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WALLING IN AND WALLING OUT

In which we recognise the influence of boundaries in encouraging cooperation and innovation.

Cooperative evolution links all living things, making connections that become the planet-wide system of Gaia. The interfaces between the cell and the environment, between one cell and another, between species, between ecosystems, all facilitate evolution by presenting challenges. Over and over again, what have appeared to be boundaries have turned into launching platforms for new forms of life.

Darwin was clearly aware that the origin of life can only be inferred from our observations of today's Earth. He saw the necessity for concentrating life's inorganic precursors within a small container, like a cell membrane, to promote the formation of connections between them. In a letter to a great friend, Professor Joseph Hooker, dated 1 February 1871, he imagined a 'warm little pond' as a device for creating a place where all the conditions necessary for the emergence of life could be brought together. Its edges, its surface and its bottom provided its boundaries with earth and air. The water provided the solvent for the chemicals of life to connect and react. The pond was warm, to provide the energy necessary for the reactions of emerging life to take place. Darwin even suggested the types of chemicals – 'all sorts of ammonia and phosphoric salts' – that could accumulate in the pond in sufficient concentration to generate the precursors of life, such as 'a protein compound ... ready to undergo still more complex changes'. This is a vivid metaphor to show how a bounded

system might create and sustain life as well as exclude non-life. From the beginning, boundaries have been as important as the contents they held. A single cell is a microcosm of that warm little pond.

Modern thinking has allowed Darwin's warm little pond to flow away. It was a remarkable metaphor for his time and, like so much of his work, it is not inconsistent with modern thinking. It is, however, now thought that the environment in which these first steps occurred was something like that created by deep-sea geothermal vents, black smokers. It seems likely that life evolved at high temperatures in a watery milieu that contained the right set of chemicals. The edges of the pond have been replaced by boundaries created by temperature and concentration gradients as the chemically rich hot water from the vents diffused into its cooler surroundings, creating an intermediate 'Goldilocks' zone where everything was 'just right' for the beginning of life.

Much thought is also being given to the idea that these early stages might have taken place on Mars (see, for example: www.space.com/22577-earth-life-from-mars-theory.html).

Mars had the right conditions about 4 billion years ago. Might the precursors of life have been transferred to Earth when meteorite impact or enormous volcanic eruption hurled out rocks that reached escape velocity and eventually fell to Earth? If there is any merit in the suggestion that the pre-cellular seeds of life originated on Mars, then crossing the boundary created by 225 million kilometres of interplanetary space was a stupendous event in life's history. It set the scene for billions of years more of negotiating boundaries. From the simplest to the most complex, every form of life exists because of a boundary that separates it from the non-living and distinguishes it as an individual.

According to the *Oxford English Dictionary*, a boundary is 'a thing which serves to mark the limit of something: the limit itself, a dividing line'. Robert Frost, in his poem *Mending Walls*, saw a boundary in terms of its function;

Before I built a wall I'd ask to know
What I was walling in or walling out

This is good advice. Biological walls, however, go far beyond this simple, poetic dichotomy; they are dynamic. It is possible to tell the whole story of organic evolution through boundaries, from black smokers to human skin.

Boundaries of non-living things may be inert and impermeable, important features that have led to people creating containers of all kinds, from biblical wineskins to leather handbags. When a boundary is merely a wall, nothing can get past it, neither in nor out, in which case they are merely containers in which the contents are preserved. Connection and collaboration with the outside world cannot take place. Nothing much can happen to anything within except its eventual decay. That thermodynamic tax, entropy (the tendency to disorder discussed in an earlier chapter), ensures this outcome. Even a vintage wine held in a tightly sealed bottle eventually becomes undrinkable.

Here is a thought experiment. Fill a tin can with blue-coloured fluid and set it upright in a bowl of water. Nothing gets in or out. The wall of the can is an impermeable membrane, a wall. Remove the can, empty it, perforate it with pinholes, add more blue liquid, and replace it in the bowl of water. You will immediately see coloured water coming out through the holes and mixing with the water in the bowl. This process will continue until the intensity of the colour is the same, inside and out. It is then in equilibrium. Nothing much else can happen without some other input from an external source. The perforated can is like a freely permeable membrane. In order for rather more exciting molecular events to take place, movement through the tin wall must somehow be controlled. In biological systems, membranes are not simple inert barriers with holes in them. They are dynamic structures, composed of fat and protein molecules; they are fluid membranes, in constant motion.

Biological membranes often have the property of semipermeability. A semipermeable membrane is a membrane with pores, but whose pores are of a size that will allow small molecules to pass through, in or out, but not larger ones. There is nothing magic about semipermeable membranes, as they can be readily created in the laboratory. Better still, flattened tubes of flexible, semipermeable, artificial membrane for experimental purposes can be purchased from a chemical supply house!

