obvious that a partially evolved eye should bring little benefit - especially when minor modifications or injuries can so easily disable a fully developed eye. But as Darwin considered the incremental and cumulative way that all things appear to have evolved, he soon realized how the complete eye must have come about - just as knowing from whence one came often identifies the path actually taken and shows why the path not taken was selected against.

Of course, any likely or even inevitable event can be made to seem highly improbable if one focuses overly on details. For example, one might recklessly conclude that an arrow traveling at finite speed would never reach its target if advised that its flight path was divisible into an infinite series of points, each of which the arrow would have to pass in turn. Still it is fair to say that only the most extraordinary series of improbable coincidences could account for the fact that you, of all people, happen to be sitting in that special chair, wearing those exact clothes and scratching that particular spot as you read this unique sentence.

But this too has come to pass - although mathematically speaking, it is so extremely improbable that it ought never have happened. In fact, anyone predicting all of these details some years ago might well have been burned at the stake. For fire permitted the dominant theology to suppress new ideas and simultaneously determine if they posed any threat, since being fireproof was considered a worrisome sign of divine backing.

On the other hand, the average, mathematically disinclined dolt of one thousand years ago would hardly view your nice books or clothes or chair as miraculous since these seem ordinary and indeed, probable outcomes. Using such a commonsense approach, the pathway along which the eye must have developed also appears unavoidable.

As a point of departure, it is logically and chemically apparent that many sorts of light-sensitive molecules were available long before the first photosynthetic bacterium absorbed its first photon almost four billion years ago. Furthermore, it seems clear that a light-sensitive spot would benefit any bacteria, protozoa, algae or multicellular organisms that prospered near the water's surface where solar energy and food were most abundant.

Even today, unicellular life often derives important directional information about light by modifying its pathway through transparent and reflective areas. And if a photosensitive spot on a multicellular creature happened to be located in a surface indentation, that dimple might sufficiently improve information about light direction to help "Dimples" become queen of the beasts - because of her increased efficiency in moving toward the surface and avoiding predation.

Of course, that advantage would only persist until some progressive multicellular descendent came up with an even deeper dimple. Thus deeper-dimple-with-a-photosensitive-bottom probably ruled until almost-covered-deeper-dimple, having accidentally invented the pinhole camera concept, became first to clearly image the world. Her reaction was not recorded, but we can hope that she found it good.

Clear-covering-over-pinhole may have been the next big advance, for a covered pinhole is less easily obstructed by debris. Those inheriting a larger covered aperture then gained sudden advantage when an unusually concentrated protein solution crystallized within that primitive orb. The resulting clear glob of protein developed a relatively spherical shape as it rolled about inside the fluid-filled eye, bringing the world in and out of focus.

Presumably that relatively spherical proto-lens - with focus dependent upon position - eventually gave rise to the modern spherical fish-eye lens whose attached fibers control its location in order to focus light on the photosensitive retina. An endless succession of similar mini-modifications surely took place before your wonderful eye lens with its perfect shape and appropriate index of refraction became available. And so it came to pass that those who saw the light most clearly, ruled more or less wisely over the rest.

## *The light path through your eye*

Light photons must traverse several transparent interfaces to reach your retinal photoreceptor cells. The foremost refractile element of each eye is the thin tough cornea - composed of crystalline collagen and surfaced by non-keratinized skin cells. And because any blood vessels crossing the corneal surface would interfere with vision, corneal cells obtain their oxygen and nutrients indirectly via nearby fluids.

The transparency of your cornea depends upon maintaining its very low water content. Cells lining the inner corneal surface therefore secrete enzymes that disrupt nearby water-attracting proteoglycan molecules and actively remove water. On the other hand, tiny droplets of trapped water reflect light away from the tough white cover around the rest of each eye. And colloidal water lends similar lustre to your pearls, which can dry out and be ruined during prolonged storage in a low-humidity bank vault - just another good reason to flaunt those pearls on your moist skin.

After passing through the cornea, light enters clear nourishing liquid in the forward eye chamber. In bright light your pigmented iris muscle constricts to form a 2 mm wide central circle. That reduced opening minimizes refractive errors consequent to incorrect off-center curvatures of the cornea or lens. Thus bright light improves visual acuity by taking you back toward the always-in-focus pinhole camera concept of your ancient ancestors. A narrowed pupil also directs all light onto the closely packed color-sensitive central retinal photoreceptors.

In contrast, darkness or an adrenalin-producing fight-or-flight reaction can dilate both pupils to about 8 mm diameter, which allows 16 times more light to enter. For during an emergency, full peripheral vision in and out of the shade becomes far more important than ideal retinal illumination or perfect focus. Ordinarily, however, your pupil size reflexively adjusts to light intensity.

The clear doubly-convex lens of each eye is held in position behind its pupil by fine suspensory ligaments. These ligaments extend from a circular muscle that rings the forward inner surface of each eyeball. Your lenses are constructed of flexible well-ordered crystallized proteins, produced locally in large amounts by the combined efforts of repeatedly duplicated genes. Elsewhere in your body the same proteins appear in appropriately tiny quantities as enzymes, heat shock proteins and so forth.

All lenses yellow and become increasingly opaque during a lifetime of use. Early lenticular opacities produce a fine halo of radial light rays about a bright object or light at night. Such a halo is sometimes mistaken for a dirty windshield or profound spiritual experience.

A lens may eventually become so opaque that it must be removed surgically and replaced by an artificial lens of appropriate curvature in order to restore useful vision. Life style and occupation often determine how much lenticular opacity can be tolerated. A long-haul trucker might opt for cataract extraction earlier than a retired person who mostly watches television and avoids driving at night.

## *Keeping an eye full*

The main portion of your eye behind the lens is inflated by a clear collagen-containing gel that - supplemented by freshly secreted fluid - maintains eye size, shape and focus regardless of your position or state of hydration. The gently curved back of your eye provides more accurate directional information than does the flat back wall of a camera.

As in your camera, the retinal image at the point of focus is left/right reversed and inverted. Because you customarily view the world in this fashion, you compensate for it without noticing. One can even get used to seeing things right side up after wearing inverting glasses for several months - just as American pedestrians in London eventually learn to look right for high-speed traffic approaching in the curb lane, if they live long enough.

## *Accommodation*

Light reaches your retina after being redirected at both cornea and lens. A normal youthful eye adjusts its lens curvature in order to focus light from nearby or far-away objects onto retinal photosensors. To see nearby objects clearly, you contract the circular ciliary muscle, thereby loosening the suspensory ligaments so the lens can bulge.

On the other hand, relaxation of the ciliary muscle that encircles your eye, flattens the lens by increasing tension on those suspensory ligaments around its periphery. Such a flattening brings more parallel light rays from distant objects to a focus at the retina while nearby objects become blurred since their diverging light rays now reach a focus behind the retina.

## *Your retina*

The photoreceptor layer of each eye includes about 3 million cone cells and 100 million rod cells. When bright light causes your pupils to constrict, the narrowed iris directs light centrally onto your densely packed color-sensitive cones. In contrast, pupillary dilation in dim light brings less closely packed, highly light-sensitive rod cells into play. Cones perform poorly in dim light because their response varies with photon wave-length, so ordinary objects gradually lose color as evening falls.

A faint star may only be visible if you look next to it rather than directly at it, since starlight too dim to excite the cones can still excite your rods. That is why persons losing peripheral vision from glaucoma or other cause have increasing difficulties with their night vision. An off-center blind spot identifies the site on each retina where nerve cell extensions gather into the optic nerve en route to your brain.

## *Right brain sees to left and left brain sees to right*

The two optic nerves meet and exchange nerve fibers before they reach your brain. Thereafter your right nerve only delivers information centrally from leftward looking photoreceptors of both eyes and vice versa. This useful arrangement allows continuous mapping of any object as it crosses your field of vision (e.g. from far left to far right).

For if each eye mapped only onto its same-side hemisphere, there would be computational discontinuity as an object appeared first on one side and later became visible to the other eye as well. Hence that crossover - plus the enhanced depth perception provided by their overlapping visual fields - permitted your primate ancestors to grab tasty insects and swing away more easily through the branches.

## *Your retina is poorly organized*

Instead of being positioned at the front of each retina to intercept all incoming photons, the photoreceptor cells of your eyes lie beneath several layers of nerve cells and blood vessels. This awkward arrangement potentially reduces your visual sensitivity. It also requires your rods and cones to “not notice” all those overlying cables and pipes. Fortunately, that not-noticing is easily achieved, as continuous minor oscillations of your eyeballs encourage each retina to ignore all retina-stationary objects.

For vision - like other sensory systems - is organized primarily to detect and report upon changing inputs. Hence a truly steady gaze at a boringly stable scene would soon cause that scene to fade. But you can never evaluate an entire scene fully, so your eyes continuously make swift voluntary eye movements between selected targets in your visual fields. And to reduce computational complexity, each oscillation is slightly preceded by an appropriate minor shift of the central image display that brings it into register with the anticipated change in peripheral input.

Nevertheless, a more efficient design would have placed your light receptors at the front of the retina, with their neural and circulatory support systems behind. That would also have eliminated your blind spots and the tiny faint circles that you sometimes see pulsing across your visual field as you gaze at a bright featureless sky. For those dots are blood cells chugging through tiny retinal-surface blood vessels, greatly magnified by reflection from the convex inner (back) surface of your lens.

Of course, design inefficiencies and illogicalities might be anticipated in an eye that evolved from a photosensitive spot by a endless succession of chance improvements. And their persistent back-of-the-eyeball position may merely reveal how much your photoreceptors depend upon their underlying black (light-absorbing) support cells - just as other neurons depend upon their support cells. So when the primitive ancestral retina gradually upgraded its computational abilities with additional processing neurons - and the blood supply inside the enclosed orb correspondingly increased - those photoreceptors became buried beneath such semi-transparent add-ons.

In similar fashion, old English homes often display parts of their plumbing amongst the ivy on their outside walls. While functional, this arrangement is hardly ideal, though exposed pipes are easier to reach when they freeze. The point here is that as eyes and older buildings evolve, every intermediate stage must have advantages over other options, which include more major renovations or starting over.

Once again, evolution is the only plausible explanation for your eye - or for that inconvenient old English home you may just have inherited. And many such less-than-ideal arrangements remain quite competitive as long as all local competitors are subject to similar limitations. But American plumbers and plumbing appliances evolved under more competitive conditions, so if they ever gain a foothold in England, they will surely spread over that island kingdom just as Africanized honey bees marched through Latin America.

## *Making a spectacle for yourself*

Being far-sighted is not uncommon among the Inuit (Eskimo) people. With their traditional prey so distant and wary, being near-sighted meant certain failure as a seal hunter. Inuit children often seem less reckless in their early explorations and less verbal, which is appropriate to their traditionally dangerous surroundings and cramped housing. Indeed, these children are encouraged to watch from the sidelines until they can contribute to group activities that they have observed and learned.

Although that approach makes them less likely to excel in a typically competitive American classroom, one can imagine that an Inuit who talked too much might risk getting heaved out of the old igloo during those long, depressingly dark winter months - which would surely be a major reproductive disadvantage. Such speculation aside, we know that the eyeball is relatively too short in any far-sighted individual. Diverging light rays from nearby sources therefore reach a focus well behind the retina, providing only a blurry view of those nearby objects.

Far-sightedness or near-sightedness can be corrected by placing an artificial lens (spectacle) in front of the cornea or - under bright light conditions on snow and ice - by peering through two tiny, properly centered openings in otherwise opaque bone “glasses” (the pinhole camera concept again, this time utilized to avoid snow-blindness from excessive glare). Note that far-sighted and near-sighted describe distances at which seeing is clearly in focus rather than blurry. But these terms do not imply hyperacute vision at any distance, since a normal eye will see as clearly at a distance as a far-sighted one does.

In fact, being far-sighted is disadvantageous, for a far-sighted person will have progressive difficulty with near vision as the maturing lens becomes less adjustable (flexible) with age. A very far-sighted older person may eventually be unable to focus images on the retina at all. Such an individual then requires corrective lenses for all distances (bifocals or trifocals).

But the bifocals you use for reading could cause you to trip or fall down the stairs, since tree roots on a forest trail, or the stairs you descend, can only be in focus through the upper prescription. Corrective glass lenses for far-sighted (relatively-too-short eyeball) people are predominately convex in order to focus light within a shorter distance.

On the other hand, near-sighted individuals have relatively-too-long eyeballs. So while light from nearby objects is easily focused upon that retina, light approaching in parallel rays from distant objects will come to a focus in front of the retina - therefore, far away objects remain blurry. Yet without their glasses, older near-sighted persons are less visually disabled than older far-sighted persons, for the near-sighted at least see nearby objects without corrective lenses.

Corrective lenses that allow a near-sighted individual to see clearly at a distance will be concave (thicker edges than middle). Those heavy-looking concave lenses cause parallel light rays from distant objects to diverge slightly (as if from a nearby object). Such artificially divergent rays are then more readily focused on the too-far-away retina. Of course, younger individuals may be quite near-sighted or far-sighted and still retain a good range of focus.

## *Fish eyes came first*

You become terribly far-sighted and everything is blurry while your face is underwater, for submerged corneas no longer bend light as they did in air. To regain useful vision while diving, you wear an air-containing helmet, face mask or goggles. However, this equipment also magnifies your hands, feet and nearby large fish due to refraction at the glass-air interface.

Some diving birds achieve clear underwater vision without goggles by markedly enhancing their lenticular and corneal curvatures during each submergence. Fish that remain underwater have flattened corneas and a highly curved (spherical) lens. One surface-feeding fish that needs to see both above and below the surface has an hourglass-shaped pupil with a bulging, backward-tilted lens that presents its flattened aspect to the upper (air) view, while waterborne light entering the lower portion of the hourglass is bent more sharply by passing through the more curved aspect of that same lens.

## *Your retinal photoreceptors*

The photoreceptor function of your rods and cones depends upon a molecule of retinol (a derivative of Vitamin A) changing shape when struck by a single photon. Vitamin A also has importance for your skin development and metabolism, and is closely related to a tissue organizer chemical - another case of slightly modified molecules serving quite different functions. The particular pigment molecules within any rod or cone cell determine what wave lengths of light will excite that cell. Genes for these photopigments are located on your X chromosome. Human males inherit one X chromosome while human females have two, so males have a far higher incidence of color vision deficiencies than do females.

Many vertebrates and invertebrates orient retinol's crucial double bond in thin organized layers, with that orientation rotated differently in different photoreceptor cells. This allows birds and bees to navigate by the polarization of daylight when the sun is obscured. Presumably it also helps fishing birds ignore light reflected from the water's surface as they size up their next victim. Similarly sensitive fish can pick up polarized light reflecting from otherwise well-camouflaged silvery fish surfaces. Since there was little reproductive advantage for your ancestors in retaining this skill, you must now purchase Polaroid glasses to see if any fish remain in that clear mountain stream.

Through its effect on a molecule of retinol, a photon of properly colored light brings about closure of leaky cell-membrane sodium ion channels. The consequent hyperpolarization of every illuminated rod or cone cell leads to variation in electrical potential across the entire photoreceptor surface (retina) that corresponds to the intensity and color of light from the scene being viewed.

Certain nerve cells report the average electrical charge in small groups of photoreceptors, providing a background against which sudden new photoreceptor information becomes dramatically evident. As a result, you can easily track moving objects during changes in background illumination that may vary by many orders of magnitude as you leave bright sunlight to enter your dark and presumably unoccupied cave. This preliminary processing and extraction of important information within your retina markedly decreases the computational burden that continuously modified individual reports from a million reporting cells in each eye would otherwise place upon your central nervous system.

The scale invariance of your eye is another useful built-in mechanism to help reduce information overload and excessive computation. For since the image of any rapidly approaching object is increasingly projected laterally (where rod cells are less closely spaced), the internal display of that approaching object is maintained at the same level of detail except for important new information received by your closely packed cone cells. That allows you to concentrate upon and get progressively more detailed information about important items such as teeth and claws.

Messages from rods are sent via party lines - any of a group of rods can report through their shared cells. This makes things seen out of the corner of your eye (or at night) more difficult to evaluate. On the other hand, each cone usually has its own dedicated line to a reporter cell. Partially preprocessed retinal messages are sent to different sectors of the thalamus for separate handling of information about color, shape and movement. The hypothalamus also keeps track of day/night and seasonal light changes in order to adjust your various internal rhythms appropriately.

