

# Your Physical Self

**Abstract** The cooperation that results in our physical bodies is described; between genes, between prokaryotes, within eukaryotes, between eukaryotes (giving rise to multicellularity), and between the bacteria in our guts and ourselves. Our physical selves consists of conglomerates of layer upon layer of cooperating parts.

## Genes

Everything biological is made of parts. But a single atom is not sufficient to give the instruction COPY ME (if that were enough, matter would replicate all around us—it doesn't). Such an instruction demands many atoms together, organized in special molecules: DNA or RNA. What these molecules do is to reorganize matter into copies of themselves. This is the most basic chemical reaction of life.

Think about the instruction COPY ME in a computer program. If you spell this instruction the least bit wrong, the computer will grind to a halt. Computers are stupid in that way and so is DNA. All the letters have to be there, united as the letters of a properly spelt word. If a piece of the code, such as OP ME, is on its own, it will soon disappear, uncopied.

Life based on the copying instructions in DNA works in exactly this way; the entire copying instruction is needed for the process to work. *Each* letter must co-exist with the others—they must function together. All instructions do not necessarily have to co-exist on the same molecule, however, as it has been shown that mixtures of RNA fragments spontaneously form cooperative catalytic cycles and networks (Vaidya et al. 2012).

Nevertheless, as an effect of this collective functioning, a unit emerges which is larger than the sum of its constituent parts, a *self-replicating molecule*; a unit that achieves something its constituent parts couldn't. The 'benefit' that the molecule reaps through the collective functioning of its parts is that it is replicated; more

copies of the whole molecule are created. This is what is implied by ‘benefit’ in evolutionary terms.

Through being copied in greater frequency if things go right, and in lower frequency if they don’t, costs and benefits now exist that can be counted and compared. ‘Good’ cooperation is cooperation that results in more copies of the self-replicating molecule, and ‘bad’ cooperation is cooperation that results in fewer copies of the self-replicating molecule. This is a criterion of benefit that will remain with us throughout the book.

But why attach value terms such as ‘good’ or ‘bad’ to differences in frequencies? This can of course be disputed, but genes with instructions resulting in more copies (‘good’) will replace genes with instructions resulting in fewer copies (‘bad’)—such competition is natural selection. What I term ‘good’ is winning this contest.

Self-copying is life’s most basic instruction, the very basis of evolution. With genes, we have arrived at something we can term a *replicator*—a unit that copies itself. Richard Dawkins has defined replicator more stringently as ‘any entity in the universe which interacts with its world, including other replicators, in such a way that copies of itself are made’ (Dawkins 1978).

This replicator consists of smaller collectively functioning units that do not become copied when they are on their own. The unity of the constituent parts thus results in something more than just the sum of the parts.

What the replicator results in is nothing less than a chemical mechanism that orders matter through the biochemical manufacturing of more copies of itself, through the assembly of separate parts. From being a scrambled mess of parts, order is achieved through relentless repetitive copying. Thus, from the very beginning, life seems to defy the fundamental physical process that results in increased entropy, that results in a larger degree of disorder (of course, life doesn’t really defy thermodynamics—energy is supplied from the outside, ultimately from the sun). This ordering capacity is one of the signs of life.

Organisms order matter by utilizing energy from their environment. Animals and mushrooms absorb order from other life forms when metabolizing or decomposing. The waste products from these processes are less ordered than what went in; this absorption of order drives the process. Plants utilize energy through transforming energy present in sunrays to energy stored in chemical bonds through the process known as photosynthesis. In this process, one of the waste products is heat—less ordered energy than what went in. Through their energy transformations animals and plants can build structures—leaves, stems, flowers, body parts, and in this way order matter on an even higher level than simply making copies of their DNA.

Some researchers believe that the initial copying instruction was given by a piece of randomly assembled RNA. Others hold that the first RNA instruction built on earlier types of self-replicating elements. At present, we simply do not know. What we do know is that the components necessary for life to emerge can emerge spontaneously, but we do not know how these components first assembled into a self-replicating molecule. Research on this topic is on-going.

With molecular copying there is immediately a possibility that the copying goes wrong in different ways. Sometimes the copy becomes so riddled with errors that that the copying ends (analogous to a misspelling: CPRK ME). However, the copying error can also make no real difference, but occur in such a way that the copying can keep working (analogous to a superfluous letter COPY ME K).