Here is another thought experiment. Cut off a length of the tube, knot one end and half fill it with a concentrated solution of household sugar in water. Squeeze out the remaining air and knot the other end to make a sort of half-filled sausage. Immerse it in a bowl of water and watch what happens.

The molecules of sugar are much bigger than those of water and they cannot pass through the pores of our semipermeable membrane. Gradually the tube begins to swell as water enters it. This process is called osmosis. No sugar molecules get out of the tube. The much smaller molecules of water, always in motion, pass through the wall of the tube. In fact, they can go in *and* out freely – except when their exit is blocked by a sugar molecule. As long as the rate of entry of water molecules exceeds the rate of departure, the spare space in the tube will start to fill up with water. Eventually, the system will come into equilibrium when the back-pressure exerted by the gradually filling tube is equal to the pressure of the water molecules bombarding the outside of the tube trying to get in. The pressure can be measured and is called the osmotic pressure.

The outer wall of a cell is a semipermeable membrane. Water always tends to get in. Because of this, when the cells are immersed in water, it enters the cell and must be disposed of to maintain the correct concentrations of important cellular contents. An amoeba, which lives its life in fresh water, has to work hard to bail it out through its contractile vacuoles.

The creation of a semipermeable membrane, enclosing all the cell metabolites, was one of the defining points in the evolution of the cell. Cell membranes, however, are not just semipermeable; they also have numerous pores of different shapes and structures. In the simplest case, think of a pore in a membrane as a hole controlled by a five-barred gate. Water molecules, which can pass between the bars of the gate, go in and out freely, while those of larger size are stopped. This is why amoebae have contractile vacuoles that continually pump out water. Energy has to be expended to do this work and any small molecules of soluble waste products can be eliminated as well.

A selectively permeable boundary is one that contains a number of ‘gates’, variously hung. Some swing both ways, letting molecules that are smaller than the gate go freely in and out. Other ‘gates’ only open inwards, letting molecules from the outside in; others only open outwards, letting molecules from the inside out. A cell has many gates under its control,

gates that can exist in either of two conditions: locked or unlocked. Desirable molecules – from the point of view of the cell – that are outside the cell hold ‘keys’ to the locks. The lock is precisely shaped so that these molecules can easily attach to it and gain entry. On the inside, molecules that need to get out also have keys to their appropriate gates. The cell is thus a device for maintaining inside itself a tiny internal environment that is totally under its control.

The concept of a dynamic boundary extends well beyond the cell membrane. A multicellular organism like a fish is covered by a membrane made up of different sorts of cells that we call skin. The continued integrity of the skin is essential for maintaining high level of organisation of the systems contained within. In fact, the immortal words of Alan Sherman, ‘skin’s the thing that if you got it outside, it helps keep your insides in’ apply both to you and an amoeba.

A cell membrane (or a skin) is an interface with the environment, and regulates all traffic, in and out. In doing so, it has to distinguish between ‘good’ molecules and ‘bad’. The cell is right to be suspicious, because the ‘bad’ molecule might poison an important internal process.

In a multicellular organism, a metaphysical boundary (a sense of ‘self’) is created by the continued interactions involved in overcoming potential invaders. Distinguishing ‘self’ from ‘non-self’ is so important that it creates a heavy selection pressure in favour of the evolution of immune systems where the recognition of ‘self’ leads to responses that protect it from pests that are ‘not-self’. Its finest expression is to be found in the exquisite immune systems of mammals and birds, because their body temperature (36–40°C) is ideal for bacterial replication (Pradeu 2012).

This metaphor of the gate applies equally well to, say, a house, a village, a walled town, a city and even a country. The concepts of self and not-self govern human behaviour, even at a societal level. From school football teams to national pride, ideas of, and distinctions between, ‘us’ and ‘them’ are strong motivators for preserving boundaries. Flocks of birds, shoals of fish, herds of buffalo and teams of people: all are affirmations of ‘us’ and the members share the risks presented by others that are ‘not-us’ by acting together, to the advantage of the whole population.

In Darwinian evolution, the physical and physiological demarcation of boundaries has always acted as a potent generator of novelty, because selection pressures are greatest where two or more boundaries meet.

If a species is to 'cross over', to adapt to the new circumstance, it must display sufficient variation to provide individuals with the requisite adaptability to allow them to flourish within the new environment. What it already possesses was defined by the old environment, yet it must be flexible for use in the new one. Thus, the swim bladder, a flotation organ found in bony fish, provides the possibility for air-breathing lungs in a lungfish; a pectoral fin becomes, variously, a wing of a pterosaur, a bird or a bat or, full circle, the fin of a whale.