Six externally attached muscles direct the gaze of each eyeball at the target with some spare capacity. Four of those muscles control up, down and sideways movements while the other two (up-and-out and down-and-out) improve control in the more important lateral directions when the other eye sees mostly nose. Eye muscles are reproductively advantageous because they permit quick changes of eye direction without moving the head. That allows you to remain completely still while keeping an eye out for predators, prey or reproductive opportunities.

In contrast, an owl must fly in the dark using subtle visual and auditory cues to capture wary victims. By eliminating eye movement entirely, the owl keeps its internal visual and auditory displays of the target location in permanent register, while compensating for the resulting fixed stare with fourteen hyper-mobile neck vertebrae that allow 270° of neck rotation in either direction - for a total of one-and-a-half full turns. Mammals have only seven neck vertebrae, so don’t try this.

Your cornea and inside-of-eyelid surfaces are kept moist by fluids from a tear gland located within each upper eyelid. The upper eyelids also include internal support plates. Eyelash hairs sprout from the edges of your upper and lower eyelids. Your eyelash-associated oil glands keep those eyelid edges greasy and thereby prevent tears from flowing across your corneas except when you blink. An ordinary rate of blinking automatically moistens and refreshes your outer corneal cells and cleans corneal surfaces. A higher rate of blinking suggests an affectation, a tic or corneal irritation.

Minor amounts of tear fluid drain away through a small opening at the inner corner of each eye to reach the nose. Larger volumes also wet your face, which can be a reproductively advantageous way of demonstrating strong and sincere emotions in a non-threatening fashion, or of washing away irritating substances.

# Chapter twelve

# Your circulation

Your blood is routed through countless tiny lung capillaries to exchange gases - through innumerable gut capillaries to pick up nutrients - through your spleen for the removal of old blood cells and other circulating debris - through your liver for the modification or storage of nutrients and the disposal of blood cell breakdown products - and through your kidneys for the elimination of excess water, salts and other soluble materials. That continuously revitalized blood also passes near your many dozen trillion cells in order to deliver essential supplies, remove metabolic wastes and maintain your multilevel defenses against invading microbes.

Despite those unlimited transactions in your various tissues, only the gas concentrations in your blood are sufficiently altered by one passage through a tissue capillary to require immediate reconstitution in a lung capillary. Therefore, your closed and circular circulation utilizes one muscle-powered pump or ventricle to drive blood returning from lungs out through tissue capillaries, and a second muscle-powered ventricle to push blood returning from tissue capillaries out through lung capillaries.

A separate muscle-enclosed blood-collecting chamber or atrium - located on the input side of each ventricle - rapidly refills that pumping chamber after each contraction. For optimal efficiency and protection, those four heart chambers are gathered centrally within your bony rib cage. There, between billowy lungs, your heart lies securely encased within its slippery fibrous pericardial sheath.

Your arms, legs and head are arranged about the circumference of your body in a fashion that maximizes their utility. Consequently, your left ventricle must move oxygenated blood returning from lung capillaries out in all directions at rather high pressures. Indeed, left ventricular pressures in an adult can intermittently raise a column of blood more than 150 cm above the heart - which exceeds the distance from your heart to your toes. In contrast, your right ventricle needs less than 30 centimeters of water pressure to push the oxygen-depleted venous blood returning from your tissues, out through innumerable nearby lung capillaries.

Blood passes through the capillaries of your different tissues in response to local demands for pick-up, delivery and pressure. Those demands vary greatly as you exercise, overeat, drink too much, think great thoughts or become sexually aroused. Sensible people avoid combining too many of these activities, since a normal blood volume cannot distend all blood vessels simultaneously - nor could the normal heart support full blood flow to all body capillaries at once.

During major physical exertion, most of your blood cycles rapidly between lung and muscle capillaries. At other times, lung and muscle vessels narrow as your circulation slows, and more blood becomes available to your gut, kidney, brain or genitalia where it still might do some good. However, all blood capillaries require ongoing access to some blood, at least most of the time.

So as you sit there fascinated by this book, you will become increasingly restless and shift your position in order to bring new blood to circulation-deprived portions of your "tired butt". In contrast, you could read for hours while nearly afloat in a full bathtub without blocking those same capillaries. And having your brain submerged in cerebrospinal fluid similarly precludes circulation-blocking pressures at sites where soft brain would otherwise rest on bone or fibrous tissue.

## *A single main pulmonary artery - a single aorta*

By keeping their blood vessels few and straight, your ancestors minimized non-productive blood storage, resistance to blood flow and risk of blood vessel injury. Therefore, bright-red freshly oxygenated blood flows directly from each lung into the back of your midline left atrium through two stubby pulmonary veins, while bluish deoxygenated venous blood from your upper and lower body enters the top and bottom of your right atrium via two short large-diameter veins known as superior vena cava and inferior vena cava.

Your right ventricle intermittently pushes bluish deoxygenated blood through your main pulmonary artery toward both lungs, while your left ventricle repeatedly forces bright-red freshly oxygenated blood through your aorta to every systemic (non-lung) artery. All of your blood vessels except the aorta and vena cavae have actively adjustable diameters. The smooth muscle cells that control your blood vessel diameters are closely regulated by the sympathetic (involuntary or vegetative) nervous system - which allows you to sustain brain capillary blood flow without cheating your feet.

Not surprisingly, your high-pressure systemic arteries have considerable smooth muscle in their walls. But because the thick-walled aorta near your heart must accept three ounces of incompressible blood during each brief contraction of your left ventricle, the aortic wall is primarily composed of elastic fibers and sturdy fibrous tissue with hardly any smooth muscle. By deflating smoothly after each refill, that distended aorta converts intermittent heartbeats into a continuous, pulsatile flow of systemic blood.

## *All muscles pump blood*

Every contraction of your heart muscle pushes blood toward all of your capillaries, including those serving your heart muscle. Each voluntary skeletal muscle contraction pushes some of that blood back toward your heart. And it all began when the very first muscle cells shortened and bulged out sideways, thereby displacing nearby fluids.

As time passed, larger muscle groups often acquired incomplete fibrous envelopes that held them in place and reduced the impact of each contraction upon nearby nerves and vessels. Yet no matter how skeletal muscles might reorganize or specialize, any considerable contraction of a muscle inevitably squeezed all blood vessels within its compartment.

So since work expended on compressing blood vessels diminishes the efficiency and impact of a skeletal muscle contraction, your naturally selected voluntary muscles enclose only their own small nutrient arteries, capillaries and veins. Nonetheless, every forcefully contracting muscle still constricts its own blood supply at a time of increasing energy need.

And that is why you cannot long sustain the repeated muscle fiber depolarizations and contractions of a truly strenuous skeletal muscle contraction. In contrast, your slowly contracting smooth muscle cells can maintain their prolonged contractions without difficulty.

## *One-way blood flow enhances circulatory efficiency*

When a skeletal muscle contraction squeezes local capillaries and veins, it pushes oxygen-depleted blood into nearby larger veins. Thin wall-mounted flaps inside those veins allow easy egress of blood during each muscle contraction, but prevent blood in larger veins from sloshing back as the muscle relaxes. Thus your venous flap valves support the one-way flow of blood through muscle capillaries and veins.

On the other hand, venous blood return from your non-contractile brain is enhanced by locating your head above your heart. And sturdy fibrous attachments to nearby bones and muscles hold your brain-surface and deep-neck veins open against the suction generated within those veins by blood falling toward your heart.

Overall, your venous drainage benefits from the intermittent respiration-and-exercise-related compression of all viscera within your chest and belly. Thus directly or indirectly, the contractions of your voluntary skeletal muscles expedite the return of venous blood from all tissues - even your skin, subcutaneous fat and bone benefit secondarily.

Arteries deliver blood to muscles at relatively high pressures, so arteries have thicker walls and narrower channels than the thin-walled veins that drain blood away at comparatively low pressures. High arterial blood pressures and relative arterial incompressibility prevent a significant reversal of arterial blood flow during local muscle contractions, so your arteries need no internal valves.

Your tiny thin-walled capillaries need no valves either, for contractile cells already regulate capillary blood inflow and blood cells barely can squeeze through open capillary channels as it is. Besides, every compression of a capillary naturally advances its blood content away from the high-pressure arterial end toward the low-pressure venous end.

By the time blood reaches the venous end of a capillary, the pressure and momentum provided by the left ventricle have mostly been dissipated. Hence the return of venous blood to your heart must be encouraged in every possible way. So you maintain extra blood vessel capacity on the venous side, with many more outflowing veins than inflowing arteries - and each of those veins has a larger channel than its corresponding artery.

Furthermore, those veins interconnect at many levels. And that meshwork pattern allows venous blood to follow the pathway of least resistance toward the heart. Were it otherwise, the inevitable compression of some veins - as you stand, sit, cross your legs or lie down - might obstruct blood passage through the capillary beds that they drain.

Therefore you have lots of veins, and lots of connections between those veins. And at every point where one vein enters another, delicate internal valves prevent venous blood from flowing back toward its most recently occupied capillary bed. In this way, each fragile one-way venous valve intermittently becomes a sturdy weight-lifter, supporting a column of blood that stretches up to the next valve.

## *Heart muscle*

The voluntary muscle fibers of a skeletal muscle motor-unit remain relaxed until the next motor nerve impulse elicits another swift and predictable response. Your inherent ability to modify the extent and duration of each motor unit contraction - and the practiced way you now meld that refined contraction with the right sequence and combination of other motor unit contractions - accounts for your impressive strength and fine motor skills.

In contrast, the heart muscle cells of your atria or ventricles must contract regularly - as well as simultaneously and rather slowly - in order to squeeze incompressible blood out of those large blood channels (heart chambers) through which all blood moves to and from your tissues. So while long, slender, skeletal muscle fibers exert their variable tensions efficiently upon distant tendons and bones, your short, stubby, securely interconnected heart muscle cells are better suited to the cooperative sustained concentric contractions of your heart.

Furthermore, heart cells await no nerve impulse to initiate the next heart beat, for all heart muscle cell membranes bear leaky ion channels that cause them to depolarize and contract regularly. Ordinarily, your right atrial muscle cells near the superior vena cava depolarize most frequently. And these cells - the heart's natural pacemaker - are especially responsive to the nerve impulses and circulating hormones that match your heart rate and contractility with your level of activity.

Hence regardless of which atrial cell happens to depolarize first, that atrial cell excitation spreads rapidly through open intercellular electrical connections to all atrial muscle cells. Both atria then contract as a unit. And after a brief conduction delay to allow time for additional ventricular filling, both ventricles follow suit with their own coordinated depolarization and contraction.

Your cone-shaped left ventricle contracts with a noticeable twist that wrings out more of its enclosed blood. This motion also squeezes blood from the simultaneously contracting, thinner-walled right ventricle that lies across the left ventricle's forward surface.

Moment-to-moment changes in pressure or flow often cause one heart chamber to pump different amounts of blood than another. However, each chamber normally sustains the same output per minute as all the others, since a persistent imbalance of output would rapidly reduce the circulating blood volume as an underperforming right or left ventricle delayed incoming blood - with the resulting back-pressure causing that blood to congest liver or lungs.

With each new systolic contraction, ventricular chamber blood pressures rapidly rise above atrial chamber blood pressures. The resulting sudden reversal of blood flow causes flexible valve leaflets located between each atrium and its ventricle, to slam shut - just as a first gust of wind slams your bedroom door. As ventricular cavity blood pressures continue to rise, small intra-cavitary extensions of ventricle wall muscle increase their tension on thin tendons that prevent the free edges of inter-chamber (atrium-to-ventricle) valve leaflets from flipping back into the atrium.

Your thin pulmonic and aortic valves open widely when intraventricular blood pressures exceed pulmonary artery and aortic pressures. Thereafter, the blood pressures in those great arteries and their respective ventricle chambers rise together. With the onset of ventricular relaxation, your pulmonic and aortic valves again slam shut as ventricular chamber blood pressures fall below current pulmonary artery and aortic pressures. Blood pressures in your initially distended pulmonary artery and aorta then gradually decline as blood flows out through all of their arterial branches.

## *Your inevitable heart*

No great imagination is needed to see how an ordinary muscle - unavoidably compressing its own blood vessels - might evolve through innumerable individually advantageous modifications to become your wonderful modern heart. Nor does your heart's slippery pericardial sheath differ greatly from the fibrous (collagenous) envelopes that enclose and separate other muscle groups (making "stew meat" cuts tough to chew before prolonged cooking).

That your larger coronary (Greek for "wreath" or "crown") arteries usually lie within soft heart-surface fat also makes sense, for that protected low-pressure location allows those arteries to distend with oxygenated blood during ventricular contraction. The smaller coronary arterial branches and capillaries that are intermittently compressed within contracting heart muscle, then admit blood from these replete surface arteries as soon as the next muscle relaxation begins.

Even the large coronary vein that delivers heart muscle venous drainage to the right atrium is exactly where it should be. For if deoxygenated venous blood from heart muscle drained into the left atrium - rather than circling around to the right atrium - that would reduce the average oxygen content of left atrial blood – fresh from the lungs and headed for your tissues.

The low entry of your main coronary vein into the right atrium makes sense as well; for those alternating atrial and ventricular contractions are least likely to disturb a low-pressure vein if it overlies the stable fibrous groove between your collecting and pumping chambers.

## *Lymph channels return tissue fluids to the circulation*

Arterial blood pressures force some of your blood's water and dissolved salts out through permeable capillary walls into the surrounding tissues. Innumerable small interconnecting valve-containing lymph channels (that develop in response to the same growth factors as blood capillaries) soon salvage and return that fluid to your closed circulation, thereby preventing chronically swollen tissues.

The soluble content and particulate debris borne by lymph is repeatedly filtered through local and regional lymph nodes where unwanted materials are identified and destroyed by special immune and eating/digesting cells. Lymph glands in your neck or armpit become noticeably swollen and tender when fighting a local infection, but ordinarily these smooth ovoid structures are most easily felt in the groin area.

Like venous blood returning to the heart, the low-pressure forward flow of lymph is encouraged by skeletal muscle contractions, internal one-way valves, and the intermittent gentle massage exerted by huge numbers of simultaneously expanding capillaries during each heart beat, as well as by tissue compression (e.g., elastic stockings) or elevation above the heart.

Lymph fluid eventually reenters the venous blood - primarily via your neck veins (where the average venous pressure is kept low by suction created as blood falls toward the heart). The same surface-tension-dependent siphon-effect sucks surplus cerebrospinal fluid across a fine mesh filter into the large vein above your brain.

## *Your parts tend to fit*

Your heart remains well-suited for its circulatory duties because cardiac growth occurs in response to persistent stimulation of the sympathetic nervous system, or to continued chemical requests for “more blood pressure” from the kidneys as they filter and adjust your circulation. Your skin, blood, lungs, gastrointestinal organs, muscles and other tissues similarly adjust to your size and the burdens that they routinely bear.

Apparently there are no preset or standard dimensions for various body parts. Had you been malnourished or chronically ill during childhood, the individual parts of a smaller you would generally have been appropriately reduced in size.

# Chapter thirteen

# From gills to lungs

*Photosynthesis splits water into hydrogen and oxygen, then stores those reactive hydrogens on carbon as carbohydrate.*

## *Photosynthesis disrupts water - combustion recombines it*

Plants utilize solar photon energy to rip hydrogen (H) atoms out of water ($H_2O$) molecules. Those reactive hydrogen atoms are then combined with carbon (C) atoms extracted from carbon dioxide ($CO_2$) molecules to create carbohydrate ($CH_2O$) molecules. This **photosynthetic** process goes:

$$H_2O + \text{solar energy} + CO_2 \rightarrow CH_2O + O_2$$

Thus photosynthesis converts captured sunlight into portable chemical bond energy that may be accessed gradually through controlled biological combustion by solar-energy-dependent life forms, or liberated catastrophically by uncontrolled chemical combustion in a raging forest fire, or by explosion of fine airborne dust in a grain silo. In each case, carbohydrate's stored solar energy is released as its captive hydrogens rejoin oxygen to form water (and its carbon is oxidized to carbon dioxide). But whether controlled or catastrophic, this **combustion** reaction goes:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O + \text{energy}$$

Until about two billion years ago, the gaseous oxygen ($O_2$) molecules released during photosynthesis soon combined with other exposed elements. But as photosynthetic life prospered, Earth's exposed minerals eventually became fully oxidized, so oxygen began to accumulate in the atmosphere.

Even the initial small buildup of free atmospheric oxygen proved toxic for many anaerobes. But some endured and adapted until Earth's increasingly aerobic life forms eventually perfected a carefully controlled oxidation - using atmospheric oxygen - that gave them complete access to energy stored in carbohydrate and other organic molecules.

