8

EVERYTHING IS CONNECTED

In which we examine the evidence for cooperative evolution and show that everything is indeed connected to everything else.

In this chapter we argue, on the basis of evidence that we consider to be incontrovertible, that the predominating way of life on Earth involves the collaboration of organisms in a grand amplification of Darwin's vision of a tangled bank. We examine, with numerous examples, the diverse forms of cooperation – partnerships, symbioses, parasitism, multicellularity and human society – from ancient cells to human beings, that illustrate the weaving of Gaia's golden network.

The mutual dependence shown by living things is one of the defining characteristics of life. Symbiosis describes the cooperative enterprise in which all parties contribute to the wellbeing of the others in the partnership. It is a phenomenon that has been well known for centuries, but it is only recently that scientists have begun to understand its full import. Every school biology book is packed with examples of animals living in mutually advantageous harmony, representing them, quite justifiably, as among the wonders of biology. They are, however, only the more spectacular tips of a very large iceberg. It is, actually, a commonplace in biology.

Symbiosis could be defined as:

> the interaction between two or more genetically different organisms living in close physical association, to the benefit of all parties.

From a philosophical point of view, this is too limited, suggesting, as it does, that cooperation occurs only between different species. In fact, symbiosis also describes the arrangements between all animals that associate – insect colonies, herds of elephant, shoals of fish and flocks of birds. Hive and herd structures benefit the whole in dealing with predators. There is 'safety in numbers' in anthills and armies.

Closer to home the definition specifically excludes the relationship between a mother and her intra-uterine baby and, later, between a mother and her newborn. It excludes the whole of human society where, according to anthropologist Margaret Mead (1928) borrowing an African proverb in her famous but much-criticised book on adolescence in Samoa, 'it takes a village to raise a child'. Some experts in mammalian reproduction have gone so far as to describe the relationship between mother and foetus as parasitic. We reject this as it groups an essential relationship with inessential tapeworms and warble flies! The definition is one that clearly has problems.

A description of symbiosis as it occurs in the real world might be to delete the word 'genetically':

> the interaction between two or more different organisms living in close association, to the benefit of all parties.

Finally if we go back to basics, let us simply talk about cells, for the first modern cells are themselves tri- or tetra-symbionts:

> the interaction between two or more different cells living in close association, to the benefit of all parties.

We now have a definition that includes the whole of biological creation. Individual animals and plants become symbiotic associations of cells. Gaia herself is a symbiotic construct of all living forms, both plant and animal. It includes animals in mated couples and human societies.

Here are some well-known examples of symbiosis between genetically different organisms.

Mammalian ruminants (sheep, cows, deer and their relatives) could not survive without the microorganisms (ancient cells and fungi) that dwell in the section of their stomachs that is called the rumen. These microsymbionts have the ability to break down cellulose and, from it, generate essential nutritious metabolic products. One study of cattle showed that the rumen is the perfect incubator for *at least* 5,000 different 'operational taxonomic units' – species of bacteria, protozoa and fungi. This was determined using modern genetic techniques. Remarkably, the populations of the rumen inhabitants of individual animals were very similar, suggesting that each animal was regulating its own population in the same way (Jami and Mizrahi 2012).

Then there are the hindgut fermenters, animals with large posterior fermentation chambers, such as elephants and rhinos, horses and tapirs. There are the stomach fermenters, like the hippopotamus and some large marsupials. Thus, most of the modern mammalian megafauna (excluding the carnivores for the moment, although they also have interesting inhabitants in their guts), depend on intestinal fermentation one way or another. Almost certainly, so did the large herbivorous dinosaurs.

What worked once for termites long before mammals appeared on the scene can work again … and again. Hindgut fermentation helps quite a few of the smaller mammals. Rabbits make up for having a small, rabbit-sized intestine by eating their own faeces. This process is called coprophagy. At night rabbits produce soft, green, partially digested faeces and eat them, giving the microbes in their intestine a second go at breaking down cellulose. Important nutrients are synthesised by symbionts in the posterior, large intestine while absorption occurs in the anterior small intestine. What else can a poor rabbit do but recycle? Coprophagy also happens in rodents and it has been observed in koalas, ringtail possums, piglets, foals, dogs and nonhuman primates. Pigs regard human faeces as an excellent source of nutrition!