Had copying been carried out without error from the beginning, life would have stopped at the initial stage and no evolution taken place. Earth would have filled up with the same self-replicating molecule until all building blocks had been utilized and that would have been the end of it. Without errors there is no possibility of improvement. For evolution to occur, copying can't be perfect all the time, but can equally well not be erroneous all the time. The right amount of errors is a crucial part of the evolution of life: mutations.

A not uncommon error in the genome is something termed gene duplication, that one gene is copied twice (COPY ME|COPY ME). This means that mutations that previously had been directly lethal for copying can now take place in one gene, while the other remains intact and carries out the instruction. This at once opens up for new instructions (for example, COPY ME|CORRECT ME). In this way, new adaptations can creep into the genome.

Already here one central component of cooperation emerges: specialization. Even though genes are the same physical phenomena (and thus an example of fraternal cooperation—cooperation between like parts), different genes carry different information and thus have different functions and consequences. This is one of the reasons that the sum of many different genes results in something so much larger than just the sum of its parts.

Some genes in our bodies carry instructions to check that the copying process of the DNA has been carried out correctly. Others carry instructions for the protection of the genome through a secure cell wall. Yet others carry instructions for acquiring energy, or getting rid of excrement, and so on.

Note the emphasis on instructions—genes carry *information*. Their chemical properties have consequences above and beyond just affecting themselves. In animals, genes for example carry information for traits such as color, tooth size and claw design, but also behavioral traits such as aggressiveness, territory size and mating displays, and even traits outside the body, such as the design of beaver dams, bird nests and termite mounds.

The proper manner to regard genes is thus as *information carriers*, not just interesting chemical compounds that happen to copy themselves. The influential American biologist George C. Williams stressed this forcefully early on, pointing out that like poems and food recipes, the importance of genes lies in the information transferred, not the exact medium that carries the information. Just as it isn't important how much a poem or recipe weighs, if it is written down on paper, memorized, or hacked into stone, likewise the importance of genetic replicators are that they are information carriers, not that they are strings of nucleotides (Williams 1992).

Mutation speed is central already from life's very beginning. If random change happens too often, the copying system breaks down and the line of inheritance stops. If random change happens too seldom, no improvements occur and the line of inheritance is overtaken by others having greater variation.

In later forms of life, in more complicated organisms such as humans, mutation speed is different in different parts of the genome. Parts of the human genome are so critical to our survival and well-being that there is no room for error at all. But of course, sometimes errors happen anyway, and things go really bad. The copying stops: death.

One example from the human genome is the disease retinoblastoma, a form of eye cancer in children. In somewhat less than half of the cases, a mutation in a single gene is the cause for the disease: the gene RB1 on chromosome 13 (Mastrangelo et al. 2008). Since this form of cancer was fatal up until recently, these mutations were ruthlessly weeded out. Death meant that the whole genome of individuals with retinoblastoma was destroyed. The cooperation between genes broke down because of an error in a single gene that consequently didn't function collectively with the other genes.

In other parts of the human genome almost anything can happen without having an effect. Here, mutations are common and the control mechanisms are more relaxed. For example, there are long stretches of DNA that seem not to provide instructions for anything. In one experiment, a whole percent of the genome in mice was removed, without any noticeable difference (Nobrega et al. 2004).

Mutations and other copying errors happen all the time. Sometimes the error results in cooperation breakdown. Then that cell line ends, self-copying stops and death ensues. When the system is fully developed it is almost impossible for a gene to make it on its own—to exit its context and carry on as a stretch of loose DNA.

Not that breaks in cooperation never happen; they happen worryingly often. Researchers have found genes that copy themselves into several places in the chromosomes, genes that jump from one place to the other, and genes that become represented with more copies than other genes at self-replication (Hooekstra 2003). But there also exist genes that code for strict control mechanisms against that form of 'cheating'.

Genes must also function together to prevent providing conflicting instructions for the construction of the organism. Genes that provide superior hunting capabilities (flexible limbs, soft pads, and an ability to predict the movement of the prey) must cooperate with genes that are good for the metabolism of meat. Genes that result in a craving for grass function better together with genes that result in molars and the ability to chew cud.

Cooperation between genes can be said to be the 'innermost' form of cooperation in a human body. The collective functioning of genes is what makes life possible and may even be the best definition of life itself. There are, however, different solutions to how one group of cooperating genes are separated from other groups of cooperating genes.