How life first organized its cautious combustion process is unclear. Perhaps the initial survivors happened to deactivate a few poisonous oxygen molecules with hydrogen atoms already stored on carbohydrate. But before long, some of the energy released during this partial internal reversal of photosynthesis, found productive use.

As oxygen levels continued to rise, successful aerobic life forms avoided spontaneous combustion by releasing carbohydrate's power slowly through a rambling series of underwater steps. However, water's high heat capacity is just one of many reasons that life's chemistry remains water-based.

For water is also a great solvent - and the removal or insertion of water molecules allows life to build or break down larger organic molecules through dehydration synthesis or hydrolysis (see digestion chapter). Furthermore, water is plentiful, and except for mercury, water is the only liquid substance naturally present on Earth's surface.

In any case, life surely arose in water. And oxidation rates were certainly restricted from the beginning by the limited availability of dissolved oxygen molecules. And those same safety considerations still prevent life from utilizing gaseous oxygen directly. Thus life's near-total dependence on sunshine, water, dissolved oxygen and minerals, explains the tremendous biological productivity of wetlands and estuaries.

## *How life deals with dissolved oxygen and carbon dioxide*

Earth's atmosphere is 21% oxygen, 78% nitrogen and 1% argon by volume. As a result of fossil fuel combustion and increasing deforestation, average atmospheric carbon dioxide levels rose from 0.0280% (or 280 parts per million) in pre-industrial times to 0.030% in 1920, 0.0315% in the 1950's, 0.0364% in 1997 and 0.0365% in 2000.

The atmosphere at sea level exerts 14.7 pounds of pressure on every square inch of exposed surface. Gases vary greatly in their water solubility. But the equilibrium concentration of any gas in water is proportional to its pressure in the adjacent atmosphere. Hence simply doubling that pressure also doubles its equilibrium concentration in water.

Of course, there are other ways to increase the gas-carrying capacity of liquids. For example, the hemoglobin molecules in one liter of your blood can transport two hundred cubic centimeters of oxygen. In contrast, a liter of water dissolves less than 10 cc of gaseous oxygen. But while 10 cc of $O_2$ per liter might not meet your needs, it easily supports an abundance of sea life. After all, a 200 gram fish (0.44 lbs) consumes just 20 to 80 cc of oxygen *per hour*.

Sea creatures less than one mm in diameter absorb sufficient oxygen through their wet surfaces to lead active, competitive, reproductively successful lives. The larger carbon dioxide molecule diffuses through water more slowly than oxygen does, but $CO_2$ is 30 times more soluble than $O_2$ and therefore is easily passed off. Hence $CO_2$ accumulation rarely becomes a problem for underwater creatures while they still get sufficient $O_2$.

As creature diameter increases and simple diffusion no longer delivers enough oxygen internally, larger underwater animals must circulate their extracellular body fluids beneath delicate respiratory surfaces in order to exchange gases effectively with adjacent waters. By pumping deoxygenated blood through their thin-walled gills in a countercurrent direction (opposite to the passing flow of water), some undersea creatures manage to extract up to 60% of that water's dissolved oxygen.

However, the efficient gill structure also has major limitations, as anyone who has ever caught a fish can tell. For if its desperate ungainly flopping does not quickly bring the landed fish back to water, it soon suffocates, gasping miserably. Thoughtful fisherpersons have long puzzled over the inability of fish to utilize the good fresh air that surrounds them on shore.

But those delicately expanded gill surfaces soon dry and shrivel on land, leaving no moisture in which atmospheric oxygen can dissolve. And any gaseous oxygen that does penetrate air-damaged gills simply causes further drying. Of course, a thoughtful fish might find it equally strange that air breathing animals and fisherpersons are so intolerant of submersion in oxygen-rich waters. For if its desperate ungainly flopping does not quickly bring the submerged air-breather back to the surface, it soon suffocates, gasping miserably.

As with gills, lungs are respiratory appendages through which deoxygenated blood circulates for renewal. But while fish gills achieve effective gas exchange through continuous immersion in passing waters, lungs must be internalized to limit water and gas exchange with the atmosphere.

You expose over 90 square meters (the floor area in a small American home) of respiratory surface to the fully humidified air within your lungs. If that entire gas exchange area were suddenly laid open to the atmosphere, the resulting evaporative fluid losses would likely kill you in less time than the average beached fish has for flopping about.

Furthermore, those thin pulmonary gas exchange surfaces are easily damaged by flooding with either fresh or salt water. And you could never move useful quantities of oxygen-rich water in and out of your lungs anyhow. But the same tiny airways that seem so useless underwater do permit easy air passage - and air delivers nearly 100,000 times more oxygen per kilogram than water can.

Fish blood always reaches close thermal contact with cold sea-water at the gills. Nonetheless, certain species of fast-moving tuna preserve part of their muscle-generated heat through countercurrent heat-exchange by pumping warm deoxygenated venous blood destined for the gills, past cold oxygenated arterial blood returning from the gills and headed toward the eyes, brain and certain muscles.

Many birds and mammals now prosper in Earth's equatorial and high latitude seas. But early birds and mammals initially perfected their warm-blooded ways on land, where the advantages of air-breathing and the inefficiencies of air-cooling, made warm-bloodedness reproductively advantageous from the start.

The average cold-blooded fish consumes far less oxygen than a warm-blooded mammal or bird of comparable weight. Nonetheless, the exposed gill surface area of some tuna is not much smaller or less efficient for gas exchange than the lung surface area of a similar-size mammal. So tuna gills adapted to high-speed oxygen acquisition as tuna became one of the fastest fish in the sea.

A typical adult human male consumes 14 liters of oxygen per hour at rest. The same person at work might utilize up to 280 liters of oxygen per hour. If dependent upon some sort of artificial underwater gill device, that hard-working individual would deoxygenate 56,000 liters of water per hour.

No cold-blooded fish could possibly acquire and utilize enough oxygen to perform a comparable amount of work. Indeed, *the enormous work capacity of warm-blooded air breathers explains why birds and mammals now rule the seas - despite the ever-present risk of drowning*.

## *Conserving water*

So how do you prevent destructive drying of the delicate respiratory surfaces exposed within your lungs? For those internal lung surfaces must be moist enough to dissolve gases, yet dry enough to allow easy air passage near your lung capillaries. Such a balance is best maintained if your moist lung surfaces only meet air that has been fully warmed (warm air holds more moisture) and humidified within your nose, mouth and throat.

When you go outside on a cold and windy day, your tear glands quickly boost that humidification process. After moistening your corneas, those tears drain into your nose where they help humidify incoming cold air. Your sinuses and nearby secretory surfaces also contribute to the moisture dripping from your nose.

Nonetheless, it also takes a copious intranasal network of small superficial blood vessels to guarantee sufficient nasal fluid for evaporative purposes. And that is why unearned bloody noses (those not due to injury based upon insult) are so common.

An internal accordion-like expansion of your nasal lining helps to warm and humidify incoming air. When next you gaze up someone's nose, note the three moist tissue folds bulging in from each side that help to warm, stir and moisten that air. Presumably, a similar benefit could be achieved by lengthening the entire structure.

Dried mucus and other solutes remain behind when nasal secretions relinquish their fluid to incoming drier air. So Alaskans must pick and blow their noses far more frequently than Hawaiians do. Quite obviously, you could never tolerate a similar build-up of dried snot in the airways of your lungs - for one thing, your fingers are too short and fat.

An explosive cough or sneeze can clear your air passages. However, most of the dust and dirt sucked into your airways is more slowly exported on a sticky mucus sheet - pulled upward by the coordinated beating of a great many tiny hair-like cilia that extend out from your airway surface cells.

That slimy mucus accumulates gradually within your voice-box at times of gentle breathing - which explains all the noisy throat clearing during quiet movements at the symphony, as well as those gurgling sounds you occasionally emit when answering the phone.

On a cold day, your breath becomes visible as a rapidly dissipating cloud, for each quickly cooled exhalation momentarily includes more water molecules than it can hold as invisible water vapor. The same principle forces warm humid air to deposit dew or frost on cold grass or iced drinks.

Lung moisture ordinarily is conserved by humidifying as little outside air as possible. An overheated dog cools its fur-enclosed self with rapid shallow breaths, since such panting evaporates water from the upper airway without drawing more fresh air into the lungs than is needed.

## *Regulating carbon dioxide*

At rest, you take a dozen half-liter breaths per minute. One-third of the air drawn in during such an ordinary breath is residual or used air that remained in an airway since your last expiration. This dead-space air contains more carbon dioxide and less oxygen than an equal volume of fresh atmospheric air.

Reduction of airway dead space is just one of many reasons (weight and balance, relationship to heart, breathing dynamics, skeletal considerations, and so on) for locating your lungs high within your body and close to the air intake. Presumably the respiratory cost of a giraffe’s extended dead-space is outweighed by its greater access to higher acacia leaves.

During vigorous exercise, you breathe more deeply and rapidly than at rest, so recycled or dead-space air becomes a smaller fraction of your total air intake. When still out of breath from running, you might wish for wider airways to improve your air flow, but the resulting increase in your dead space would require you to move more air at rest.

On the other hand, narrower airways would minimize your dead space air and reduce the volume of air to be moved at rest, but so restrict your airflows that you could no longer outrun the competition. Overall, it seems advantageous to have airways of moderate diameter that adjust somewhat to suit your varying needs.

Alterations of airway diameter are achieved by the reflex contraction or relaxation of smooth muscle cells in the walls of your smaller airways. The adrenalin rush of a “fight or flight” response opens your airways widely - those airways again narrow as you breathe at rest.

A liter of used air remains within your air passages and air sacs following a forceful expiration. Some of that residual dead-space air can still be expelled through vigorous compression of your upper abdomen. Such a Heimlich Maneuver may dislodge food blocking the airway.

An ordinary exhalation leaves behind an additional liter of air that could still be pushed out with a more vigorous expiratory effort. So you retain over two liters of stale air within your lungs and airways after every normal expiration.

Furthermore, every 500 ml breath at rest adds only 350 ml of fresh air to the 2 liters of stale air already inside. Evidently you could improve your breathing efficiency, enhance your blood oxygen levels and eliminate more carbon dioxide simply by breathing more deeply and frequently. Right?

Well, no, no, and not for long. And you really don’t want to do that. For your lungs must continuously balance three closely interrelated functions; water conservation, oxygen uptake and carbon dioxide elimination. At rest, these goals are comfortably achieved with a dozen half-liter breaths per minute. And during intense physical exertion - when plenty of carbon dioxide is produced and oxygen uptake becomes far more urgent than water conservation - your lungs are ventilated maximally.

But at other times the choice between optimizing your oxygen uptake or carefully controlling your carbon dioxide elimination is not so simple, for while oxygen is essential, carbon dioxide also serves several important regulatory functions before being discarded from your body.

As it turned out, your ancestors outperformed their competitors by breathing primarily in response to arterial-blood carbon dioxide levels except when their arterial blood oxygen levels fell at least 50% below normal - an uncommon occurrence in healthy individuals living near sea level.

This simple physiological arrangement solved several problems simultaneously. For lungs must remain partially inflated to allow easy air entry and keep a little oxygen on tap - and that essential dead space unavoidably retains water vapor and carbon dioxide.

Fortunately, carbon dioxide is so soluble in body fluids that just a slight concentration gradient moves it from tissues to lungs. So by breathing in response to arterial blood $CO_2$ levels and using lungs of appropriate size, your remote ancestors regulated their carbon dioxide and still provided plenty of oxygen to all hemoglobin molecules passing through their lungs. But while paying close attention to carbon dioxide levels allowed them to handle oxygen usefully, the reverse would not have been true.

Careful control of arterial blood carbon dioxide levels was a key factor in stabilizing the acidity of your ancestor's blood, since much of the carbon dioxide entering blood reacts swiftly with water to form carbonic acid - thereby contributing acidity to that blood, as $CO_2$ does to carbonated beverages. Hence by breathing to control their arterial-blood carbon dioxide levels, your ancestors maintained appropriate blood acidity for their delicate cells.

That ability to regulate blood acidity by breathing responsively was especially helpful because the acidity of human blood is subject to many different internal and external factors - ranging from altered kidney function to diabetic acidosis - and from eating too much acid-laden fruit to excessive losses of stomach acid through persistent vomiting.

So if your blood becomes too acidic for any reason, simply breathe more deeply and rapidly to blow off a little more carbon dioxide. Not acidic enough? Shallow and slow breathing both encourage the $CO_2$ retention which will readjust your blood acidity toward normal.

Furthermore, there is no need to carry this book with you everywhere just to remind you how to breathe, for you automatically adjust your breathing that way already. And no matter how that breathing may be modified, you will still draw in plenty of oxygen. In other words, ***a proper amount of stale air within your lungs is good for you.***

## *There are several ways to exchange gases on land*

Just as "Fish gotta swim" (or at least gulp) to move oxygenated water past their gills, all but the smallest land creatures must move air in and out of their lungs. Certain snails and scorpions get by on gas diffusion without ventilation. And many insects depend upon diffusion to maintain useful gas mixtures in the air passages serving their internal cells.

Some insects have covers that control air passage openings through their wax-coated surfaces. Others, including aphids, utilize air-passage openings too tiny to admit ordinary water droplets (as does Gore-tex). But aphids soon drown when sprayed with slightly soapy water, for soap reduces droplet size sufficiently so water can flood their airways.

Frogs squeeze large mouthfuls of air to drive it down into their lungs. You suck atmospheric air into your lungs by expanding your chest cavity to reduce air pressure inside. Land mammals and birds generally coordinate their breathing with limb movements to enhance efficiency. A galloping horse inhales during extension of the body and exhales as muscles flexing the body force air out.

Despite having ungainly legs that stick out sideways, your distant reptile relations run as efficiently as mammals do. However, reptiles gain length of stride by flexing from side to side as they advance. These ancient fish-like swimming movements interfere with chest expansion. Therefore, those reptiles that cannot compress large mouthfuls of air to drive it into their lungs, must regularly stop running in order to breathe.

A few air-breathing vertebrates also exchange gases effectively while underwater. Among those performing both activities reasonably well are amphibians. Thus frog and salamander larvae have gills, while adult forms exchange gases through lung and skin surfaces.

Certain fish swallow air to supplement oxygen uptake at their gill or other surfaces. Others absorb oxygen through specialized air sacs, or via simple supplementary lungs. Primitive respiratory structures allow some fish to undertake short strolls between ponds or even climb trees, using their fins as legs.

Yet creationists still try to discredit Evolution Theory by pointing out that "missing links" (intermediate or transitional forms) between species haven't been discovered because God didn't create them. However, no play on words can obscure the clear continuum and obvious overlap of forms, abilities, functions, requirements and relationships between totally gill-dependent and totally lung-dependent creatures.

Fortunately for those who oppose Evolution Theory on theological grounds, this argument need never end, since every new intermediate species discovered or defined automatically creates additional "missing links" on either side. Yet scientific disputes about classification - whether a particular fish belongs to a certain species or genus or should be assigned its own species - often revolve around the acquisition and presumed evolutionary significance of certain fishy structures or characteristics.

In fact, a species assignment often reflects an apparent absence of sexual reproduction between otherwise comparable forms. So since species classifications are evolution-based categories to begin with, how can theologians possibly claim that all creatures have remained "each of their own kind" ever since creation? Especially with such overwhelming fossil evidence to the contrary.

For example, the vestigial pelvic bones of modern whales that now serve only to anchor the penis, also confirm that whales were once land-based with well-developed limbs before they resumed a fully aquatic existence. Presumably, those ancestral whales initially went down to the sea in trips because air breathing gave them efficient access to gill-dependent sea life. But the most successful and well-insulated proto-whales soon became too fat, streamlined and otherwise specialized to remain competitive on land.

Hence whales provide another obvious example of evolution at work, even though many ancestral transitional forms may have gone unrecorded (or un-fossilized) by virtue of having been available and competitive for only a short time. Many birds, from puffins to pelicans to penguins, have similarly enhanced their ability to harvest underwater life forms with innumerable structural and lifestyle adaptations.

## *How you breathe*

So how do you move air in and out of your lungs? Well, during quiet inspiration, your chest wall muscles lift your ribs up and out as your upwardly domed diaphragm muscles contract to push your abdominal viscera downward. The resulting expansion of your chest cavity reduces air pressure inside the lungs, encouraging atmospheric air to enter through your widening airways into your enlarging air sacs.