Vertebrates, however, are a very small class in the biological scheme of things so let us widen the search. Algae have a truly remarkable record of living with the cells of other organisms and cooperating with their owners. Lichens (fungi with algal symbionts, either ancient blue-green algae as well as modern single-celled algae) are a whole class of organisms that would not exist were it not for an obligate symbiosis between a fungus and an alga (Nash 2008).

Algae live in the cells of the reef-building stony corals; the Great Barrier Reef would not have existed if it were not for them. Coral bleaching occurs when those symbiotic algae are lost – unless the symbiosis can be re-established the reef dies. Other algae live in the fleshy 'lips' of giant clams, providing them with excess photosynthesis products in return for protection and, probably, micronutrients. One truly remarkable mollusc, the sea slug *Elysia*, consumes algae and then makes use of their chloroplasts which go on photosynthesising for a considerable time, relocated in the skin of the sea slug and turning it into a 'crawling green leaf' (Mujer et al. 1996, and for images of this remarkable animal visit: en.wikipedia.org/wiki/Elysia_chlorotica). If that does not hint at the ancient cellular origin of chloroplasts, nothing does.

Whole organisms enter into symbiosis with equal enthusiasm. Crabs use sea anemones or seaweed for protection. The decorator crab covers its pincers with tiny relatives of sea anemones, to take advantage of their stinging cells to kill small fish. Is this how tool-using began? Crocodiles employ birds as flying toothpicks to the benefit of bird and reptile. Oxpeckers live with zebra and cattle, eating external parasites. Bees pollinate flowers while collecting nectar and pollen. Ants farm fungi; the fungus gets propagated and the ants use it as a source of food. A good example is a small fish, a goby, that shares the burrow of the blind pistol shrimp, increasing the chances of survival of both. The goby uses its eyes and alerts the shrimp to impending attack by predators. The shrimp maintains contact with the goby by its antennae. When alerted, it snaps its claws with a sound that is compared to a pistol shot that scares or even damages the attacker. Human examples of beneficial associations include companion animals and the millions of bacteria in our guts. Even the vegetables that form part of our diet gain from their association with us. They get propagated in numbers that would not be possible in the wild. This list of mutual dependence goes on and on.

All of these examples, however, are superimposed on the most remarkable symbiosis of all, the great founding symbiosis that produced the modern cell. Sheep, cows, deer, crabs, sea anemones, seaweed, clams, algae, plants, fungi and humans are all constructs of the modern type of cell; each depends on the integrated activities of symbiotic modern organisms and the genomes of three or four ancient prokaryote ancestors. Our origins proclaim 'original symbiosis' rather than original sin!

In order to make the case for evolution, Charles Darwin buried his readers under a pile of unambiguous examples of evolution. In case you are not yet convinced, we have tried the same tactic here by providing you with yet more complex cases of symbiosis. Those who are now on the side of symbiosis may like to skip the next two pages. Never fear, however:

by comparison with Darwin's compendium, this is only a tiny list, but it justifies the central theme of this book, that life is a great universal cooperative enterprise.

The examples given here were gleaned from a short search of the literature. They testify to the fact that obligatory symbiosis is extremely common if not universal – although we think it to be universal. Here they are, in no particular order:

Bacteria living internally within insects provide essential nutrients in all species of insect so far studied (McCutcheon et al. 2009). As the Smithsonian has estimated that the number of species of insect is almost 1 billion, this is likely to produce a very large number of likely symbioses. As well as providing nutrients to insects, symbionts in insects can also have far-reaching indirect influences through insect- and plant-mediated effects at the community level. These include their impact on insect reproduction, on natural enemies of herbivores or on plant-associated microorganisms.

The pea aphid (*Acyrthosiphon pisum*) has an endosymbiont bacterium called *Buchnera*; its primary role is to synthesise essential amino acids that the aphid cannot acquire from plant sap (Wilson et al. 2010).