## Simple Cells—Prokaryotes

The simplest life with DNA or RNA that completely runs its own reproduction are single-celled organisms without a nucleus: the prokaryotes, or—as they are termed now—bacteria and archaea.<sup>1</sup> It is from this stage we have the first evidence of life, from at least 3.5 billion years ago (Schopf et al. 2002), though new evidence pushes this date as far back as 4.1 billion years ago (Bell et al. 2015).

Within cells of this kind, all parts work together to run the cell's machinery in the same way as the cell's genes cooperate in order to be copied. In this type of life, each cell is its own individual.

The genes of prokaryotes are collected in a single ring molecule—a nucleoid. These genes not only contain copying instructions but also instructions for the cell's metabolism and maintenance. Genes that carry good instructions for a well-functioning cell machinery get copied to a higher extent than genes that carry instructions for a less well-functioning machinery. But it is equally true that a cell with better functioning cell machinery replicates more often than a cell with less well-functioning cell machinery. The cell is in this way also a replicator, a continuation of the genes. The 'interests' of the genes and the 'interests' of the cell concur—though not completely.

For example, bacteria sometimes exchange genetic material. The process starts with the outgrowth of a small spear-shaped extension from one bacterium into the next. Then genes traverse the outgrowth and are in this way passed on from one cell to the other. Not all genes, though; genes that are central for keeping the bacterium alive stay put. One example of genes that can move like this is the type that provides bacteria with resistance to antibiotics.

What the recipient bacterium has to gain from the transfer is obvious: it gains some genetically coded trait and can in this way survive and keep making copies of itself. But why does the other bacterium send over the genes—what is in it for the sender?

This mechanism is more easily understood if you change perspective and investigate what advantage there is for the genes instead of what advantage there is for the bacteria. An 'ordinary' gene—a gene that does not jump between individuals—spreads only through one process: through cell fissioning from one cell generation to the next.

But a gene that also carries instructions to be contagious from one cell to the next has more reproductive potential than this, because such a gene can reproduce and be copied in two ways: through cell fission and through contagion. It is not so hard to see that a gene that gets copied in two ways becomes more numerous than a gene that gets copied in only one way.

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<sup>1</sup>A key difference between bacteria and archaea is that the cell wall of archaeans consists of pseudomurein while the cell wall of bacteria consists of peptidoglykan.

Thus, what looks as self-sacrificial cooperative behavior turns out to be nothing else than the product of selfish genes—a form of beneficial genetic ‘disease’ that spreads through populations of bacteria. In this way, selfishness on a genetic level becomes something that looks as costly cooperation on an individual (cellular) level. The unit that has the benefit from the genetic donation is not the donating bacterium itself, but the genes that carry the instructions for antibiotic resistance.

This is a common theme in many types of cooperation, that to understand what is going on, it is crucial to change perspective from individuals to replicators. Cooperation on one level (individuals) has its foundation in an advantage for replicators on another level (genes).

To understand cooperation one must therefore constantly ask the question that is the title of this book, ‘For whose benefit?’—*Cui bono?* This will become even clearer on the next level, where several bacteria gang together and life enters a more entangled stage—cells with nuclei.

## More Complex Cells—Eukaryotes

In 1967 a sensational scientific article was published with the title ‘On the origin of mitosing cells’ in the *Journal of Theoretical Biology*. The author was a young faculty member in the Department of Biology at the University of Boston, Lynn Margulis (Lynn Sagan at the time, as she was married to the famous astronomer Carl Sagan) (Sagan 1967). The idea she presented was so controversial that according to her own story the manuscript was ‘rejected by about fifteen scientific journals’ before being accepted for publication (Brockman 1995).

Margulis had authored a milestone article where she presented a theory that at first sight seemed almost wacky, but eventually proved to be correct. The article outlined the evolution of cell organelles<sup>2</sup> within the type of cells that carry the name *eukaryotes*. Where the term prokaryote comes from the Greek *pro* = before and *karyon* = nucleus (i.e. before the nucleus) eukaryote instead has the prefix *eu* = true. It is thus the presence of a true cell nucleus that gives eukaryotes their name.

While prokaryotes (bacteria and archaea) have their genetic material collected in a ring, eukaryotes have their genetic material collected in chromosomes. These lie protected within an extra cell membrane inside the cell: the cell nucleus. Multicellular animals are eukaryotes, as are multicellular plants and fungi—we all have an extra cell membrane that protects our DNA within (almost) all cells in our body.