But soon the muscles helpful to expiration come into play. Then your thin elastic diaphragm muscle relaxes and is stretched back up into your chest - pulled along by lung recoil and pushed by abdominal wall muscle pressure on your viscera. At the same time, your chest wall muscles relax, allowing your ribs to move down and in. The resulting slow compression pushes lung air out to the atmosphere.

When a severely emphysematous cigarette smoker finally suffocates, his over-inflated lungs will balloon forth as the chest is opened at autopsy. Normally, however, the resting size of a chest cavity remains larger than the resting size of the healthy lungs within. Hence your smooth and wet outer lung surfaces pull gently as they slide across the smooth and wet inner aspect of your chest wall and diaphragm during quiet breathing.

However, your lungs cannot pull away from that adjacent chest wall unless free air or fluid becomes available to fill the space thereby created - just as you cannot lift an inverted wet plate off a smooth plastic countertop without first inserting a knife tip to allow air entry. When released from the chest wall, a healthy lung quickly deflates to a smaller size. Such a relaxed lung (e.g., within an open chest at surgery) still retains a modest volume of air and resists further compression.

A torn balloon or lung surface will continue to leak gas as long as its air content is replaced. But soft rubber balloons and lung air sacs both collapse when surrounding air pressures exceed air pressure within. Therefore, adjacent free air cannot reenter a torn balloon or damaged lung surface - and a persistent air leak from lung can easily export enough air to fatally compress lungs and heart - unless the over-filled chest cavity is decompressed by timely insertion of a large hollow tube.

With such an open tube in place, the life-threatening emergency is over, for the opposite lung and even the damaged lung can again exchange air - and the no-longer-compressed heart refills freely after each systolic contraction. Under such circumstances, every expiration pushes air out of the open chest tube and out of the mouth, while every inspiration draws atmospheric air back through those holes leading into the chest cavity or its enclosed lung.

The above observations demonstrate that chest cavity air pressures always exceed atmospheric pressure during normal expiration - for otherwise air would not flow out of the lungs. And chest cavity air pressures remain sub-atmospheric throughout normal inspiration as atmospheric air is drawn in.

Of course, your breathing efficiency is somewhat reduced when a hollow tube passes through the chest wall, for air moving in and out of that tube makes no contribution to respiratory gas exchange. Therefore, such an open tube is commonly connected to a non-obstructive one-way valve that allows air to escape from the chest cavity but not return.

## *Breathing makes sense*

Gas exchange follows relatively simple rules. And the simple physical constraints imposed by gas solubilities, gas diffusion, air pressures and air flows, make it extremely unlikely that incredibly efficient mutant individuals sporting radically new respiratory systems will suddenly arise to overwhelm all who stick with the tried and true methods of multicellular gas exchange that have evolved over the past 700 million years.

But the same cannot be said for your amazingly complex hormonal and immune responses - about which we still have so much to learn. For over the last four billion years, life has continued to develop new signal-receptor interactions, better chemical attacks, improved techniques in self-defense and clever ways of getting even or just jamming up another’s chemistry.

Furthermore, in your responses to bacteria and other parasites, anything goes and the nastier the better. Yet even the latest innovation may barely provide reproductive advantage before the enemy again catches on and catches up. As a result, most discoveries in endocrinology or immunology will continue to surprise you.

In contrast, once you understand the important parameters, you should be able to figure out the rules of respiration for all time. These might seem like contradictory examples of natural selection at work, but gas exchange is easily optimized, while almost any molecule can carry information, and fighting efficiency depends entirely upon the enemy and the terrain.

# Chapter fourteen

# Digestion

## *Your victims become you*

All living DNA delivery systems require regular refueling and refurbishment. But rather than laboriously pursue the ancient and honorable art of photosynthesis, you simply hijack used body parts from life's other players. Those stolen roots, fruits, shoots, muscles and organs are then swiftly disassembled in your internal chop-shop by a highly organized gang of enzymes.

As soon as the previous owner can no longer be identified, his/her molecular components are hustled through dark internal passageways for recycling by enzymes responsible for repairs and revisions - or burned to fuel your naturally selected thieving design. Any leftovers are attractively stashed at various locations against future need.

With no obvious limits on enzyme varieties and interactions, it seems an equally endless assortment of organic molecules and life forms could be constructed or customized, using the same involuntarily shared parts. However, life is subject to major constraints, among them the fact that life began in water and still depends upon water.

Thus the overall shapes assumed by life's membranes and other complex organic molecules generally reflect the varying solubilities of their different segments in water - and water is where life's chemical reactions mostly take place.

For example, the routine enzyme-directed energy-consuming reaction known as dehydration synthesis, removes intervening H's and OH's when joining simpler units to create proteins, fats or carbohydrates. And those larger molecules are eventually disassembled by the routine enzyme-directed energy-releasing reinsertion of water known as hydrolysis.

A bacterium may live and reproduce within its relatively enormous food supply while absorbing nutrients from the tissues and wastes of its live or deceased benefactor. An amoeba engulfs its tiny bacterial prey before reducing it to life's usual constituents at an intracellular digestive site. And every cell of a sponge colony captures and dissolves its own prey.

But you are a more advanced killing machine - so some of your cells make plans and send messages while others carry out the attack by running fast and hitting hard. However, that interdependence and close coordination of your highly specialized neurons, muscle fibers and other support cells comes at a cost, for those finely tuned, highly competitive cells can no longer rip off and absorb their fair share of each struggling victim.

Hence you must rely upon additional groups of highly specialized cells to break down, sort, inventory and release the standard construction materials and stored solar power previously invested in a live moose or chocolate mousse. The ordinary organic molecules provided by that preliminary digestion are then cracked, refined and converted within cellular and mitochondrial centers so they can enter into or power your essential enzymatic processes.

Those mitochondria are life's true mercenaries, working with equal fervor inside each cell on any side of every bloody transaction to secure their ongoing share of the spoils.

## *Laundering those stolen assets*

The tissues and organs of your powerful digestive system are many and diverse, for it is no simple matter to keep your own body intact while disassembling the very similar tissues of those you have overpowered. Indeed, the old alchemists puzzled endlessly over such questions as "When we finally create the universal solvent, what shall we keep it in?"

Your own digestive system pursues a more pragmatic course by partially deconstructing others in a progressive manner that minimizes risk to itself. Hence your food is broken down slowly in discrete stages as it advances through suitably protected segments of the long hollow gastrointestinal tract that connects your mouth to your anus.

When that gut - supported by the specialist cells in your pancreas, liver and gall bladder - finally breaks apart your latest victim's most energy rich (therefore, tastiest) tissues, the ordinary amino acids, sugars and fatty acids thus set free might equally derive from yogurt, a yak or a yam. However, the overall quantity and variety of important building blocks made available by that internal hydrolysis - as well as the presence or absence of particular amino acids, fatty acids, vitamins, minerals and so on - still differs considerably, depending upon what you just ate.

As a top consumer in Nature's food chain, you may acquire and enjoy almost any part of almost any life form that appeals to your taste. And while "There's no accounting for tastes!", the relative appeal of various foods to a healthy active hungry person is likely to reflect an actual or potential internal shortage of useful components that were previously acquired from such a source. And because similar biological materials, mechanisms and processes support all living things, the more important nutrients tend to be widely available from your usual plant or animal victims.

Of course, there is no reproductive advantage in working hard to produce items that are inexpensive, widely available or easily acquired through theft. Or as lobbyists often point out "Why spend money running for office when politicians come so cheap?" One might therefore anticipate that so-called *essential* amino acids, fatty acids and vitamins should have little relevance to your daily survival.

Indeed, it usually takes long months of severe deprivation under unusual circumstances before specific dietary deficiencies develop - which suggests that the most easily stolen, low priority items only became "essential" because your ancestors found no further reproductive advantage in manufacturing them.

## *There is no need to finish everything on your plate*

A first-class digestive system should be able to break down and absorb an entire duck, including guts, feathers and feet, or an entire apple tree. Yet you prefer to eat roast duck liver, muscle, skin and fat - or Mom's baked, sweetened, cored apples wrapped in her fabulous fat-laden crust.

Furthermore, you would find raw duck feathers and apple tree limbs quite indigestible, and too many apple seeds might endanger your life with their cyanide content. Yet we know that bacteria, fungi, worms and insects compete eagerly for a chance to digest leftover duck and tree parts. Were it otherwise, the landscape would be piled high with feathers, beaks, seeds and knot holes.

It does not pay a gold miner to extract the very last ounce from his claim, nor is it reproductively advantageous for a bird to search out the last juicy bug or berry on a bush. And there is no reproductive advantage in developing a more complex digestive system that could easily degrade anything you might consider eating, when it is so simple to construct an anus.

For life's contests are not won by those who finish everything on their plate or produce the least waste. Rather, reproductive advantage comes to those who earn a consistent energy or material profit from whatever they happen to eat. So not surprisingly, the cells of your gastrointestinal tract provide preferential handling to the sorts of high-energy foods that your ancestors were likely to acquire.

On the other hand, your gut cells waste little time on cellulose, or on the low-value keratin proteins in fluffy hard-to-chew-and-swallow feathers and hair. Similarly, crude oil is scarce on Earth's surface, and it contains many toxic or otherwise indigestible hydrocarbons for which your ancestors never acquired a taste or appropriate enzymes.

Nonetheless, within a surprisingly wide range, you can break down most of the proteins, carbohydrates and fats that you are likely to buy, gather, catch or kill. Still, you prefer rich (high calorie) foods such as honey regurgitated by busy bees - or fresh muscle fibers fried in fat (hamburgers, deep fried fish) - or starchy foods cooked in oil (the heat-damaged plant starch in french fries and donuts is more easily digested into sugars).

For the intestinal hydrolysis of those foods provides a more persistent inner satisfaction than any meal of lettuce, celery, radishes or cornstalks. That good feeling inside comes not only from providing for your own cells but also from feeding a huge population of other gut residents, for it pays to keep those uninvited guests happy as well.

## *How you eat*

In order to benefit from food that you catch and then cook till it is partially denatured and somewhat hydrolysed, you first must dissolve it. So after you inspect, smell and taste it, you begin to chew, tear, crush and grind each bite into smaller fragments while adding saliva - a complex fluid that contains slippery mucus binder as well as enzymes to speed carbohydrate hydrolysis.

As you then taste, feel, sort, stir and squeeze that delightful morsel of rabbit flesh or heat-injured potato with your tongue, it soon becomes a moist, pleasantly mushy, slimy clump that you would instantly send back if it arrived on your plate in such an abominable condition.

Yet it is necessary to create this mucoid mass so your victuals can safely slide past the opening of your voice-box and enter the upper esophagus without spilling food fragments into your airway en route. And as you have surely noted, that transfer remains far from foolproof - for your larynx occupies a lower, more hazardous position than it held in early hominids who preferred to eat and run rather than discuss the meaning of life while scavenging the kill of a temporarily absent lion or leopard.

In any case, the throat muscles involved in your intricately coordinated swallowing mechanism, routinely lift the upper airway (voicebox and windpipe) against the midline epiglottis (a plow-shaped cartilaginous cap that fits nicely onto the larynx) while properly chewed food slips past on both sides. At other times, its back-of-the-tongue attachment holds the epiglottis up and away from your open airway.

The many agile muscles of your tongue are securely anchored to surrounding structures. Although big and bulky, your tongue is adept at sorting and pushing food about within your mouth for grinding and processing. Indeed, it performs that task with consummate skill and daring while dodging in and out amongst those unshielded choppers and grinders (such a design would never be allowed under current OSHA regulations).

The sensitive surface of your tongue can taste, determine temperature and feel pain. It even allows you to detect, manipulate and extract a single hair that came in your soup. And a substantial section of your cerebral sensory cortex is devoted to analyzing subtle sensory signals from that surface. So your eyes water and you feel uncommon concern whenever you accidentally bite your own tongue - which merely emphasizes how carefully your own pampered tissues are protected from the rough treatment accorded to very similar items designated for digestion.

As your tongue finally collects and squishes each moistened slimy clump of chopped, ground and mixed food posteriorly past the epiglottis, the circular muscle around your upper esophagus automatically relaxes to accept that welcome bolus. If you enjoy comparing tongues, you have already noted that your dog's tongue is not nearly as bulky, strong or useful for chewing and swallowing as your own. Indeed, your tongue more closely resembles one of those beef tongues so tastefully displayed amongst other chunks of animal muscle, fat, viscera, brains, faces and feet on the meat counter of your kindly neighborhood grocer.

Canine (dog) teeth are pointed and arranged for grabbing and slicing rather than grinding, so while a dog's long and slender tongue curls usefully for drinking, it contributes little to sorting and pushing food about. In fact, a dog cannot efficiently tongue-transfer the bloody ripped-off flesh it so enjoys, back to where concentric waves of posterior throat and esophageal muscle contraction will take over.

Therefore, a dog *wolfs* down meat, tossing it backward while moving the head forward around it. Such inertial feeding is rapid, competitive and reproductively advantageous, though perhaps over too soon.

## *How you swallow*

All body surfaces normally subject to abrasion (your skin, mouth, throat, esophagus and vagina) are covered by layers of dead, shingle-like cells. Newer cells from deeper levels replace these protective cells as they rub off. This allows your esophageal epithelium to resist wear and tear from hard or sharp items on your menu such as bones, eggshells and nutshells. In addition, many mucus glands slime the firm, longitudinally folded esophageal surface to help speed food on its way.

A large mouthful of food momentarily dilates your empty esophagus, just as a snake distends when swallowing yet another unwilling victim. But while a snake has room to expand in most directions, your own esophagus cannot enlarge posteriorly against those solid vertebrae. So when your flat, wide and empty esophagus becomes full and round, it necessarily presses forward against the back wall of your windpipe or trachea.

A cold-blooded snake absorbs some oxygen across its skin during the twenty minutes a large victim being swallowed may block that snake's airway. In contrast, you must continue breathing throughout every meal. So your airway walls are reinforced and held open by individual cartilaginous rings that - like the wire or plastic spirals holding open a vacuum cleaner hose - prevent those airways from collapsing.

However, to ease the passage of large bites from your latest victim, you utilize U-shaped tracheal rings that stiffen only the front and sides of the trachea. Thus passing food simply indents the soft back wall of the windpipe, rather than bumping down along an entire series of complete tracheal rings.

Consequently, if a large bite of food lodges within your upper esophagus, it will push the adjacent soft back wall of your trachea forward and somewhat narrow your airway. Such a blocked esophagus is uncomfortable, frightening and accompanied by copious drooling as saliva is released to flush the stuck food on through.

Under these circumstances you will be sitting up and gagging, not lying flat on your back - for you rely upon the esophagus to drain fluid from the back of your throat - which is another good reason for locating your trachea in front of the esophagus. Fortunately, even a completely obstructed esophagus still allows you to talk or at least whisper, and you won't choke to death.

This also implies that a vigorous Heimlich Maneuver (compression of the upper abdomen) is not likely to relieve esophageal obstruction in either snakes or humans. So save that dramatic effort for a person who has food blocking the larynx and cannot move any air. Such an acutely endangered individual will be unable to talk, cough or even whisper.

When food becomes lodged in the esophagus, it may require careful esophagoscopic removal to minimize the risk of esophageal injury and determine why the food arrested. For food ordinarily slithers through your esophagus far more rapidly than you can read this sentence.

It is a mere fraction of a meter from the back of your tongue to your anus as the crow flies. Yet your entire gut between those two points is seven meters (22 feet) in length. Of necessity, your hollow gastrointestinal tract therefore follows a highly variable and tortuous path within the thin slippery peritoneal lining of your abdominal cavity.

And while you exert a certain amount of voluntary control at each end of that GI tract, your cerebral neurons have no control over what happens in between. Indeed, once food reaches the posterior third of your tongue, an involuntary swallowing reflex rushes it down into the stygian blackness. All subsequent digestive decisions originate in lower brain centers and are forwarded via vegetative nerves and hormones.

Your entire gastrointestinal tract is surrounded by a layer of circularly oriented smooth muscle cells. In turn, this circular layer is enclosed within an outer layer of longitudinally arranged smooth muscle cells. The coordinated contractions of these sturdy muscle layers milks food forward through the various stations of your gastrointestinal tract - with circular fibers constricting progressively to move bowel content forward as adjacent longitudinal muscles shorten. That propulsive peristaltic process is often accompanied by audible gurgling.

## *Dissolving your prey*

Your J-shaped stomach is compartmentalized by large surface folds that delay food passage. But eventually each mushy food packet is tipped into a hydrochloric acid bath containing an acid-activated protein-chopping enzyme known as pepsin. The resulting corrosive treatment gradually converts your food into a dilute suspension of nutrients that is then intermittently squirted into the small intestine.