The boundary crossings from one ecosystem to another are physical or geographical. To an organism, the environment is effectively a complex system of edges, a jigsaw puzzle, each piece carrying a different suite of attributes and a new roll call of foreign organisms. It is the same wherever you look, even in three dimensions. In the sea, plankton drifts with the current and undertakes daily migrations up and down in the water column. One boundary for plankton is the interface between water of different temperatures; another is the interface between water and land or ice. For the blue whale that feeds on plankton, survival depends on responding to this complex environment.

Many types of boundaries exist. They may be physiological. The transition zone between sea and freshwater is a barrier to the many organisms that lack either the physiological equipment to deal with the osmotic stress exerted by fresh water or, going the other way, with the salt loading imposed by the marine environment. An estuary offers a huge challenge; the mouths of rivers are populated by species that have learned to survive in waters where the salt content is low or variable. Further upstream, the inhabitants have learned to cope with freshwater and now cannot survive in saltwater. Humans are able to cross these potent environmental barriers only by means of technical solutions – diving bells, wet suits and boats.

Humans have their own barriers. Physical characteristics can act as social boundaries. Language, skin colour, eye shape and food customs have in the past isolated communities as if they existed on islands. With time, the differences are sufficiently emphasised to create whole nations. Think of China, Europe and India. Social boundaries in turn can reinforce geographical boundaries.

Behavioural boundaries are common. In a widely spread population of birds, say, differences in sexual behaviour may become entrenched at the extremes of their distribution. If birds from the extremities are reunited,

their behavioural ‘accents’ may restrict or even prohibit breeding. Such birds are known as ‘ring species’. Greenish warblers form a species ring around the Himalayas. They ‘set out’ from their supposed point of origin in Nepal, form a chain of breeding around the Tibetan Plateau and meet up again in Siberia. By this time, their geographical displacement has led to the creation of a new breeding barrier. Nevertheless, it is still feasible, if unlikely, for a mutated gene to travel the whole circumference of the ring. (We are grateful to the late Professor Colin Groves, who drew our attention to the greenish warbler. Apparently the first example of a ring species we chose, a European seagull, is no longer considered to be one.)

If this effect of separation is difficult to accept, consider the more recent history of the English language. In 1607 the first successful English colony was established in Virginia, in what would become the USA. As the colony expanded, pioneers moved inland and settled in the Appalachians. Here they established new settlements and had little commerce with the mainstream colony. In this relative isolation, their dialect maintained its strong Elizabethan accent and vocabulary so that it has become almost incomprehensible to native English speakers from the south of England in the twentieth century (West Virginia Archives and History: www.wvculture.org/history/journal_wvh/wvh30-2.html).

The Romani (previously referred to in English as ‘Gypsies’) are notable among human societies for their nomadic lifestyles. Originally a wandering, low-caste Indian tribe, they were transported to Persia in the fifth century and their subsequent diaspora has led them to many countries of the Middle East and Europe. In their journeying they adopted many of the social *mores* of the lands in which they travelled, at the same time retaining a version of their own language for use among themselves. People at the opposite ends of the migration would have trouble communicating without their own specifically conserved language (see: en.wikipedia.org/wiki/Romani_people).

On land, geology and geography combine to create biological boundaries that control the distribution of plants and animals. The occurrence of barrier mountain ranges and of different rock types, varying soil structure and components, availability of water, rainfall, temperature, streams and rivers, all create an intricate mosaic of environmental types.

Human activity contributes to this complexity by adding the selection pressures of hunting and gathering, agriculture and animal husbandry, and the construction of towns and cities and their infrastructure. Neolithic human societies created the first cities in Mesopotamia 8,000 years ago. City walls were attempts to regulate and keep people safe within their newly established environments. Within the cities, humans set up social structures that were defined by the metaphysical boundaries of 'us' and 'not-us'. All this created, and continues to create, new biological niches, opportunities for life forms old and new – such as urban foxes and European magpies in London and the ever-opportunistic rats and mice. But think also of the opportunities offered to pests and parasites by humans living close to one another in villages and in close contact with animals – plague, tuberculosis, mumps, measles, smallpox, coronavirus and HIV/AIDS. So far we have risen to the challenges that they presented us with, but there is always something poised to have its day at our expense, such as Ebola virus. Crossing boundaries is an important property of life and it happens continually.