The tsetse fly *Glossina* has an endosymbiotic bacterium that is called, rather grandly, *Wigglesworthia,* a name that also commemorates a famous entomologist. *Wigglesworthia* synthesises vitamins that the tsetse fly cannot get from the blood it feeds on (Soumana et al. 2014). Without its endosymbiont, the tsetse fly could not survive – and the world would be free of the scourge of sleeping sickness.

Species of *Wolbachia* bacteria pop up everywhere (Bandi et al. 1999). Filarial nematodes (roundworms) are parasitic in humans, living in blood and lymph vessels. They live part of their lives as larvae in insects and are transmitted to humans when the insect bites them. They thrive in their intermediate insect hosts only because of an obligate endosymbiosis with *Wolbachia* spp. In many insect species, bacteria of the genus *Wolbachia* appear to play an important role in antiviral protection. The ovaries of the parasitoid wasp *Asobara* die if their *Wolbachia* bacterial symbionts are lacking. The wasps cannot then reproduce.

The mealy bug *Planococcus* lives on citrus trees. It harbors a bacterium, *Tremblaya princeps*, which, in turn, harbors a bacterium, *Moranella endobia* – rather like Russian dolls (McCutcheon and von Dohlen 2011)!

Obligate wood-digesting endosymbiotic protozoa live in the intestines of termites. The symbiosis is obligate in that neither the protozoa nor the insect can survive without the other (Sutherland 1933). We chose to cite this paper because it describes the discovery of Margulis's (1970) pin-up symbiont, the wood-eating *Myxotricha*, a fivefold symbiont that is itself symbiotic within a termite.

Riftia is a marine worm that lives its strange life in close proximity to black smokers. *Riftia* lacks a gut and so relies for nutrition on endosymbiotic bacteria that can deal with this extreme environment (Bandi et al. 1999).

Symbiodinium is one of the dinoflagellates, ancient cells of the blue-green algal sort. It is a photosynthesiser and it is found as an endosymbiont in corals and molluscs, providing them with photosynthetic products in return for shelter and other nutrients (Fitt 1984).

Symbiotic algae on the egg jelly of salamander eggs produce the oxygen necessary for the survival of the spotted salamander embryos (Kerney 2011). Newborn of the squid *Euprymna scolopes* lack a light organ; it is only developed in cooperation with luminescent bacteria (*Vibrio fischeri*) in their skin (Ruby and Lee 1998).

The development of the immune and the digestive systems in mice raised *without* gut endosymbionts cannot be completed. All known mammals, including humans, have gut symbionts that contribute to their wellbeing (Round and Mazmanian 2009). In the zebra fish, microbes regulate the normal proliferation of the intestinal stem cells. Without these microbes, the intestinal epithelium has fewer cells, and it lacks goblet cells altogether, so the fish cannot survive unless it can recruit its symbionts (Kanther and Rawls 2010).

In plants, there are fungi that live out most of their life cycle in plant tissue and improve immunity in the plant (Wani et al. 2015). They also discourage herbivores – perhaps by tasting nasty.

We have, however, left the best to last. In recent years much work has been devoted to 'common mycorrhizal networks'. These are networks created by fungi living on dead plant material, such as leaf litter and humus in the forest floor (Tlaika et al. 2008). The fungi connect plants to one another by fungal tubes called hyphae. The networks can transport water and soluble compounds containing carbon, phosphorus and nitrogen from one plant to another. They can also transport molecular 'alarm' and 'defence' signals. Some networks are not fussy and connect up all the plants in their neighbourhood, while others concentrate on a single group of related species. This net runs through woodlands and forests like a closed computer system, ensuring all the trees are connected. Not only this, but surplus photosynthetic products from the leaves in the forest canopy flow down the trees to the roots and are distributed by the fungal network to the shaded plants below. It is an excellent example of energy flow from the 'source' (the sun on the canopy) to the 'sink', (the denizens of the forest floor). It is an ancient networked communication system.

We rest our case. It is very doubtful if there is a single animal or plant that does not have at least one symbiont.