The single-cell-thick stomach lining extends down into many deep irregular crypts and crevices. This maximizes your gastric secretory surface while minimizing the total area that must be protected from acid stomach fluids by a layer of alkaline mucus.

## *Dissolving your bacterial competitors*

Regardless of how faithfully you may brush, floss, pick, rinse and gargle, your mouth remains a veritable zoo wherein one might easily encounter 300 species of bacteria and other tiny life forms, each hoping to raise countless generations of happy descendents in this wonderfully warm, moist and nutritive environment. Not surprisingly, human bites often cause serious infections by introducing that zoo into the wonderfully warm, moist and nutritive tissues of the fist or other body part.

Nonetheless, many of these long-term residents have little ill effect in your mouth - some even bring benefit by suppressing more harmful forms. However, streptococcus mutans is frequently associated with tooth decay and gum disease - and helicobacter pylori can cause inflammation and ulcers in the stomach or duodenum. So no matter how clean the restaurant, how hot the soup or how often you have washed your hands, every bite of food that you swallow includes millions of bacteria and other microorganisms.

Of course, few of those tiny passengers are likely to survive the wild ride through your seething cauldron of stomach acid. Persons troubled by an excessively sour stomach may even have an offsetting advantage when it comes to destroying the tuberculosis bacteria that could be present in delightfully fresh unpasteurized whole milk.

Newborn humans and other mammals ordinarily subsist on breast milk. Though their stomachs produce little hydrochloric acid, newborns secrete an enzyme (rennin) that coagulates milk protein, thereby slowing its transit. The curdled and denatured milk protein that results is then mixed, mashed, broken down, dissolved and hydrolysed into more easily absorbed constituents.

Commercial rennin from the stomachs of slaughtered calves, produces curds (potentially tasty cheese solids) from milk, leaving whey (the fluid residue). And human infant stomachs also secrete lipase - an enzyme that initiates the breakdown of milk fats into fatty acids.

Newborns do not digest proteins very effectively, so maternal antibodies in breast milk shield the infant's GI tract surfaces directly - after protecting its lung airways incidentally via milk that "went down the wrong way". Small bowel lining cells then capture the remaining intact antibodies for direct transfer into the infant's blood stream.

Throughout the nursing period, their close physical contact helps mother's milk-antibody production match her infant's need for passive immune protection against prevalent or newly troublesome microbes. Breast milk also includes mucin, which protects against infectious infantile diarrhea.

## *Gastrointestinal fluids and their movements*

Once salivary enzymes are inactivated by stomach acid, there is little additional breakdown of carbohydrate within your adult stomach. Nor does an adult human stomach produce enzymes for hydrolysing fat. And pepsin only hydrolyses protein molecules at a few specific sites to help them unravel and enter solution.

So the dilute, dissolved, acidified nutrients that intermittently squirt from your stomach into the duodenum after an ordinary meal include undigested fats, partially hydrolysed carbohydrates and large fragments of unraveled protein. This conservative approach to digestion seems eminently sensible, for an acidified adult stomach that could completely hydrolyse fats, carbohydrates and proteins, would be well on the way to dissolving itself.

Water equilibrates freely across your stomach wall. Consequently, those delicious sugar molecules escaping from the large candy bar now entering your stomach will soon pull water from your circulation. So candy rarely tempts when you are dehydrated, as it would then make you feel even more tired or wobbly until sugar-laden intestinal fluids reentered your circulation across the small bowel wall.

Presumably, your inherited sequence of gastrointestinal stations with their many built-in digestive delays - and a general absence of candy bars - allowed your ancestors to absorb their usual mixed diet without such troubles. And breast milk is already so dilute that hydrolyzing breast milk fats and sugars in an infant's stomach cannot cause detrimental fluid shifts.

A pint of water soon moves across the stomach or small bowel lining to dilute your cellular and body fluids, for fluids naturally shift to reduce water concentration gradients or - as The Second Law of Thermodynamics would have it - increase disorder. Excess water is then eliminated as urine. In contrast, water taken with a meal just reduces the fluid your stomach must contribute to process that meal.

The rate at which food and drink are absorbed from your stomach or small bowel is altered by many factors such as your initial state of hydration, the quantities and varieties of foods and fluids that you ingest, and the rate and order in which you ingest them. An appropriate mix of food and fluids in your stomach can release water and nutrients slowly enough to allow a pleasant canteen-free hike when those same fluids alone would merely encourage early urination without reducing later thirst.

Alkaline secretions from your pancreas neutralize the acidified nutrients that leave your stomach. Without acid, pepsin becomes inactive and other protein-busting enzymes take over. The detergent action of bile - released on demand into your duodenum from your gall bladder - helps your intestinal fluids to dissolve dietary fats.

Your pancreatic secretions include enzymes that hydrolyze fats, carbohydrates and pepsin-unraveled proteins. Individual cells of your small bowel lining secrete other enzymes locally to further disassemble sugars and amino acid chains prior to their local absorption.

Many irregular surface folds slow the passage of food through your small bowel. Countless tiny finger-like projections known as villi, enhance the intestinal absorptive surface, lending it a velvety appearance. Individual cells covering those villi amplify their own exposure to the passing food stream by extending a great many microscopic cell-surface projections.

And there, on those expanded small bowel cell surfaces - beneath a thin protective meshwork of digestion-resistant filaments - your final digestion and food absorption takes place. Undigested food ordinarily takes several hours to pass through the entire small bowel.

## *Even after eating, you must fight for your lunch*

A large glucose meal (say soda pop and candy) delivers lots of glucose to your gut lining cells by passive diffusion. So why waste energy on the active absorption of glucose, amino acids and other valuable molecules when you could simply wait for them to diffuse out of your continuously stirred intestinal contents on their own? Wouldn't it be more efficient to delay active absorption until you determine which of the nutrients in your intestinal tract you still need?

Well, actually, the sooner you withdraw potentially useful molecules and electrolytes from that bowel content, the sooner you recapture the precious water in which they are dissolved. And your intestine must work quickly, for hordes of hungry microbes live in your lower small bowel and colon, intent upon eating your lunch if you don't absorb it first. Indeed, these tough survivors remain locked in a life-and-death struggle with each other and your intestinal lining cells to see who gets what.

Of course, intestinal cells have many advantages including their blood-borne oxygen supply, supportive immune cells and antibodies. But conditions truly are difficult out there in the intestinal channel, with little if any available oxygen and usually no free iron, plus a great many destructive enzymes and various antibodies - all mixed in with bile and other toxins put out by you and your chaotically flourishing inner population of bacteria, protozoa, fungi and even worms.

Furthermore, any time you change your diet, you greatly affect those uninvited internal competitors and codependents. So while you may initially note few signs of bacterial distress (some "hunger pains" perhaps?) as your new or inadequate diet leads to the wholesale death and destruction of previously acclimated microorganisms, you soon become aware of that devastation as newly dominant bacterial varieties cause various temporary symptoms such as excessive gas production, cramps and diarrhea.

It is easy to see why human herbivores (vegetarians) and carnivores often get "an upset stomach" when they annoy their current intestinal inhabitants with the other diet. As in any zoo or prison, when your intestinal inmates are upset, they will probably roar to let you know about it. Similarly, when someone has a loose bowel movement and then prepares your lovely salad with their unwashed shit-contaminated hands, you will probably endure yet another fierce takeover battle between your resident bacteria and the nasty newcomers forwarded from that person's intestine.

The latter microbes need not even be dangerous - though often they are, since hands are more readily contaminated by diarrheal stools. They merely need to be tough and different enough to upset your bowels. Or if your food contains milk and you are one of many adults who cannot digest lactose efficiently, that lactose will soon be taken up by your bowel inhabitants. But as lactose-loving bacteria then flourish, you may develop gas, cramps and diarrhea due to their additional metabolism and the solutes left behind in your gut.

So just as it makes sense for you to eat only what you need, it also makes sense for your intestinal lining cells to quickly grab all useful or high-energy nutrients - along with the water in which they are dissolved - on your behalf. Once they are actively absorbed, those sugars and amino acids enter intestinal wall blood capillaries for transport to the liver - while hydrolyzed fats are passively absorbed across your fatty intestinal-cell-surface membranes and taken up by lymphatics for transfer into your venous blood.

Intestinal content that reaches the far end of your small bowel has a porridge-like consistency and is recognizably stool. The first portion of your large bowel - usually located in your right lower abdomen - is the caecum, which has a single tubular sealed-tip appendix arising from its bulging lower end. In post-gastric or hind-gut fermenters such as the horse or rabbit, a greatly enlarged caecum is the site of vegetable matter breakdown by cellulose-digesting bacteria and various single-cell life forms.

Rabbits eat their own soft fluffy cecal content directly as it is released at the anus in order to recapture the food value being generated by hind-gut cellulose fermentation. They then set this material aside for further fermentation in the stomach before its final digestion and elimination as ordinary fecal pellets on the second pass.

In contrast, even the most confirmed human vegetarians achieve only partial breakdown of dietary cellulose within their GI tract. And rather than being retained for completion of fermentation, a high-fiber diet passes through you rather quickly to allow a greater intake of that low-nutrient vegetable matter. Your large bowel continues the drying-out process, while moving bowel content forward slowly until evacuation takes place.

The voluntary muscle around your anus usually controls when you will defecate. However, there is a limit to how long it can withstand forceful colonic contractions, particularly as the normally supportive nearby smooth muscle sphincter automatically relaxes during each rectal contraction. Note that your more or less solid, smelly brown feces do not rapidly swell up or fall apart upon entering water in the toilet bowl, for few soluble ions and molecules remain in that stool.

Stool surfaces soon dry and oxidize, causing their odor to diminish rapidly. But as anyone who has cleaned up after the neighbor's dog knows, newly fragmented dog poop releases additional smelly vapors. For in the presence of oxygen, partially digested organic molecules are soon oxidized as bacteria happily acquire that residual chemical energy. Hence aeration plays a major role in sewage treatment. And the eventual output, after proper sewage treatment, should be $CO_2$ and clean water, along with a residue of less-easily oxidized substances commonly referred to as sludge - which may include toxic heavy metals.

## *Your output still has value*

As you can see, a lot of life and energy remains in any stool - especially within herbivore manure. Back on the farm, vigorously fermenting fresh horse manure often was packed into a shallow trench to warm the small greenhouse-like enclosure known as a cold frame, so seeds could be started before outdoor spring planting was possible.

Dogs, pigs, ravens and rats often eat feces for their nutrient value. Farmers have successfully raised hogs beneath chicken houses, with those hogs subsisting for six months solely on chicken manure and spilled chicken feed. Although hogs reportedly prosper in such low-budget accommodations, they are best finished on a grain diet to eliminate their "off" flavor before the slaughter.

No vertebrate and few invertebrates can digest plant cellulose fibers unassisted. Consequently, cows and other ruminant herbivores maintain a warm wet internal fermentation site where contented cellulose-digesting bacteria meet regurgitated-and-rechewed cellulose fibers. And those complex, carefully maintained, microbial cultures are lovingly passed on from cow to calf as the proud mother licks her beautiful offspring's face - much as you add a bit of yeast to the latest batch of bread.

A few fermenting cows will warm an uninsulated dairy barn on a freezing January morning. Indeed, before central heating was available or affordable, farmhouses often were built above the cowshed. The short-chain organic molecules released early in that anaerobic, internal fermentation process are rapidly absorbed and utilized by the herbivore host, while most of those flourishing cellulose-digesters soon fall prey to other bacteria and protozoa.

Eventually it is the well-fed protozoal population, rather than the original low-nutrient-value grass, that moves onward to the cow's intestinal cells for digestion and absorption. In this fashion, truly staggering numbers of microbes are digested by one cow over a lifetime - yet it takes just a minimal starter culture to begin the same digestive process anew in her calf. An ordinary cow's digestion therefore provides us with yet another revelation about the incredible magnitude of ordinary microbial replication.

Bovine intestinal microbes are mostly digested after their contribution to internal fermentation. Therefore, cow manure cannot heat a cold frame. Such an efficient digestion is especially advantageous to cows when forage is scarce and of low quality. Many weed seeds that pass unscathed through horses or bears are easily digested by cows. In dry areas where wood is scarce, cow manure is stable enough to be used both as fuel and as a home-building material.

Even the casually discarded output of your own intestinal tract retains a great deal of food value - half of that fecal bulk may be living and dead bacteria representing over 500 different species at an average concentration of 100 billion to 1 trillion bacteria per gram. Your stool also includes many important nitrogen compounds and minerals needed by plant roots and shoots.

A high fiber or high cellulose diet reduces your intestinal transit time and increases your fecal output. A low residue diet does the opposite, as you successfully extract most of those concentrated nutrients before your resident bacteria can access the rest. Consequently, a low-residue diet minimizes your output of stool (bacteria and dietary debris) as well as flatus (the gaseous metabolic wastes of your intestinal inhabitants, plus swallowed air).

The hydrogen, methane and other gases produced by intestinal microbes may cause discomfort when politely withheld. But when those gases are absorbed by the colonic blood circulation, they can also escape through your lungs - along with other gaseous wastes (onion and garlic sulfides, the various breakdown products of your expensive alcoholic beverages and so on). That indirect pulmonary release of waste intestinal gases may cause less annoyance if you are not one of those close face-to-face communicators.

When a hunter kills an herbivore that has the usual full stomach and intestine, its live gastrointestinal residents continue to generate heat and gases, ferment and digest, transfer DNA, reproduce, fight and die. As a result, dead herbivore gut wall soon disintegrates, allowing widespread bacterial contamination and overgrowth - unless that herbivore is gutted soon after death.

Undamaged meat (voluntary skeletal muscle) remaining on the carcass can then cool and age properly (decompose more gradually in a drier, microbe-resistant mode). Interestingly, bears and other carnivores often consume the abdominal contents of their kill before eating the rest. And the Inuit (Eskimo) have known for millennia that caribou stomach content makes a tasty and digestible salad, quite unlike its flavorless lichen source.

## *Your liver is in charge*

All of the nutrient-laden oxygen-depleted venous blood from your gastrointestinal system is routed to your liver. There it flows slowly through countless tiny tortuous blood channels (liver sinusoids) where bacteria, worn blood constituents, just-absorbed nutrients and dangerous dietary toxins are handled. Well-oxygenated arterial blood also enters these sinusoids to support their complex metabolic activities. Fully processed, nutrient-containing blood then passes out through liver veins to join vena cava blood returning from your lower body to your right atrium.

This two-capillary-beds sequence - in which the blood from tiny bowel-wall capillaries drains through intestinal veins to reach tiny liver sinusoids - gives your liver cells first crack at all absorbed nutrients except for the fats diverted via intestinal lymphatics into your neck veins for rapid distribution to your many fat deposits.

In addition to storing extra iron, Vitamin $B_{12}$ and the fat-soluble vitamins (A, D, E, K), your liver modifies Vitamin D (prior to its final activation in the kidneys), stores excess glucose as glycogen or animal starch, and produces many other important body chemicals for release into your circulation as necessary.

The naturally selected absence of alternate venous channels through which digestive system venous blood might bypass your liver, reveals how important it is to force all of that nutrient-laden blood through those relatively obstructive liver sinusoids. As the obligatory destination for reclaimed animal and vegetable parts, and your primary recycling center, the liver is your major metabolic organ.

## *Soil is alive - it may be healthy or sick*

Deep-sea rift colonies are energized by the bacterial oxidation of hydrogen sulphide emerging from sea floor hot water vents. Some underground bacterial life forms have a mineral-based energy cycle. Certain microbes get by on little more than carbon dioxide, hydrogen and nitrogen. However, all visible life at Earth’s surface is sustained by solar energy trapped in organic molecules through microbial and plant photosynthesis.

Most plants acquire essential nutrients from soil. Ordinary soil is far more than a random mix of clay, silt, sand and gravel released from weathered rock, for fertile soil also includes uncounted hordes of living things and all manner of cast-off organic materials. In addition to its enormous density of plant roots and their fungal extensions, soil is constantly replenished by rotting vegetation, decomposing animal matter and herbivore manure. Because they are fewer in number and on a low-residue high-herbivore diet, carnivores contribute far less fecal matter than herbivores.

Every farmer knows that soil can be improved by adding limited amounts of manure and compost (composting refers to the accelerated biological digestion of organic wastes). And that occasionally letting land lie fallow for a year gives unharvested plant material time to decay - which upgrades soil conditions for the following year’s crop.