But not only that, we also have *mitochondria*. These are the energy factories of our cells. Within eukaryote cells, mitochondria convert glucose and oxygen to adenosine triphosphate, or ATP, the molecule used as energy source in most energy-demanding processes in cells. In addition, plants also have *chloroplasts* containing chlorophyll. This is where photosynthesis occurs.

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<sup>2</sup>The cell’s ‘organs’.

So where do cell nuclei, mitochondria and chloroplasts come from? How did they evolve? Interestingly, all three contain DNA. While the cell nucleus seems to be the evolutionary result of the cell's own cell wall folding in on itself and detaching, Margulis suggested a radical proposal for other organelles. Many bacteria gain nutrients through absorbing material around them. Research has now confirmed Margulis' hypothesis, that the organelles were once bacteria ingested by another bacterium without being digested. Instead, the eaten bacteria were able to carry on living and reproducing within the other bacteria; they were 'symbiotically acquired' (Sagan 1967).

These intruder bacteria could make their living on stuff that the host bacteria ingested, or on free-flowing detritus within the host. The tight interdependence that slowly emerged is what in biology is termed *symbiosis*—a close, mutually dependent, long-term relationship between different species. Over time, roles crystallized—the symbiotic bacteria specialized. Some of the intruder bacteria became energy factories: the mitochondria. In plants, chloroplasts evolved in a similar manner.

Mitochondria and chloroplasts are of special importance to evolutionary biologists as they carry their own DNA. At cell fission, some mitochondria and chloroplasts follow one half of the cell while some follow the other. This means that two genetic inheritances are transferred in each cell fission (or three, in plants, through the chloroplasts).

The unique thing about mitochondria and chloroplasts is that they are transmitted only via egg or ovules of a flower, never via sperm or pollen. This means that their DNA is transmitted only through the female lineage; this inheritance is totally maternal.

Interestingly, some plants have mutations in their mitochondria that have resulted in the termination of cooperation with the rest of the organism. Since mitochondria are transmitted only on the female side they derive no necessary benefit from the squandering of resources on males—so these mutations in the mitochondrial genome result in sterile males. This is another example of a mutation resulting in a gene in conflict with the rest of the genes in the organism, resulting in cooperation breakdown.

The mitochondria present in human cells means that we are related to bacteria along one line and through another to archaea. Foremost, the relationship is through the original evolutionary line of the DNA in our cell nuclei, but we also carry a separate relatedness through our mitochondria—but only on our mother's side.

Recent developments indicate that the story of bacterial endosymbiosis is even stranger than we thought—some eukaryotes seem to have acquired their chloroplasts by ingesting not another photosynthetic bacterium, but another eukaryote who already had gained a chloroplast through ingesting a photosynthetic bacteria. Even more complicated, some dinoflagellates (a type of plankton) have acquired their chloroplast by eating some of *those* eukaryotes. Further, some reef-forming corals contain this type of dinoflagellates *and* some of the photosynthetic bacteria that were ingested by the 'first' ingesting host bacteria (Godfrey-Smith 2009).

It is not currently known exactly when the first eukaryotes emerged, the current estimate is sometime around 1.5–2.5 billion years ago. Free-living eukaryotes still exist; we know them as protozoa, one-celled animals, and cyanobacteria, one-celled plants. But eukaryotes have also evolved into such remarkable creatures as fungi, plants and—not the least—animals as ourselves.

Thus, (almost) each and every cell in our bodies consists of cooperating cells within cells, specialized units that from the beginning were separate organisms (and thus an example of egalitarian cooperation—cooperation between unlike parts) but now have lost their autonomy and are so integrated that they are indivisible units. Their internal cooperation is for the benefit of all the cells and their genes.

As before, the benefit of this cooperation is assessed through the number of genes present in the next generation. Genes that result in traits that give cells and their mitochondria an edge will over time be represented more numerous. One such successful way to become more numerous has been for the cells within cells (the eukaryotes) to cooperate with each other.

Note that the emergence of eukaryotes is a coming-together of different bacterial species to a new type of organism, where the component parts eventually become so interdependent that they cannot live without each other. This is not the last time we will see examples of this kind, think for example of the fungi and algae that make up lichen. What exactly constitutes an ‘organism’ can therefore be difficult to sort out (Queller and Strassmann 2009). Because evolution occurs gradually, there exist blurry phases along the way from separate organisms to one organism.