But the story doesn't end there. There is the problem of parasitism. Is a parasite merely an organism on the way to negotiating a beneficial symbiotic relationship with its host or is it something else? The world is full of parasites. One definition of a parasite could be:

> an organism whose survival depends on the genome of another organism, to the latter's disadvantage.

Yet again, a reductionist definition wants to restrict parasitism to a single relationship, the genetic one. It ignores within-species parasitism, the most human-referenced examples of this being slavery and cannibalism.

All known viruses are obligate parasites by this definition, as they move in on cells and take over their genetic mechanisms to make more viruses, after which the cells die. Some, very few, bacteria among an uncountable number of different sorts are parasites and cause disease in humans.

Arthropods, belonging to the great phylum containing crustaceans, insects and spiders, are particularly innovative when it comes to the development of parasitic forms. One eats out the tongue of a fish and simply replaces it with its own body and remains in the mouth, acting like the original tongue (Eman et al. 2014). It is an isopod, belonging to the same order as the slaters and woodlice in your back garden. Is this symbiosis or parasitism? *Sacculina* is a parasite of crabs. It belongs to the barnacle family – yes, they are arthropods! – and burrows into crabs, castrates them and lives happily ever after (Lafferty and Kuris 2009). Pea crabs are tiny crabs that live within the shells of oysters and mussels and rely on them for food and shelter.

It is obvious that mutually beneficial biological relationships are not created overnight. They take generations to establish. The pistol shrimp and the guppy did not negotiate accommodation – it just happens that guppies living in pistol shrimp holes did better than their neighbours and so did the shrimp. The pistol shrimp had to learn that the turbulence of the water, as the guppy fled into its hole meant danger and to react with its deafening and disorienting 'pistol shot'.

Parasitism is so common that we also use the word freely in describing aspects of human relationships, where one person 'sponges' on or is otherwise dependent on another. (This, by the way, is a terrible slander on an inoffensive group of animals that do little but sit on the seabed and filter sea water!)

Definitions to scientists are thus rather like words to Lewis Carroll's Humpty Dumpty:

> 'When I use a word,' Humpty Dumpty said in rather a scornful tone, 'it means just what I choose it to mean – neither more nor less.'

Every organism so far studied has at least one parasite; it is a habit of life that is so common that one can confidently claim that the number of parasites on this planet exceeds the number of the free-living organisms – by at least one! Jonathan Swift understood this as far back as the eighteenth century:

> So, naturalists observe, a flea
> Hath smaller fleas that on him prey;
> And these have smaller still to bite 'em;
> And so proceed ad infinitum.

Now for symbiosis and parasitism in humans. The way the relationship between two people commonly develops provides an analogy to clarify the process.

The beginning of a human being follows the obvious symbiosis between ova and sperm: they both die if they do not meet. The developing foetus is totally dependent on the mother, a very intimate relationship that some have argued is essentially parasitic. Once born, the child must be raised, and this requires another individual or individuals or they do not survive. Children have often been raised by their siblings or by their grandparents. Sometimes they have even been 'raised' by wolves or other animals, although the idealised life of Mowgli in Kipling's *Jungle Book* is a very long way from the sordid truth. According to Mary-Ann Ochota, these children are unwanted and usually the victims of extreme neglect (www.youtube.com/watch?v=3n7ZtATu0cU).

The fact remains that it occurs and provides an example of human–feral animal interaction that is at least mutually tolerant. Normal development in children, however, requires the establishment of a relationship with at least one other human, male or female. Speech and empathy do not develop without it. The parent ('host'!) is genetically programmed for an emotional bond with the newborn ('parasite'!), accentuated in mammals by the connection of breastfeeding.

As the child grows, what are the characteristics of the symbiotic relationship between it and other humans? Is it equal and caring or is it asymmetric, with one taking advantage of the other? Sadly, when a child is not accepted as part of a relationship, it can be rejected as if it were indeed a parasite. Finally comes the establishment of a fresh relationship between two adults, and cohabitation follows. Cohabitation may turn out to be a great success – or sadly, may turn out to be toxic for one partner who is really in the role of prey.