Insects contribute greatly to the mechanical breakdown of soil organic matter. And the fine particulate organic content of soil passes repeatedly through the intestines of worms that - unlike yourself - are about as long as their intestinal tracts. Soil organic matter also is continuously degraded by bacteria, fungi and protozoa. And all of these life forms prey upon each other as well. But to really appreciate life's recycling capabilities, one need only recall that the combined weight of every thing that ever lived on Earth roughly equals the entire mass of our planet.

It is likely that solar-powered bioregenerative modules will soon become practical for home food production. Future food crops may bear little resemblance to their wild or domesticated agricultural antecedents, as the easily optimized conditions within such bio-ag units should permit a far more intensive, selective and efficient production of nutritive plant parts than is possible within the current Whole Earth biosystem - which forces plants to do many other things for reproductive advantage beyond merely converting solar power into glucose and oxygen.

An optimist might view the soil of such a self-regenerating food production and waste recycling biosystem as a marvelous living entity from which other life draws sustenance. A pessimist might call it shit. Both would be correct.

# Chapter fifteen

# Reproduction

## *Dedicating your life to the next generation*

A glance. A touch. A kiss. Those moments of bliss. Rapture! No one ever felt like this before! It's magic! Well, maybe not magic, but nonetheless rather impressive. That after four billion years of selecting reproductively advantageous traits, Nature's favored response to a "stunning" reproductive opportunity is to cloud the previously clear mind until it can see only six inches into the future.

Small wonder that temptation is more easily avoided than resisted. Were it otherwise, you might never have been born. Your potential parents could have gone bowling instead. But fortunately for our overpopulated planet and its hordes of nearly identical people, humans finally have managed to separate the inherent irrationality and urgency of sexual intercourse from their own deliberate reproductive decisions. Yet this is hardly a new idea.

After all, our bacterial forebears separated sex from reproduction since life's beginning. And despite the profound protestations of a few old men who would burden our reproductively advantageous (hence inherited) strong sex drives with great guilt that only they can absolve, it seems clear that most humans would rather pursue quality-of-life issues than add as many children as possible to this challenging and overpopulated world.

Indeed, wherever adequate health care and reliable contraception are readily available, the birth rate automatically settles toward population-stabilizing levels - which merely confirms our instinctive realization that sexual desire and the urge to reproduce are entirely different interests that only occasionally coincide.

Of course, under ordinary circumstances, the strong urge to enjoy frequent heterosexual intercourse overshadows our equally innate long-term desire to have children. Only when sexual intercourse becomes difficult or distasteful, or if contraception reliably prevents reproduction, can the wish to bear children determine if and when a pregnancy may occur.

By allowing a man and woman to first develop an intimate mental/physical/sexual relationship, effective safe contraception converts the frequently unplanned, often dreaded and even intolerable burden of pregnancy into an eagerly anticipated life-long responsibility. Nonetheless, a strong primary sex drive and regular sexual intercourse certainly help to initiate a pregnancy and sustain long-term parental relationships.

The fact that sexual activities are usually exciting and pleasurable simply reconfirms the intrinsic importance of reproductively advantageous behavior. So it shouldn't matter that sexual intercourse originated in deviant bacterial behavior induced by infectious information to encourage its own transfer. It only matters that some exchanges of infectious DNA-based advice proved advantageous, both for the infective information and its bearers who - once they learned how - lived sexually ever after.

All self-sustaining human populations are based upon the family unit, for only close relatives gain consistent reproductive advantage by sharing food with nursing mothers and helping them care for their helpless or dependent descendents. Female mammals generally inherit a strong inclination to help their own progeny at the expense of others, as do swans, some crocodiles and certain fish.

Nevertheless, many human adults are not loving, willing and able (strong, stable, healthy, tolerant and wealthy) enough to sustain the necessary long-term commitments. Parental bonding therefore becomes critically important. And while every mother knows that her newborn carries many of her genes, fathers regularly require reassurance.

So it is not by chance that the usual first remark of a proud new mother to a proud new father is "He/She looks just like you, dear! (honest!)". And that is sure to please him, even though their generic-looking, wrinkled, messy infant might be voted just plain ugly by any panel of objective observers.

Not uncommonly, one reads of child abuse, spousal murder or divorce when the husband suspects infidelity. Wives tend to be more tolerant of this sin as long as the husband continues to show interest and support the family. A recent photo-recognition-and-matching study suggests that year-old human infants more closely resemble their fathers than older children do. And it certainly seems logical that a male parent would respond more warmly to those who are obviously his own at their time of greatest need.

As if to emphasize that point, a male lion taking over a group of female lions usually kills all cubs, thereby instinctively improving his own chances for reproductive success before he in turn is displaced or killed by younger, stronger males. By terminating breast feeding and milk production, infanticide encourages ovulation and opens the way for a new pregnancy in all mammals.

As a matter of fact, breast feeding remains the principal method for spacing children in many third world countries. And that spacing is important, since risk of death for the last infant rises if the mother becomes pregnant soon again, especially under circumstances where nutritional resources other than breast milk are limited and sanitation is poor.

However, if the family system really enhances human survival to reproductive adulthood, there ought to be evidence of human adaptation to the constraints of family life. And such changes do appear in reproductive habits that served our group-living primate ancestors so effectively.

For example, unlike other mammals that advertise female ovulation by attention-seeking behavior, genital swelling or coloration changes, or alterations in the odor and taste of vaginal secretions, human females strengthen family bonding and reduce family instability by remaining sexually receptive through most of the monthly ovulation cycle - as well as by not overtly signaling each month's moment of optimum fertility to all available males.

Family stability is additionally enhanced by a relatively poor sense of smell that leaves adult human males less consciously aware of any subtle signals being emitted by currently ovulating females. Not perceiving when their spouses are most fertile might also encourage human males to engage in sexual intercourse more frequently at home. And if frequent intercourse increases male confidence in the paternity of their children, such males might be more supportive of the family.

A strong human male sex drive and a massive overproduction of sperm are traits likely to be inherited since they increase the probability of pregnancy. Other reasons to overproduce sperm include the fact that they are cheap - that in competitive situations, each represents another ticket in life's lottery - and that your remote undersea ancestors formerly released great barrages of sperm to seek out all available eggs.

The persistent human male sex drive also seems well-adapted to the slow maturation of children and the ongoing benefit that child care and apprenticeship to available and interested adults can provide. This is especially apparent when comparing a stable family structure with other options such as intercourse only during a mating season, involving hazardous combat and nutritional depletion.

In reconfiguring human males to this family model, natural selection has markedly diminished the reproductive payoff for stronger and more aggressive males, whose dangerously combative life styles formerly allowed a few to dominate seasonal matings among group-living mammals. Nonetheless, men still feel an ancient competitive urge to demonstrate and exaggerate their reproductive desirability. However, except in gangs or other criminal enterprises, modern American male competitive behaviors tend to center upon business and sports - financial success and physical fitness - rather than mortal combat.

But most human males will never become billionaires or sports heroes or grow peacock tails, so their impractical displays often include sport cars, motorcycles, expensive running shoes, macho trucks, hunting gear - everything a credit card can provide. And many remain unwilling to drive a minivan or don an apron except when sending out smoke signals of a successful hunt as they grill an expensive buy, catch or kill.

An inherently anti-female bias ("glass ceiling") would therefore be expected in activities where masculine displays of physical and mental prowess might best reassure a potential spouse about good genes, good health and the ability to provide ongoing support for the children. So we are not surprised that our society chronically undervalues the capabilities of women - or that the clichés and common deeds of unremarkable men receive undue esteem when associated with ostentatious displays of wealth.

## *It took a lot of preparation*

Early life grew and grew, then divided in two. But dividing in two is no longer a realistic option for a complex specialized multicellular creature that must detect, decipher, dream and digest as well as rip and run. Hence your only hope for reproductive success lies in producing new descendents more or less from scratch - starting with tiny individual cells crammed full of the most intimate inherited admonitions.

Such a potential human must then be nurtured internally until its circulation, lungs, digestive system, kidneys and overall metabolism can function independently. Before being externalized, your latest descendent should also be capable of processing basic information and signaling loudly (if not accurately) regarding its needs for environmental change, more intake, removal of output and so on.

Being unable to produce useful descendents by subdivision therefore obliges you to multiply laboriously, more or less one descendent at a time, until sometimes it seems that your entire life has been invested in your pampered progeny. Of course, the human race would long since have vanished from this dangerous world if the average adult only gave rise to a single potentially adult descendent.

Yet multiple-unit human pregnancies (twins, triplets, etc) have historically had a reduced rate of success due to the long-term burdens they place upon limited internal and external resources. Thus multiple human births never really caught on, and human females (unlike dogs, cats and pigs that customarily produce litters) usually display only one pair of breasts.

Nonetheless, additional nipples and breast tissue are occasionally encountered on individual humans of either sex. And those supernumerary nipples or tissues - located along the milk line above or below the usual breast - remind us that single births were not always the ancestral norm.

Furthermore, there is increasing evidence that human pregnancies often begin with more than one embryo. Apparently, post-fertilization deaths and dissolutions share responsibility for the high percentage of single births. Indeed, it is estimated that only one fourth of all human embryos are carried to term - the rest undergo spontaneous abortion, often without being noticed.

You have already devoted a remarkable amount of time and effort to thinking and talking about, or perhaps even experimenting with sex. Yet that involuntary lifelong investment is dwarfed when the need arises to nurture each new human for whom you have parental responsibility. And as is true for art, stocks and diamonds, your dependents tend to take on whatever value you give them. So the more time and appreciation you invest in them, the greater the return.

And since you and human society tend to view happy, competent, reproductively successful descendents as one of life's major payoffs, such an outcome alone may have to justify all of your efforts and sacrifices - even if your health and other assets are consumed in the process, and those descendents do not seem nearly as appreciative as you feel they ought to be (does that sound like something your parents might have said about you?).

Speaking of being consumed in the process, a certain species of mite (a microscopic insect) provides a good example of total parental investment, for its one male and fourteen female embryos become sexually mature while still inside mother mite. And as soon as the male embryo has enjoyed sexual intercourse with each of his 14 sisters, those pregnant siblings eat him (nothing wasted so far) before launching their own equally brief careers by consuming their mother from the inside.

A just and loving God might not want to draw undue attention to this particular design which persists because it remains reproductively advantageous to utilize parental resources completely. Interestingly, the more customary ratio of 7 males to 7 females would be wasteful under such sheltered circumstances. For by relying upon one good male and true to complete the entire project before lunch and within budget, each pregnant female can double its output of egg-producing descendents.

This inbred reproductive system may have originated when an unfortunate delay in egg-laying was associated with accelerated sexual maturation. Of course, incest among embryos fails to introduce proven new genetic material, which is what sex is about. So in essence, that mitey male did little to justify his existence except provide lunch. But in the outside world, where sexual intercourse brings evolutionary advantage and is therefore reinforced by great pleasure, the ratio of males to females usually remains close to even.

That ratio endures because any female predominance out there would reward each lusty male with more descendents than an individual female could hope to produce. The reproductive advantage in being male would soon be dissipated, however, as mostly male litters gained temporary reproductive advantage and came to predominate. Those investing only in females could similarly maximize their descendents if the world had a large male excess, until producers of females again predominated.

Such a competition-derived equilibrium state might not hold in certain special cases - e.g. among humans and other social mammals where inherited social status can confer reproductive advantage upon upper class males. Under such circumstances, persistently wealthy and powerful families should have more sons than daughters. In contrast, while lower class males may fail to attract any mate, lower class females can always produce descendents. So families of persistently lower social status should produce a preponderance of daughters (as yet, there is insufficient evidence to evaluate this hypothesis).

Interestingly, the temperature at which reptile eggs are incubated often determines whether the outcome will be male or female. So it is possible that a catastrophic warming or cooling of Earth could have caused all surviving dinosaur hatchlings to emerge as individuals of the same sex - surely a frustrating way to end The Great Age of Dinosaurs.

Be that as it may, the descendents of ordinary male/female sexual relationships inevitably bear some recombined characteristics of each parent. Indeed sex is the only natural mechanism - excluding the infective or so-called horizontal transfer of inherited information from which sex may well have arisen - that allows unrelated individuals to variously recombine some of their different traits within their mutual descendents.

In contrast, the DNA-based inheritance passed along by asexually reproducing individuals only changes through random genetic errors or due to information acquired by infection. But variation is inevitable, even among clonal populations where no male contributes information to the inheritance. So with resources always limited and some more fit than others, fierce competition and natural selection cannot be avoided either.

Successful clonal populations often remain adapted to their circumstances for prolonged periods of time. However, the greater variability found among offspring of sexual unions ensures that as environments change drastically, some sexual subset will usually outperform even such efficiently reproduced asexual forms as dandelions and whiptail lizards.

An inbred population of cotton, corn, humans or hogs represents an intermediate state of reduced chromosomal variability. Even under ordinary circumstances, such a sexually reproducing population is likely to display weaknesses or deficiencies not prevalent in the wild strain. This comes about because individuals differ in their susceptibilities to disease and all carry some frankly deleterious genes.

The owners of really harmful dominant (expressed) genes soon die out, but recessive (hidden) genes may have little or no impact for generations - as long as they are masked by dissimilar dominant genes on the matching chromosome. But close relatives share numerous recessive genes by definition, and many recessive genes are harmful.

Therefore, inbreeding enhances the likelihood of embryo loss, reduced fertility, mental retardation, deafness, bad hip joints and so on. And even if persistent inbreeding within an environmentally constrained population did allow natural selection to reduce or eliminate certain detrimental recessive genes, an entire inbred group ought always be more susceptible to at least some epidemics that ordinarily might afflict only certain members of a more varied group.

As the opposite of inbreeding, unrelated and quite dissimilar parents ought to have few recessive genes in common. By reducing the likelihood that deleterious recessive genes will be expressed, out-breeding promotes hybrid vigor (above average growth rate and perhaps intelligence) of hybrid corn and some mongrel dogs, cross-breed cows or people.

But sooner or later, things are sure to change drastically. And with each non-clonal individual introducing yet another unique recombination of two already successful parents, sexual reproduction offers a greater variety of beneficial and detrimental recombinations of naturally selected characteristics to speed adaptation. So sex seems here to stay, at least for humanity's foreseeable future.

## *The egg came first*

If you are a human female, you closely resemble other female mammals, from tiny shrew to great blue whale, in the complex and magnificent hormonal and structural adaptions that enable you to first nourish your embryo internally, then feed your externalized infant with the secretions of your mammary (modified sweat) glands. Because females dominate reproduction while males merely contribute genetic information, we will first consider female reproductive anatomy and physiology.

The organs within which ova (female germ cells or eggs) arise are known as ovaries. At birth, those two tiny ovaries still include a few hundred thousand eggs. But unlike the substantial chicken egg, which encloses all the food and water a cute but not terribly bright baby chick will need until it pecks out through that porous (for gas exchange) egg shell, a microscopic information-packed human egg clearly requires ongoing metabolic support by the ovary, tube and uterus.

## *How it works*

A hen has a single external (cloacal) outlet. The human female has three - a small urethral opening located at the front of the vagina and the anus to the rear. These midline openings reflect the internal placement of their related organs. So the urinary bladder lies in front of the uterus and ovaries - up against the bony forward arch of the pelvis (which buttresses the human lower abdomen at the pubic hair level). And the rectum lies behind the uterus and ovaries, along the posterior pelvic wall and lowest vertebrae.

The bony coccygeal tip of the vertebral column can be felt behind the anus. That coccyx formerly supported the embryo's tail (in Whose image?). A similar tail once protected your primate ancestor's pelvic-floor openings from flies and other insects attracted to those sensitive, hairless and nourishing mucosal surfaces. The posteriorly placed anus directs feces backwards, away from other body openings.

A forward bladder location allows squatting or spreading the legs to direct urine away from the body and feet, but urine washing across the vaginal outlet or rectum is usually sterile in any case. Indeed, ammonia released by urea-splitting vaginal bacteria may help to suppress more troublesome microorganisms. In contrast, regular fecal soiling of a bladder outlet located behind the anus would increase the risk of urinary tract infection.

The vagina - a central passage through the soft muscle-supported female pelvic floor - undergoes tremendous dilation during childbirth. If this opening were located farther forward or back, the surrounding tissues would not stretch as uniformly. Such an asymmetrical vagina would be more liable to tear, and the emerging baby might be caught under the longer side (as in the hood of a sweatshirt).

The need to cushion and direct the fetal head away from nearby bony prominences may help to account for the posterior placement of the soft rectum and the anterior location of the soft bladder in both females and males. Of course, there are numerous other structural constraints as well.