## Multi-cellularity

The next layer of cooperation within humans is multi-cellularity: cooperation between cells. Cooperation between cells in general exists in two flavors: cooperation between cells with *different* genetic material (egalitarian cooperation) and cooperation between cells with *the same* genetic material (fraternal cooperation) (Queller 1997). Humans are (mainly) multi-cellular in the latter sense, so we will focus on that now: a form of cooperation that has evolved more than 25 times whereof three have led to the evolution of more complex organisms: plants, fungi and animals. Cooperation among entities with *different* genetic material will be discussed later.

Bacteria that replicate through fission will ultimately result in a large number of cells with the same genetic material gathered in a heap of many cells. But these cells all look the same, function the same and don’t depend on each other for their existence; they are a colony of cells, not one multi-cellular organism. True multi-cellularity is instead when many cells from a single origin form a distinct unit where cells depend on each other for the survival and reproduction of the larger unit.

Cells in fungi, animals and plants are specialized—different cells carrying the same genetic information having different functions. During individual development, each cell receives signals from its surroundings resulting in genes turning on or off which in turn is what causes specialization. This process ensures that the right organ ends up in the right place—a process completely guided by the interaction of the genetic material with its immediate surroundings.

This is how we get heart, lungs, muscles and a brain; this is how trees end up with trunks, branches, twigs, roots and leaves. The specialized parts carry out specialized tasks for the benefit of the whole organism. Despite their marked differences, all these parts are built of cells possessing the same genome. The differentiation into organs is entirely caused by differences in the signals the cells receive depending on where they happen to be in the body. Understanding this process is a hot current research topic.

Just as was the case with the genes, the cells' specializations open up for new possibilities of evolving complexity. Without specialization you just end up with many similar cells stuck together doing the same thing. With specialization, new forms of organisms can be built; big bodies consisting of specialized organs.

One spectacular consequence of specialization in multi-cellular organisms is that because all cells have the same genetic material, genes can now code for pre-programmed death—cell death. As long as all genes are copied effectively from generation to generation, the survival of single cells is of no consequence. One consequence of multi-cellularity is therefore that death becomes built into life itself.

Many structures in multi-cellular organisms actually consist of, or are the result of, dead cells. The discovery of programmed cell death resulted in the 2002 Nobel Prize in medicine for the South African Sydney Brenner, American Robert Horvitz and Briton John Sulston.<sup>3</sup> One of the most extreme examples of cell death is the wood of trees. Wood consists of cells that have grown and then been instructed by their genes to die. The overwhelmingly largest proportion of a tree thus consists of dead cells.

Even humans are constructed in this way. For example, the outermost layer of human skin consists of 25–30 layers of dead cells that have also been programmed to die. The human skeleton, however, instead consists mostly of living cells, even though the cavities in the skeleton are the result of programmed cell death.

Cell death is an important part of human development all the way from the fertilized egg to adult being. For example, without programmed cell death you wouldn't have separate fingers and toes. During fetal development, fingers are stuck together on each hand and toes are stuck together on each foot. Only later do cells between the fingers and toes die so that these become separated. If something goes wrong in this process—which isn't entirely uncommon—you are born with fingers or toes stuck together.

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<sup>3</sup>The Nobel Prize in Physiology or Medicine 2002 was awarded jointly to Sydney Brenner, H. Robert Horvitz and John E. Sulston 'for their discoveries concerning 'genetic regulation of organ development and programmed cell death'.

Cooperation between cells that have the same genes means that ‘individual’ is no longer synonymous with ‘cell’. Instead, individuals now consist of a collection of cooperating cells. Australian philosopher Peter Godfrey-Smith has termed this process ‘de-Darwinizing’, where individual cells of a body no longer compete with each other, having lost their autonomy they instead cooperate together for the good of the individual (Godfrey-Smith 2009)—or for the good of the common genome, depending on perspective. The same process has occurred for organelles (mitochondria and chloroplasts) and genes.

It is one of these collectives of specialized cells you see when you look at yourself in the mirror.

Cooperation between cells with the same genes is also what has led to aging and death. In single-celled organisms death also exists, of course, but not as a programmed component of life. All death in single-celled organisms is due to accident, not design. Bacteria and other single-celled organisms are potentially immortal; they just go on fissioning and have done so since the dawn of life. From the first bacterium to all bacteria that exist today there is an unbroken chain of cell fission where no ‘new’ cell is the descendant of another, but largely the same cell in two versions. Mutations occur in individual cells and are transmitted to later copies through duplication.