This description of the human condition is not really analogy at all. Peel away the human associations and you have a perfect description of the establishment of a relationship that can be symbiotic but may be exploitative. Parasitic relationships between two organisms are asymmetric and are therefore in the toxic range. In extreme form in humans, this could be displayed as domestic violence.

Here are three instances of parasitism. The stages discussed above are readily identifiable.

Naegleria is a free-living amoeba that lives in soil and freshwater. Occasionally, in warm countries, the amoebae form a bloom in water holes, and someone who jumps in may force them up their nose (contact). The amoebae can move anywhere in the body and most won't survive.

But some may migrate along the olfactory nerve (cohabitation) into the brain (John 1982). There, they proliferate and cause lesions that are frequently fatal (extremely toxic).

Humans gain many of their parasites from the animals with which they live in close association, not necessarily by choice. These pathogens may have preference for animal hosts, but occasionally they infect humans – perhaps the unfortunate person is immunocompromised in some way. That makes human-to-human infection possible and that in turn gives the invader a chance to become adapted to humans. It now has the opportunity to infect more and more people and the animal source may later be cut out of the cycle. Thus, while rabies is only contracted from rabid animals, Ebola and dengue viruses continue to be recruited from an animal source, as well being transferred between humans, while AIDS is transmitted predominantly between humans.

Civilisation offers some unexpected opportunities for establishing interspecific relationships. Foxes have their own breed of tapeworm. Riding to hounds, a favourite pastime of the nobility, provided the opportunity for a parasite to extend its range. Gradually the fox tapeworm was transmitted to the pack of hounds, and from the hounds to the dog handlers and members of the hunt. Oscar Wilde, who wittily described foxhunting 'as the unspeakable in pursuit of the uneatable' would have been pleased to know that the 'uneatable' member of the hunting relationship got its own back on the 'unspeakables' by bequeathing them a unique and aristocratic type of parasitic fellow traveller.

The evolution of the malaria parasite is yet one more example that demonstrates the readiness of different genomes to cooperate, one within another, which characterises so much life on Earth (Okamoto and McFadden 2008). An ancient cell, a blue-green alga, was first engulfed by a modern cell but was not digested and formed a symbiotic relationship with its host cell. The result of this primary endosymbiosis was a photosynthetic alga, of the modern type. A descendant of this alga was then itself engulfed by a non-photosynthetic modern cell and another symbiotic relationship was established. This complex arrangement eventually became the malarial parasite transmitted by mosquitoes, causing disease in people and animals. This suggests that there are many forms of modern cells containing different combinations of inclusions, which in turn indicates that the type of symbiotic event that produced them was common.

Is parasitism simply an association between two organisms that have not yet learned to live in mutual harmony? Mutual harmony is the level of true symbiosis where both or all of the partners benefit. Perhaps this is the level to which all parasitic associations eventually aspire, but as we have caught them in mid-development, as it were, we have a tendency to think that what we see are end points whereas they are only end points thus far.

Which brings us to the question: what is an individual person? Every one of us is a cluster of interacting genomes all contributing to our mutual survival. Our good health depends on hundreds of different species of ancient cells living on and in us. These constitute the human biome and there are many papers in the literature ascribing a variety of human disorders to perturbations of this biome. In 2016, the US government announced a $500-million project to explore this 'inner space'.

The fact that we depend on our intestinal flora and fauna for a healthy life explains why living in a totally clean environment might not be as healthy as those who sell disinfectants would like us to think. As an example, the sale of disinfectants that kill more than 90 per cent of known bacteria in a porcelain toilet bowl is, quite apart from being a cynical money grab, no more effective than flushing with water. Our world *ought* to be a bit dirty, so that we can continually recruit our beneficent allies and hone our capacity to repel boarders. You, and me, and the whole living world of plants, animals and fungi, each one of us is a holobiont, a community of organisms. There is more opportunity for natural selection to work with than Darwin ever dreamed of.