For example, locating the spine in back maximizes protection, strength, flexibility and movement. A relatively rigid spine also provides the best possible shelter and support for the aorta and large veins. In turn, kidney function clearly requires proximity to aorta and vena cava, since the two kidneys process a great deal of blood.

Furthermore, the nutrient-laden venous blood returning from your gastrointestinal viscera must remain inside the peritoneal cavity until processed and released through the liver. In contrast, the deoxygenated blood in all other systemic veins should remain outside of the peritoneal cavity and flow freely back to the heart and lungs for rapid reoxygenation.

Thus the veins that drain your reproductive system (ovaries, tubes, uterus, vagina) - and even the tiny veins serving your pencil-width ureters (the muscle-enclosed tubes conducting urine from each kidney to the bladder) - must pass behind and below the thin peritoneal cavity lining that cleanly separates nutrient-laden venous blood from all veins that bypass the liver. For any small interconnecting veins might easily enlarge to let gastrointestinal venous blood bypass the liver as well.

Except for its extra-peritoneal circulation, however, the female reproductive system primarily resides within the slippery peritoneal surfaces of the remarkably distensible and readily reorganized abdominal cavity, in order to accommodate the dramatic uterine enlargement of pregnancy.

Consequently, every enlarging egg-bearing follicle that ruptures through the ovarian surface releases its egg directly into the free abdominal cavity - an event sometimes associated with minor ovarian bleeding and lower abdominal discomfort. That newly liberated egg is soon swept into the open end of a nearby mobile fallopian tube.

With appropriately timed or regular sexual intercourse, successful fertilization usually occurs as the egg passes through the narrow irregular fallopian channel toward the uterine cavity. Up to four hundred eggs might follow this route over a single reproductive lifetime. Of course, every pregnancy diminishes that sum by stopping monthly ovulatory cycles until well after the child is born.

The ovarian release of one or more eggs ordinarily takes place about once a month in human females of reproductive age. An associated surge in ovarian estrogen and progesterone production stimulates the uterine lining to thicken and prepare for pregnancy.

Hormone production then declines precipitously if pregnancy did not occur. This drop causes surface layers of that overgrown uterine lining to lose circulatory support and be shed. Uncomfortable uterine contractions may accompany expulsion of the resulting bloody menstrual discharge through the vagina.

The premenstrual escalation of estrogen and progesterone production can cause breast swelling and tenderness, as well as fluid retention, slight weight gain and mental irritability. Those signs and symptoms subside as the next monthly cycle again prepares the reproductive organs for possible fertilization and pregnancy.

The cycles of female-hormone production and ovulation cease gradually or suddenly as a woman reaches her mid-to-late 40's or early 50's. And while a female may release hundreds of eggs during her reproductive lifetime, only a few of her original several hundred thousand eggs still remain in the ovaries at menopause. For many eggs respond to the initiating signals of each cycle, but most are insufficiently stimulated to complete development so they die.

## *Those inside-out connections*

An open passage through the vagina, cervix, uterus and fallopian tubes connects every female's abdominal cavity to the microbe-infested outer world. Female fertility depends upon that connection remaining open so eggs and sperm can meet. Yet this route also offers opportunities for microbial invasion.

The moist vaginal opening between urethra and anus encounters a great variety of viruses, bacteria, protozoa and fungi from the woman's own body surface and gastrointestinal tract. Many other microbes that also have the potential to cause irritation or infection, may be brought in by her sexual partner(s) .

However, the sturdy vaginal wall and cervical canal are protected by bacteria-resistant secretions, so the best opportunity for microbial entry may be when sperm or bloody menstrual discharge lead the way. Significant infections of the female genital tract are commonly referred to as pelvic inflammatory disease or P.I.D.

Any disease primarily transferred by penis to vagina contact is called a venereal disease to honor Venus, the Goddess of Love. Having sexual intercourse with an individual who has had intercourse with other persons carries a portion of the risk one might take by having intercourse with all of those other persons and their past partners, the previous partners of those partners and so on.

Fortunately, that overwhelming risk of infection is markedly reduced by the fact that some of those individuals were relatively immune, careful or lucky - or were successfully treated for their most recent venereal infection prior to the intercourse in question. Nonetheless, many (most?) adult humans support mild or symptom-free, but often chronic protozoal, bacterial and viral infections that were acquired during sexual intercourse.

Like other unwanted guests, those venereal free-riders often improve their chances for a long stay plus transfer to other lusty adults by not causing too much trouble. In fact, the most successful may merely cause a mild irritation that encourages further intercourse - thereby enhancing the likelihood that they will be passed along.

## *Testes hang out to be cool*

Testes and ovaries both arise behind the abdominal cavity. Ovaries work well within the warm protected peritoneal cavity, but testes cannot function properly at normal body temperature. So before birth, testes migrate out into an external scrotal skin pouch where they will enjoy lower temperatures.

Testicles produce the male germ cells known as sperm. They also secrete the testosterone necessary for male puberty, male-pattern muscle and bone growth, enlargement of male sex organs and the larynx, production and maturation of sperm, enhanced growth of body hair and male pattern baldness.

Scrotal skin tends to loosen when warm, and constrict or shrivel upward when exposed to cold. The muscles around each spermatic cord also draw the testicle upward toward warmth, or out of harm's way when the inner aspect of the thigh is touched or stroked.

A spermatic cord often encloses multiple testicular veins. Testicle cooling may be aided by countercurrent heat exchanges between opposing blood flows in the testicular artery and adjacent veins. Each spermatic cord also includes small nerves and a tubular, muscle-enclosed vas deferens that pumps sperm from the epididymis (a multi-tube cap-like structure on the testicle) to the penis.

The epididymis is where mature sperm are stored until roused into action during sexual intercourse, or discharged during masturbation or a "wet dream", or until engulfed by local cleanup cells as those sperm become outdated. Testicles produce sperm continuously and ordinarily maintain a fine inventory of mature sperm.

However, when sperm production consistently exceeds the sperm discharge rate, testicle cells eventually reduce their sperm and hormone production. This partially explains the "use it or lose it" experience of older males - and suggests that masturbation may help to maintain male sexual function when acceptable alternatives for the regular discharge of sperm are not readily available.

## *Sperm need help*

A tiny sperm includes as little metabolic machinery as possible. And it can hardly access any of the very tightly coiled genetic information it is supposed to deliver. But even without such limitations, a sperm would still require external metabolic support during the six or more weeks needed to reach maturity.

For the single set of 23 chromosomes carried by every sperm or egg always includes detrimental recessive genes that could harm any sperm or egg that was dependent upon its own DNA for advice. In contrast, a fertilized egg bears 23 matching chromosome pairs, with one of each pair derived from mother's egg and one from father's sperm. Under these circumstances, detrimental recessive genes are likely to be masked by normal genes on the matching chromosome.

The particular chromosomes contributed by father's sperm and mother's egg represent yet another unique recombination of ancestral genes that each inherited. But despite incessant revisions, those chromosomes retain the critically important sequential order that allows them to pair with and match other recombined sets of chromosomes in human eggs or sperm.

In addition to its twenty-two recombined paternal chromosomes, each male-determining sperm bears a very small **y** chromosome - while each female-producing sperm carries a large **X** chromosome instead of that **y**. Not surprisingly, a small **y** chromosome lacks most of the essential genetic information borne on the much larger **X** chromosome with which it pairs in a male-producing egg.

So even if they could access all of their own information and had no deleterious recessive genes, male-producing sperm would still require external life-support to make up for important **X** information not present on the **y**.

## *Delivering those sperm*

A temporary penile erection results whenever nitric-oxide (NO) induced smooth muscle relaxation allows penile arteries and blood-containing chambers to distend. A comparable erection of the far less prominent clitoris, along with swelling of the vulva, also enhances female sexual sensitivity during intercourse.

As sexual excitement mounts, sperm are transported through epididymal and vas deferens ducts by the peristalsis of those tubes. Various nutrient, supportive and facilitating secretions are added en route before sperm finally are pumped from the urethra of the erect penis during orgasm.

The urgent preparations for this potential reproductive event include an initial release of clear alkaline fluid to neutralize any acids left in the urethra by prior urination. A bladder reflex prevents male or female urination during intercourse. Copious prostate gland secretions contribute to sperm nourishment and support.

Area-wide congestion of blood vessels maintains the erection and swelling of male and female genital structures as long as arterial inflow markedly exceeds (and impedes) venous drainage - usually until male ejaculation and female orgasm (which are comparable events) or until sexual excitement wears off and arterial inflows decrease.

As you might expect, individuals vary greatly in their sexual responses, appetites and sensations. And there is far more to an intact and functioning person (or any other really complex mechanism) than just their parts and how these work and interact. Even the simple act of human sexual intercourse can be brutal and dehumanizing or a truly magical moment in a wonderful long-term relationship or more commonly, something in between.

Furthermore, the two partners involved in a particular sexual interaction may interpret all aspects of that event quite differently. And with so much of what we do so easily misinterpreted, human relationships tend to improve when there is an open and friendly communication of wants, needs, fears, pleasures and displeasures.

## *Tracing your inheritance*

In addition to its tiny male-determining portion and a few other genes, the y chromosome carries numerous non-functioning nucleotide sequences that undergo slow random changes without affecting the fitness of their male human bearer. These y sequence variations can serve as useful tools for estimating the relatedness or line of descent of males from different population groups.

With mitochondria almost entirely or entirely inherited through the egg, similarly random non-functional changes within mitochondrial genes provide useful information about the female line of descent. Evidence of this sort will eventually improve our understanding of when and where the first human male and female walked hand in hand under the stars.

However, it is already clear that the unknown number of ancestral primate couples (often lumped together as Adam and Eve) who gave rise to the human line of descent, initially differed only imperceptibly from their cousins, whose modern descendents are gorillas and chimpanzees.

# Chapter sixteen

## The embryo’s story

You are the product of an unlikely encounter between a vigorous weeks-old sperm and the near-perfect egg that it roused from decades of magical slumber. Although barely mature, both were mere hours from death when their individually incomplete information packets came together inside your mother.

In contrast, your sea-dwelling invertebrate and vertebrate ancestors usually released their sperm and eggs for external fertilization. Most synchronized the discharge of their sex cells in seasonal, even momentary, mass matings that created a brief and glorious excess of sperm, eggs and larvae to overwhelm all predators without supporting an increase in their numbers.

This synchronized underwater group sex also increased the likelihood that each freshly released egg would meet a lucky sperm suitor of the same species. In contrast, an innocent egg seduced by some fast-swimming sperm of a different species was automatically sentenced to death - a tragic waste of two fine (though misguided) young germ cells.

Yet despite the most perfect timing, the enormous numbers of sperm from many different species being released into the sea during certain seasons made it essential that each species develop specific barriers against fertilization by inappropriate sperm, while still encouraging sperm of the right species to prove their mettle in a winner-take-all joust for each ovum’s affections.

The installation of a species-specific sperm-recognition-and-frustration system around each egg therefore brought great reproductive advantage. And that is just another reason why your mother never risked accidental fertilization by the countless trillion sperm that may have been released from corals and other sea creatures as she snorkeled beyond the reef. Being a mammal, she depended upon a penis for internal delivery of sperm anyhow - which further reduced opportunities for accidental fertilization by sperm of another species.

The Hebrew Bible (Old Testament) reports that God strongly disapproved of human sexual intercourse with animals. More recently discovered interspecies fertility barriers suggest that those biblical injunctions were not necessary to reduce the prevalence of centaurs (half man, half wild horse) or mermaids (half woman, half cold fish) - so presumably interspecies fornication was at least a perceived problem in the Days of the Prophets. More recent quips about virgin wool coming from sheep that can outrun sheep herders bear similar implications.

In any case, whether you are an outcome of careful planning or “a coolie” (quickie in the snow), only the tiniest fraction of the several hundred million sperm swiftly pumped into your mother’s vagina by your father’s erect penis ever got anywhere close to the egg drifting within one of her fallopian tubes. Perhaps the first sperm to arrive were pushed along by the piston-like effect of penis in vagina, as well as the peristaltic contractions of your mother’s genital tract during and after her orgasm.

But all sperm approaching that egg had first to be activated by fluids of mother’s genital tract so they would be ready to release the enzymes that could dissolve various proteins and complex sugars surrounding the ovum. Such activation obviously involved some delay, but it also prevented those sperm from releasing their introductory chemicals prematurely or too late - for in love as in war, timing is everything.

Still it took a cooperative chemical attack by many excited sperm to break down the virginal integrity of cellular and acellular layers enclosing the ovum - until finally your tiny founder sperm wriggled through into that huge (0.1 mm diameter), splendidly provisioned egg. But first the sperm had to prove its identity and suitability by establishing contact with the actual egg surface - whereupon certain enzymes exposed upon the sperm’s forward tip adhered to matching egg-surface molecules.

Upon entering the ovum’s chaste cytoplasm, your father’s successful sperm dropped its propulsive tailpiece. The sperm nucleus was then borne in triumph toward egg central as your mother’s slumbering egg nucleus finally awoke.

## *The egg that would be you*

Once sperm entry was confirmed, your egg initiated electrical and enzymatically induced changes that brought about rapid hardening of its surface layers, making them impenetrable to other sperm. The outermost layers of the just-fertilized egg then rotated about the inner egg - a 30° twist that provided the fertilized cell with bilateral symmetry (left and right, front and back) where previously it only had radial symmetry (head and foot).

Doing the post-fertilization twist probably brought previously segregated cytoplasmic ingredients together and thereby initiated all of those complex and wonderful molecular interactions that would eventually become you. Of course, many nurse cells in mother’s ovary had cooperatively organized and provisioned the egg - filling it with copious amounts of ready-to-express information as well as essential nutrients. A solitary egg nucleus could never have established and prepared such a large egg by itself.

Within minutes to hours after that momentous intercourse, the sperm-induced metabolic awakening activated ancestral advice that had been deposited within the egg decades earlier, while mother was still within grandmother's uterus. Yet half of that day passed with little apparent activity as sperm and egg nuclei were brought closer together and their chromosomes duplicated. Only then, as the fertilized egg finally divided in two, did sperm and egg nuclei at last pair up their matching chromosomes so that information inherited from each parent could meet and interact.

However, even the full complement of appropriately matched and activated or suppressed information still left the ongoing development of your fertilized ovum dependent upon an endless number of past and future events - ranging from proper initial preparation of the egg while grandmother was still pregnant, to the correct combination of a sperm and egg that carried competitively useful information, to an appropriately supportive maternal genital tract.  A lot of other special circumstances also had to be just right, so it is hardly surprising that most fertilized eggs fail to implant successfully.

The first two days probably passed with the fertilized egg still inside of the fallopian tube as cell division proceeded under the guidance of long-ago pre-positioned molecular instructions. For the ancient and beautifully complex rituals underlying this initial burst of activity still exceeded the ability of each newly formed cell to generate its own fresh instructions. And before long, that single fertilized ovum was subdivided into a crowded embryonic ball composed of many smaller cells - all still enclosed within the same clear flexible outer cover.

Upon reaching your mother's uterine cavity, that hardened outermost layer finally split and was discarded. Had this occurred prematurely, you might have implanted in the tube. But your hollowing clump of cells arrived at a time when the lush uterine surface and its secretory activity were optimal, so you prospered as you soaked up nourishment from the surrounding "uterine milk".

Indeed, you had a really great start, with no bacterial or other cellular competitors - unless some sibling was developing nearby. If non-identical, that sibling originated from another simultaneously shed and fertilized egg. But any identical sibling(s) arose through a complete separation of your earliest embryonic cells while those initial cells still had access to all the information necessary for forming an entire person.

As your cells increased in number, their future career possibilities correspondingly became restricted to more specific tasks within particular regions and tissues. That progressive concentration upon specific informational subsets - with its attendant limitations - undoubtedly reflected the inherent maturational impacts of multiple cell divisions and specific neighboring-cell-and-position effects.

Furthermore, all of these activities were influenced by the appropriately timed release and limited spread of various cell-organizer molecules. These molecules critically affected many of the sequential interactions designated by certain long-established organizer gene sequences. Interestingly, the same organizer genes play equally essential roles in the worm, the fly and the rat. Thus many influences guided each member of your expanding cell population as it specialized and sub-specialized along well-established ancestral pathways.

Your uncovered and enlarging mammalian cell bundle soon settled down and digested its way into mother's nourishing uterine lining. Well below that lush endometrial surface, those cells entered a fresh puddle of mother's blood that was constantly being replenished by her uterine arteries and emptied by her uterine veins. So that is where "future you" took root, soaking up the plentiful oxygen and nutrients of your mother's bounteous blood - into which your wastes and urgent instructions also diffused.