Multi-cellular organisms function according to a different principle. Here, most cells have as their task to maintain life in the whole collection of cells; the whole organism. Only a select few cells have reproduction as their main task (in humans, these are sperm and eggs). If mutations happen in the cells that are *not* involved in reproduction, these are consequently *not* transmitted to the offspring.

Almost all multi-cellular organisms go through a single-celled stage when reproducing, often by combining their genetic material with that of another individual in the process we term sexual reproduction. We are all single-celled, initially. If you want to reverse the perspective, you can thus say that our bodies are really a very roundabout way of single-celled organisms to get together to reproduce. Or, as the British satirist Samuel Butler phrased it already 1877: ‘A hen is only an egg’s way of making another egg.’

As long as reproduction has occurred, all other cells of the body are unimportant and can be discarded, which is exactly what happens. After our reproductive age, our bodies start slowly malfunctioning, a process slowed only by the advent of modern medicine. In the end, all multi-cellular organisms die, leaving only their offspring behind to go through the same process. Evidence points to all living things on earth coming from the same initial cell; all living forms represent genetic lineages that have not yet died out. Though our bodies are mortal, our genetic lineages are potentially not.

The single-cell phase, that takes place just after fertilization, ensures that all cells in the resulting body will have the same genetic material. Thus, individual cells from the body will have little incentive to break cooperation and leave to live on their own to the detriment of the whole. If such a mutation occurs in a subsequently developed body cell, it is not transmitted to the next generation.

But this is a truth with caveats. For example, many plants can reproduce through saplings. It can be argued that this is a form of growth, rather than reproduction, even though unity is broken with the parent organism when the sapling loses contact with the parent tree. Such reproduction through saplings is similar to bacteria fissioning—a splitting of organisms where the offspring is genetically identical to the parent (almost—there are always a few mutations).

Peter Godfrey-Smith has pointed out that there exist three varieties of reproduction, basic, collective and scaffolded. Fissioning of bacteria and through saplings is what can be termed ‘basic’, whereas our type is collective in that it requires more than one individual for reproduction to succeed through sexual reproduction. Finally, viruses, chromosomes, mitochondria and ‘memes’ (we will get to them later in the book) reproduce by high-jacking another system and thus require the existence of another structure than themselves to reproduce.

Nevertheless, it is still overwhelmingly common that a unicellular phase exists somewhere in multi-cellular organisms’ life cycles (also for trees that can reproduce through saplings). For people this is fortunate, otherwise mutations would have accumulated in the genome at terrifying speed.

We humans have a mutation frequency of about 0.000000025 mutations per nucleotide (one nucleotide is a ‘letter’ in a string of DNA) (Nachman and Crowell 2000).<sup>4</sup> This means that each person leaves about 175 new mutations to each child. However, most mutations are completely harmless and pointless.

In 1961 the American anatomist Leonard Hayflick presented results indicating that human cells can handle about 40–60 cell divisions before they stop fissioning (Hayflick and Moorhead 1961). At the end of the life cycle of a cell that has gone through about 60 divisions, around 10,000 mutations ( $60 \times 175 = 10,500$ ) have thus accumulated. What stops further cell divisions and causes the death of the cell is that the ends of the chromosomes—the so-called telomeres—accumulate mutations and become shorter and shorter.

Would continued cell division be desirable? If we could in some way reconstruct the telomeres, wouldn’t we be able to stop suffering and death?

There are actually some cells that produce a substance called telomerase that achieve exactly this. Telomerase allows some cells to divide indefinitely. We call these cells *cancer*.

The infinite replication of cancer cells has the consequence that more and more mutations accumulate as they divide. Cancer cells thus function less and less as the initial cells from which they developed and instead become more and more defective. Researchers are consequently now investigating the possibility of medicating cancer by terminating the production or function of telomerase.

Thus, cancer is nothing less than cells that have broken cooperation because the genes that exist to control the cooperation of single cells or control the copying of

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<sup>4</sup>More precisely, mutation rate is between  $1.3 \times 10^{-8}$  and  $3.4 \times 10^{-8}$  mutations per nucleotide (a nucleotide is a ‘letter’ in a DNA string). This means that every person bequeaths approx. between 91 and 238 new mutations to every child.

genes have been destroyed or have mutated. Even if single genes are merely components of cells, and single cells are merely components of multi-cellular individuals, cancer functions as a drastic reminder that we really are collections of cells.