The biological world is a much more wonderful place to be today than it was 60 years ago when the authors both 'read' biology at a university. Modern philosophers of science now allow us to ascribe a form of purpose to life and, of course, as we have always suspected, living systems do have purpose. Darwin certainly thought so. That purpose is maintaining the self-regulating system, staying alive and staying alive long enough to reproduce. We are now allowed to believe that an organism can exhibit intelligent behaviour without being conscious and we can allow sentience at various levels to a wide range of animals – mammals, birds, octopuses – but dog and horse lovers have always known this. Natural selection is still with us but nature is not necessarily red in tooth and claw. It is far more often cooperative.

A study of evolution shows that complexity increases with time. Organisms do not become more complex by inventing brand-new ways of doing things; instead, evolution relies on processes that have been successful in the past and repeats them at higher levels of organisation. A consistent pattern appears. Evolutionary novelty arises after a period of collaborative experiment, the outcome of which is subject to Darwinian natural selection that rejects or accepts the innovation.

A metaorganism (like you and me, and sharks and tomato plants and mushrooms – think of all of us as primary bionts) is not a standalone entity. It provides a series of perfect environments for a whole range of other organisms. We will ignore for the moment such mega-parasites as worms and fungi and consider only ancient lodgers such as bacteria and other single-celled organisms. It is now thought that we humans represent housing for the accommodation of hundreds of different species of age-old symbionts. They live on the skin, in the alimentary tract, nasal cavities, reproductive system – in fact, almost anywhere. One casualty of these ideas is the thought that one might recover the ancient DNA from a frozen mammoth, say, and use it to recreate the extinct species. Without knowledge of its fellow travellers, however, the experimenters may be doomed to disappointment. If they haven't done so already, the researchers would do well to return to their frozen specimen in Siberia and see what they can resurrect from its intestine!

There is today great interest in humans as holobionts. The National Institutes of Health Human Microbiome project is concerned with the study of all the organisms that are to be found in the complex ecosystem that is the human body and make up to 3 per cent of our bodyweight. These microbes are generally not harmful to us, in fact they are essential for maintaining health. They produce some vitamins that we do not have the genes to make, break down our food to extract nutrients we need to survive, teach our immune systems how to recognise dangerous invaders and even produce helpful anti-inflammatory compounds that fight off other disease-causing microbes.

A vanishingly small proportion of microbes is responsible for human disease. The majority of them, such as *Yersinia pestis*, which causes plague, are just opportunistic freeloaders, a by-product of whose activity is the death of the victim, the holobiont. Sometimes, an individual can come to an equilibrium with a disease organism. 'Typhoid Mary' was such a person; a cook, she carried *Salmonella typhi* without harm to herself and left a trail of disease and death behind her.

Changes in the composition of the gut biome correlate with certain disease conditions. New techniques, such as faecal transplants, are found to be effective in treating them. Several autoimmune diseases are improved by infecting the patient with intestinal worms. It is as if their immune systems have been misdirecting their well-meant activity and the worms give them a more appropriate target to aim at. It is also possible that inhabitants of our intestines have a greater say than we ever thought in our peace of mind. Our gut symbionts can produce almost every neurotransmitter that keeps our brains in good working order. It may be that anxiety and depression can be treated by regulating their output.

Everywhere you look there are cycles, and cycles of cycles. Humans and human social systems are part of, not separate from, this huge and intricate system. Dynasties rise and fall, families go from rags to riches and back again. The cyclical nature of life has not been lost on historians. Spengler, writing during World War I, in *The Decline of the West* (1932 reprint), made the intellectual leap of considering human society to be an ecological system, or even an organism, in that it experiences periods of growth, maturity and decline. Toynbee, in *A Study of History* (1972), saw the parallel with evolutionary innovation that necessarily occurs at the boundaries of two or more conflicting ecosystems, and suggested that new civilisations arose when faced with physical or social challenges provided by those already present. If societies fail to meet these challenges, they have a tendency to fall apart.

The long history of humanity is the history of the biosphere. Interdependence is one major strand of the golden thread that connects the biosphere. Along with energy flows and genetic inheritance, and for humans, language and social customs, the thread becomes part of Gaia's self-maintaining systems that make our world.

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