Soon your chorion (the outermost embryonic cell layer) fused with mother's adjacent uterine lining to form the placenta. This fusion event represented a huge evolutionary advance that apparently originated when an early ancestral egg or sperm became infected by retroviral information that has persisted in chromosomes inherited by all placental mammals ever since.

For under the influence of that appropriately reactivated retroviral envelope protein, a layer of cells within the partly-you/partly-mother placental tissue formed into a thin multinuclear sheet that became the relatively huge exchange surface between mother's blood coursing by on one side and your embryonic and fetal blood pulsing past on the other. That surface then served as your early embryo's GI tract, kidney and lung.

But long before your placenta became organized or had any semblance of a circulation, your chorionic tissues were already regulating mother's hormonal system on your behalf. The first and most pressing chorionic commandment released into mother's blood stream was chorionic gonadotropin - which incidentally caused mother's blood or urine to give a positive pregnancy test within eight days after fertilization.

This critically important hormone instructed mother's ovary to maintain full estrogen and progesterone production rather than drop its output of those hormones to end the monthly cycle. Quite obviously, you needed to delay mother's next endometrial separation and menstrual discharge until after your birth, since such a menstrual discharge would almost surely have expelled your embryo as well.

Thus your chorionic gonadotropin took charge of mother's ovary many days before her first missed menstrual period. And that was merely a start. For soon the placenta itself was producing estrogens, progesterone and other hormones to ensure your continued control of mother's reproductive physiology.

As the exposed surface of a half-foreign parasite invading your mother's tissues, that placenta also had to suppress mother's usual immune attack upon any foreign (in this case, paternal) molecules exposed to mother's uterine circulation. Yet despite the real risks involved in exposing such foreign molecules, your father's genes and proteins took the dominant role in your placental function.

This unexpected molecular bias reflects the fact that a pregnancy often represents the father's and fetus's best reproductive interests even when it is detrimental to the mother's health and/or reproductive interests. For example, during tough times - or when fully occupied with other children in whom she already has made a substantial and so-far successful investment - it can be reproductively advantageous for the mother to conserve her resources by discontinuing a new pregnancy.

In contrast, it is generally in the unborn's best interest to have the pregnancy continue regardless of whether it endangers a previous child or harms the mother's health. Similar evolutionary logic applies even more to the father, who may have no genetic relationship with those previous children even when he thinks he does - and quite often he knows that he doesn't.

So since the father-to-be may never get another reproductive opportunity - or if he does it could well be with another woman - his reproductive interests are usually best served by forcing the current pregnancy to completion regardless of its effect on the mother or her previous children. Presumably this conflict of interests - with father and fetus on one side, and mother plus previous children on the other - was far more common in earlier mammalian times when placentas from different fathers might compete directly for limited uterine resources.

But even today, only a devoted husband and loving father sharing a long-term relationship with a woman he trusts is in a position to benefit reproductively by discontinuing an unwanted pregnancy. And prevalent divorce rates suggest that marital relationships often fail to meet that standard. On the other hand, the less concern a potential father feels for the welfare of a woman and her other children, the more likely it is that he will benefit reproductively by forcing her and - by a natural extension of this self-serving logic - all others similarly situated, to complete any unwanted pregnancy.

Hence those who insist that all unwanted pregnancies be carried to term despite possible adverse impacts upon mother or her other children are mindlessly mimicking the naturally selected, selfish behavior of every placenta and rapist - no matter what rationale they may advance. And their strong bias in favor of the unborn implies a corresponding disinterest in the welfare of the mother and her other children. Consequently, those most loudly opposed to abortion are self-identified as unloving and anti-family.

## *In Her image?*

Your fish and amphibian ancestors had to breed in water. Only after amniote eggs capable of enclosing useful quantities of food and water became available were reptiles and their direct descendents (you and the birds) finally free to reproduce on dry land.

Similar egg casings allowed terrestrial invertebrates such as the insects to spread widely as well. But the tough and porous egg shells that provided protection and pre-packaged sustenance also necessitated internal fertilization before outer shell layers could be applied in the female reptile's oviduct.

An oviduct had long been essential for laying eggs. The penis only became an important tool for the internal delivery of sperm on dry land. So while you may treasure your penis or that of a friend, the female structure is the more basic. Presumably that explains why genetically male (**Xy**) or female (**XX**) embryos that lack testes or ovaries (a very rare problem that may only be recognized when no puberty occurs), always produce normal female external structures: And why males develop useless nipples and must hang their testicles out to cool.

A lot of other evidence confirms that the female structure is more fundamental (what could be more basic than giving birth?) and durable (women generally outlive men under comparable conditions). Those who are incurably devout might therefore conclude that God created woman in Her own image - which suggests that women are the legitimate rulers of all God-based religions.

But such metaphysical ruminations become moot when one realizes that the majority of your early embryo's cells were destined to serve in one of four different egg membranes - each of which played a critically important role in your reptilian forebears, but then lost its original designated function when mammalian embryos developed placentas. Nevertheless, your embryo compulsively constructed all four of these obsolete membranes in typical reptilian fashion before modifying them for other purposes or recycling them.

For example, your outermost chorion membrane soon fused with its underlying amnion, which then secreted amniotic fluid to protect and float your soft and initially unsupported substance. By the time that amniotic sac - also known as mother's "bag of waters" - finally emptied onto the seat of father's new sport car as they sped to the hospital, you already had sufficient internal bracing to maintain your subjectively adorable shape, even on dry land.

Although the placenta rendered mammalian egg yolk obsolete over 200 million years ago, your embryo nonetheless constructed a fine new yolk sac in continuity with its gut - even extending embryonic blood vessels onto that yolk sac in strict accordance with your inherited reptilian schedule. But soon that functionless yolk sac and its blood vessels atrophied and disappeared, after contributing to midgut and placental vessels.

However, being useless and inactive made the yolk sac a tranquil temporary refuge where your germ cells (future eggs or sperm) could park temporarily to evade the surrounding cellular clamor and avoid accidental activation, suppression or any other serious misunderstandings that might be induced by the passing flood of molecular messages.

Your embryo formed yet another ancestrally essential membranous sac known as the allantois. The reptilian role of this sac was to maintain a sanitary environment within the egg shell until hatching by collecting the urates that are excreted by all bird and reptile embryos. However, humans only produce urates in minor amounts - and the mammalian uterus (an enlarged oviduct) easily eliminates all such embryonic wastes via the placenta.

Thus your allantois already was outmoded and useless when constructed. Yet it showed up anyhow in strict accordance with the old reptilian schedule, and eventually contributed blood vessel segments to and from the placenta. So your irrelevant allantois became just another reminder of your humble reptilian origins. But fortunately, the tiny island of future-you cells adjacent to those four outmoded egg sacs was not idle during this time.

And soon after you formed two detectably different embryonic cell layers, a third layer moved between them and then split to form your central body cavity. Your nervous system originated as a midline infolding of your outer cell layer - the germ cells migrated back from your yolk sac - and most of your other organs arose during the eight busy weeks following fertilization.

Luckily your cells were generously provisioned by your mother’s metabolic and mineral reserves, and protected from physical harm by the surrounding amniotic fluid. For this period of rapid cell division with ritually choreographed streams and layers of cells flowing and growing around and across each other was a critical time when chemical injury (mother’s use of medications, alcohol or illicit drugs) or illness (mother getting German measles, for example) could easily have led to serious disability or deformity even unto death. Happily, the thin placental barrier protected you from mother’s many minor indiscretions and infections.

Those eight busy weeks also brought you to a point (often referred to as the end of embryonic development and the start of fetal life) at which your tiny embryo began to differ more obviously from a similar-stage fish, turtle, pig or chimpanzee embryo. But at this early stage, your future status as a fully accredited human remained far from evident. Nor could an average jury have found important qualitative differences between your early embryo and that of a pig or chimpanzee - either of which can legally be purchased and consumed in many lands.

When you come right down to it, there is remarkably little chemical difference between steroid hormones such as the estrogen and testosterone that eventually signaled your entry into puberty, and the ecdysone which orders insect larvae to molt and pupate. Nor should it amaze you that some plants have acquired the DNA necessary for producing insect juvenile hormones - which allows those plants to stop the maturation and reproduction of certain insect pests that feed solely upon them - or that other plants manage to produce enough estrogen to promote contraception in mammalian herbivores.

Furthermore, the same prolactin hormone that encourages breast milk production in humans also causes frogs to retain their larval (tadpole) status. In addition, prolactin remains the signal that initiates the second salamander metamorphosis in preparation for a return to life in the water and spawning. Note again how frugal evolution is, with its many appropriate but wildly divergent uses for already established signal molecules and their long time receptors.

As another example, consider how the thyroid hormone that regulates your metabolic rate also stimulates the metamorphosis of tadpoles into frogs. Among important changes induced by thyroid hormone is the transition from humble tadpole (prey and herbivore) demeanor to that of fierce frog (predator). As an herbivore, the tadpole was well served by eyes located laterally - with the tadpole's right optic nerve going entirely to the left brain and vice versa.

But an adult frog's brain must continuously track moving visual images and utilize binocular vision for depth perception. And it is more efficient to involve both sides of the frog's brain from the start. So as frog eyes approach their new forward position, they extend additional connections to the brain until only half of each frog optic nerve crosses the midline - just as your optic nerves do.

Clearly, in you or a frog, the thyroid activates some genes, suppresses others and leaves still others unaffected. And there are important threshold effects, so that frog legs start to grow at a lower thyroid concentration than that which causes tadpole tail regression, thereby maintaining mobility throughout metamorphosis.

## *Changing patterns*

The growth and development of every living thing fits seamlessly into the unbroken and ever-adaptive process of birth, maturation and reproduction that stretches back to life's beginning. Hence life's important molecules are widely distributed within bacteria, single-celled creatures, plants and animals. Yet the particular messages that those molecules carry, and the structures or even sequences that they designate, may resemble one another or vary endlessly.

Nonetheless, the rules are simple - forgo needless complexity, avoid extravagance, recycle everything and above all, out-reproduce the competition. In this way, by chance and endless reiterations, during good times and bad, natural selection eventually happened upon exactly the right information to build the real you.

Change is inevitable. The universe and its galaxies and their stars and planets continue to evolve and so does any life in or about them. Before your embryo lost its tail, it closely resembled the embryo of a rabbit or a bird or a turtle. For all vertebrate embryos compulsively follow the same old step-by-step developmental process that gave rise to the embryos of your fishy ancestors - with each vertebrate embryo eventually deviating from that standard pattern in order to become yet another of its own kind.

But unlike your fishy ancestors, your early embryo had no possible use for its gill arches and 6 pairs of aortic arches - nor did any design principle require pre-placement of a simple notochord before you could lay down your spinal cord - neither had you any rational excuse for growing a temporary pre-kidney, or a cute little tail, or skin like a fish embryo.

Your early embryo resembled those other early embryos simply because the embryos of your recent ancestors still passed through and developed from that same generic, highly successful, fish embryo pattern - which in turn came about by repeated minor modifications of what went before.

You had to start somewhere. There was no way or need to revise every previous step each time your ancestors became slightly different. But had you been fully designed directly from scratch, your Creator could easily have come up with an endless number of far less complex, hence safer and more reliable routes by which to form the final you.

As it is, three out of four human embryos are naturally discarded before birth due to design or developmental defects. Yet human embryos are so easily produced that this silent majority is simply tested and trashed at no apparent reproductive cost.

Look at it this way. How does a fish become a frog, or a human, or perhaps a bird? Verrry slowly. And in the process it must undergo a whole lot of modifications. Some of the endless intermediate steps taken by your own distant ancestors were still easy for your embryo to retrace, for the trails remained in use and essential markers were in place.

Quite clearly, a huge number of delicately adjusted, sequential modifications contributed to your own fleeting version of a fish-embryo-like structure. And each of those many steps represented yet another rendition of a long-established ancestral pattern that no longer had the slightest relevance to your eventual delightful design.

The stepwise construction and revision of your embryo provides important evidence about the progressively modified embryos of your remote ancestors. It also explains why your own embryonic cells and tissues had to move past, over, under, around and through each other in order to reach locations where they could best serve in you.

It would have been far simpler had your cells just marched out there with the band playing your song and formed you directly. Simpler for God to design or an embryologist to describe, that is. But for your embryonic cells, such a direct approach presented insuperable organizational difficulties in comparison to just repeating all of those long ago choreographed and endlessly perfected steps one more time.

When the half-time band at a football game already performs several sequential patterns perfectly, it is far simpler to make further modifications from where players are currently stationed than to reorganize everyone in the band back to their position on emergence from under the stands. Your cells persist in their difficult rituals and complex marches because that is more or less how equivalent embryonic cells did it in your earlier ancestors.

“We’ve always done it that way” does not mean it is easier or even right. It merely states the obvious - one more repetition is usually simpler than completely changing one’s ways, even for a very good reason. So while no fundamental rationale or design consideration required that you be produced in this fashion, it happens to be the way things came about.

Of course, had you been created directly in His image, the nerves to your diaphragm could have emerged from your lower thoracic spinal cord rather than stretching all the way down from your neck - and your single aortic arch would have developed in direct continuity with your head arteries from the start, rather than being formed from some parts of paired arches #3 and 4 while pairs 1, 2, and 5 disappeared - and certainly you would not have bothered to grow a tail just so it could later undergo programmed cell death, along with the tissues between your webbed embryonic toes.

Nor would branches of your vagus nerves extend down from your neck to encircle arteries in your chest on their way back to your throat. Yet that hardly seems inconvenient at all when you consider how those same nerves still loop down into the giraffe's chest before returning to its voice box. Those extra meters of nerve interposed between brain and voice box make the impressive silence of giraffes a bit less surprising.

Surely no competent designer would ever build in such an unnecessary delay between thought and vocalization. For while you have often regretted your words immediately, the giraffe has a much longer delay during which to regret messages still en route. But presumably that recurrent laryngeal nerve once followed a straight and narrow path across the short fat neck of your tiny ancestral mammal as it squeaked a quick warning of incoming pterodactyl.

Furthermore, your olfactory nerve would probably bypass your cerebrum, and head off to the thalamus with the rest of your sensory input, if that first small group of cerebral nerve cells had not already been dedicated to some long-ago ancestor's interpretation of odors. Yet were it otherwise, you might think quite differently as well.

A great deal of similar evidence strongly suggests that your uniquely human pattern is hardly the inevitable climax toward which all of Nature and life have been striving ever since Creation. Indeed, it is impossible to show that humans are anything more than the most effective information processors among the many complex and specialized multicellular organisms currently alive.

However, even that statement ignores the far larger brains of whales, dolphins and elephants as well as the embarrassingly greater brain-to-body-size ratio of monkeys, red squirrels and jumping mice (compared to your own). And let us not forget that all cellular life is built of bacteria, revised by bacteria, powered by bacteria, dependent upon bacteria and recycled by bacteria.

But while the latter observation clearly is relevant, interesting and true, it has only moderate explanatory or predictive power - just as one might acquire unlimited data about your subatomic particles, molecules, in-house bacteria, cells, birth order and ancestry without gaining additional insight into the time, place or content of your next insightful idea.

Nor would the most detailed measurements of oceanic and atmospheric conditions, solar input and so on, allow you to fully predict the dates and tracks of next year's hurricanes. Yet ideas arise and hurricanes happen.

Apparently the reductionist, in-depth evaluation of an entity's components is a necessary but insufficient undertaking for those who seek to comprehend an entire system and how it interacts and responds at higher levels of complexity. For just as the future is more than a linear extrapolation of the past - an entire organism or society or civilization or biosphere is more than a linear extrapolation of all functions, qualities and possibilities inherent in its parts.

Indeed, unprecedented new information - such as you or The Beatles or Evolution Theory or “Scientific Creationism” - can only come about through the revision, reorganization, recombination and extension of preexisting information.

So while most components of any larger entity continue to make their anticipated contributions - a full accounting of their complicated interactions and final impacts cannot be determined until these too come to pass. Thus information’s emergent qualities guarantee interest and unpredictability. And humanity could only have reached its unequaled level of development by a lengthy and circuitous route.

Random informational changes are meaningless by definition. Nonetheless, they gave your ancestors a significant reproductive advantage over most of their peers. And innumerable random changes - endlessly recombined through simple recursive rules and subjected to natural selection - is what brought about life’s sublime, hierarchical realities.

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