Interestingly, cancer in some organisms is not equally detrimental as in animals. In trees, for example, cancer can emerge and kill a part of the individual but in general seem to be not nearly as harmful as in animals like us. Part of the reason is that cancer cells cannot spread around the tree due to their more rigid cell walls. Thus, problems at one site doesn't necessarily end in the death of the whole organism.

It is a part of the life cycle of healthy cells in humans to die after about 40–60 cell divisions, for the benefit of the whole organism (and the organism's genes). In this way, the body is purged of accumulated mutations. However, certain cells exist that do not accumulate mutations: stem cells—cells that yet haven't been specialized to become, for example, liver cells or eye cells. These exist in different places in the body and continuously replace dead cells and in this way function as the body repair system. How stem cells can keep dividing without accumulating mutations is another really hot research topic (Nature Reports: Stem Cells).

Since genetic information from the body at large is not transmitted to offspring, sexual reproduction is one protection against 'selfish' cells having lost their ability to cooperate. But sexual reproduction also has another advantage (ok, two), in that beneficial mutations from several independent individuals through this form of reproduction can be combined into a single genome.

How does this work? Imagine a situation where a good adaptation occurs in one individual and another good adaptation in another individual. In organisms without sexual reproduction these two adaptations will never meet. In organisms with sexual reproduction, on the other hand, individuals can mate and have offspring carrying both adaptations. Sex is thus a form of cooperation between two individuals with different genomes that speeds up the evolutionary process. We will get back to why and when sex evolved in a later chapter.

As we have seen before, bacteria have instead solved this problem through gene donations. Antibiotic resistance can thus be seen as a form of bacterial sex.

The death of a single cell is no catastrophe for a multi-cellular organism, whether death is pre-programmed or random (if you happen to cut your finger, for example). Your existence does not depend on the survival of some 'key cell' or 'executive cell'. On the contrary, your body can lose many cells due to natural processes or random cell death without this killing you.

There is simply a surplus of cells, which makes your body very robust in relation to the individual cells. This surplus makes the whole more resilient than if you had been built by just enough cells to run a functioning body. This is a common theme where cooperation between units has developed into a new, larger entity—functioning cooperation in nature isn't trimmed and lean, but instead characterized by abundance, resulting in truly impressive resilience.

Further, organisms consisting of several cells represent a higher degree of order. When a multi-cellular organism grows from being one cell to being adult, the building blocks (molecules) are sorted successively according to a blueprint coded in the genes of every cell, the cells themselves ordered into a multi-cellular unit—an individual. More and more matter is bound in ordered structures on each level of cooperation in our body—in the genes, in the cells and in the body.

The Austrian physicist Erwin Schrödinger formulated it thus: ‘The essential thing in metabolism is that the organism succeeds in freeing itself from all entropy<sup>5</sup> it cannot help producing while alive.’ Organisms liberate themselves from entropy by absorbing order from the environment. Animals and fungi do this by ingesting once or currently living things, which they digest and excrete in a more disorderly state. Plants do it through transforming order in sunlight into chemical bonds (and heat).

Multi-cellular organisms where all cells have the same genetic make-up is the type of organism that we commonly notice around us. Humans, ants, plants, fungi—all large-scale life is multi-cellular. Individuals in these groups are composites of a large number of cooperating parts—cells—where life and death are unimportant for the single cells as long as the composite individual lives on.

Such steps of ever higher-level cooperation have been termed ‘major transitions in evolution’ in an important book by the evolutionary biologists John Maynard Smith from Great Britain and the Hungarian Eörs Szathmáry (Maynard Smith and Szathmáry 1995).<sup>6</sup> They postulate that many traits are in common in each transition. For example, each level of increasing cooperation is characterized by the specialization of common units.

It is thus not *more of the same* that is the explanation of how the whole can become more than the sum of its parts, but *more specialized units*. When the building blocks have been specialized, they most often lose the ability to multiply on their own, outside the cooperative context.

On each higher level of cooperation there are control mechanisms to keep the parts from breaking unity through behaving selfishly to the detriment of the whole. On each level there is also redundancy of constituent parts that makes the whole resilient to the loss of single parts. The picture that emerges is that our bodies are like series of Russian dolls where each higher level of cooperation includes another, more fundamental level of cooperation, all the way down to the self-replicating molecules: the genes—the replicators.

But incredibly, our bodies consist not only of cells with our own genetic code. There is much more to us than meets the eye in the mirror.

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<sup>5</sup>Disorder.

<sup>6</sup>They include a few more steps, principally at the outset of life, which are unimportant for the argument since those steps are not part of the cooperation that makes up the human body or the ‘id’, and do not include the ‘ecosystem step’ that I describe above.

## Mobile Eco-systems

It is estimated that about 90% of the cells in our body are not our own, but belong to bacteria, mostly in the gut. About 100,000 billion bacteria of 36,000 species (Frank and Pace 2008) live there, together weighing about 1.5 k. Some of these exist in the stomach and the small intestine, but most live in the colon. The number of different *types of genes* that exist in these bacteria is more than ten times as numerous as our own: approximately 20,000 genes (Arumugam et al. 2011). Counting the *total number of copies of genes*, we carry more than 100 times the number of bacterial genes as our own.

To an extent, this incredible diversity defines us; it turns out that humanity is divisible into three different groups—‘enterotypes’—depending on the bacterial ecosystem in our gut microbiome—there are only certain mixes of bacteria that result in stable internal eco-systems (Child and Macfarlane 2008). These bacteria are welcome and necessary guests in our bodies as they cooperate with us in exchange for room and board.

Normally, these cooperating bacteria out-compete disease-causing bacteria. You notice this if you ever ingest broad-spectrum antibiotics—the type that indiscriminately kills many types of bacteria—because by doing so you partly weaken your natural protection. It is therefore not surprising that one of the common side effects of antibiotic-treatment is stomach problems.

It is estimated that 5–30% of the nutrients our bodies absorb are not derived from the food itself, but are instead waste products from our friendly bacteria-symbionts who are the ones actually processing some of the food we eat. We also get K-vitamins and other necessary ‘waste’ products from bacteria in this way. This is why newborns in many countries are given K-vitamin supplement. The gut flora of babies takes a while to become established.

Bacteria that produce waste products that the body doesn’t want are of course not welcome. Nor are viruses that move into our cells and hijack them from within to make more viruses (this is how viruses ‘live’). Our immune systems are constantly busy with these intruders and trying to get rid of them.

‘Our’ bacteria co-habit with us because it is beneficial for them—they get both room and board. Our immune system doesn’t attack the ‘good’ bacteria since our bodies are better served by having them in place than not having them there; a mutual dependency that both parties derive benefits from. A kind of *symbiosis*, actually, since we can’t live without them and they can’t live without us. Cooperation where all parties gain benefits is also termed *mutualism*.

But can we really count these bacteria as part of our bodies, our physical selves? If we include them this would be our third form of kinship with bacteria; our first alliance is through the genes in our cell nuclei, the second via the genes in the mitochondria (the energy factories of the cells) and now the third form of kinship via the large number of bacteria that we are totally dependent on inhabiting our guts. Including them would immediately increase the number of human genes by

two orders of magnitude. But no, we currently count as interdependent species of organisms, not the same species.

There are many other stowaways on and in the human body, some that we would rather be without: tapeworms in the intestines, lice, fleas, ticks and other small pests. These are not examples of cooperation but are instead an example of another type of interaction where only one of the parties derives a benefit: *parasitism*. Note, however, that a parasitic relationship can be symbiotic—symbiosis does not only refer to cases where with parties benefit.

But what about the organisms that live on and in us, but neither benefit nor harm? There are, for example, two species of small arthropods (*Demodex folliculorum* and *Demodex brevis*) that live only in human eyelashes, without causing any ill symptoms whatsoever. About half of all humans carry them; they are a bit rarer in children and a bit more common in the elderly. They use us only as substrate and food source without providing any benefit or costing us anything. This is an interaction termed *commensalism*.

From this it should be evident that a human being is not just a collection of cooperating cells with common DNA, but rather a mobile eco-system. Every human is a sort of super-organism with one overarching common evolutionary goal: everyone striving to reproduce; all genes to get copied.

Do you see this collective, this layered eco system, when you look at yourself in a mirror? Or does your self stubbornly persist in presenting a single unified individual? If you still cannot help but see yourself as a single unified physical individual then don't worry—it gets worse. This far we have only considered your *physical* self. But what does your *psychological* self consist of—the self that discerns 'its own' mirror image?

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