Two personal examples illustrate the complexity of boundaries, how easy they are to create and, paradoxically, how difficult they may be to detect. One of us (Bryant 1983) worked for many years on the biochemistry of parasites. One of these projects involved a nematode (roundworm) that is parasitic in rats. This particular nematode is a much-used experimental organism, but intense study – very reductionist! – showed that there were differences in the biochemical profiles of worms maintained by his research group in Australia and those of a Canadian group. This was odd, because both cultivars were derived originally from the same source. After much puzzling and comparing of notes, the source of the variation was identified. The cultivars were kept under identical conditions – except that in Australia, the research group collected rat faeces containing parasite eggs in the morning while in Canada, they found it more convenient to collect them in the evening. Rats are diurnal and their physiology varies during the day. This results in 'morning eggs' experiencing a different physiological climate from 'evening eggs', which then was reflected in changes in the biochemistry of the hatched worms. In retrospect, this difference might be attributable to epigenesis – another chance of fame and fortune missed!

The second example concerns human groups. Valerie Brown (Brown and Harris 2014) once worked with local councils within the single province of Western Sydney, trying to establish a program of coordinated

environmental management across the whole area. Once staff from the different councils came together it became apparent that the differences between them far outweighed their desire to collaborate. The differences flowed from different environmental philosophies, creating subtly different environments in their areas of jurisdiction. This exerted different selection pressures on their human residents (and many cohabiting species). For instance, the category 'open space' was defined variously as parkland, wilderness areas, car parks, sporting fields, community gardens and even light industrial areas! As well as these differences, councils might have a closed hierarchical management style, or a long tradition of community partnership. This wide range of potential difference was not only apparent in physical differences in their territories, but also in different ways of life within the same area.

The fact that people are able to teach their offspring means children learn from preceding generations. In addition, humans preserve their knowledge in books, parchments, papyri, vellum, clay tablets, metalwork, stone tools, cave walls and even fossils. The barrier created by the inability to read another civilisation's scripts is illustrated by the Rosetta Stone. It was only possible to decipher it because three different scripts were used in turn to describe the same events. The Rosetta Stone is a little more than 2,000 years old. The human insights of 200,000 years, from stone tools to the present day, are available to those with the skills to read the artefacts.

Each one of the means of communication mentioned in the previous paragraph represents a lesser or a greater barrier encountered and overcome. The first stone tools solved fundamental problems of survival, making fire (flints), keeping warm (prepared animal skins) and providing access to high-energy food (butchering). The cohesiveness of family groups and their interaction with others enabled the new knowledge to diffuse laterally and also to flow down the generations and – uniquely – to persist, to *accumulate*. As each barrier was crossed, the emergent consequences were enormous. The stock market is implicit in the first friendly barter of a stone axe for an animal skin, the Industrial Revolution in the first successful smelting of iron ore.

To state yet again the basic proposition of this book, the story of life, from the first appearance of ancient cells, is one of cooperation. It is a story of mutual encouragement and mutual aid. The part of it that is the animal kingdom is a very small part of the whole. Across the whole biota, cooperation and competition have been, and still are, occurring

simultaneously. Among the oldest forms of cooperation between organisms is a process – sexual reproduction – that started at least 3 billion years ago and is with us today. It is not just an interesting biological sidelight but an important evolutionary engine.

Negotiating a way of life between two or more ancient cells to create the modern cell billions of years ago is responsible for a phenomenon of such biological imperative that it still obsesses humanity to this day. That is sex; its physical manifestations and its psychological effects drive so much of human creativity. Biologists have had difficulty explaining why such an apparently risky phenomenon as sexual reproduction should be maintained in nearly all organisms except possibly an immortal jellyfish or two. The usual explanation is that sexual recombination increases variation and provides the raw material for evolution.

Think, however, of the number of boundaries that the reproductive process in humans has to bridge, without harming the evolutionary desirable outcome in the process. They are, first, the problems of human relationships; next the lottery of sperm and ovum in fertilisation; then the partitioning of the sex chromosomes X and Y. Many genetic disorders occur at this stage, but the risks are the price of creating genetic variation, the raw material for future survival.

So, why so much sex? Asexual reproduction is certainly not out of the question. It is common in plants and in many animals. Stem cell research has already given us the ability to clone animals. A compelling new hypothesis derives from the intrinsic properties of the ancient cells that make up the modern ones (Havird et al. 2015). In animals, the rate of change of mitochondrial DNA is about 10 times that of nuclear DNA. Cell division in the nucleus during sexual reproduction creates considerable DNA variation. It is argued that this is necessary because it provides sufficient novelty to allow the nucleus to keep up with mitochondrial variation and thus maintain the exquisite regulatory balance that must exist between the two.

Geneticists and genealogists both exploit the high rate of variation of mitochondrial DNA to determine relatedness. It is relatively small – in humans, about 16,000 base pairs code for 37 genes – easily identified and sequenced, so differences between two samples can be readily identified. There is, however, an additional reason why it is so useful. The nuclear DNA of the human tadpole-like sperm cell is all in its bulbous head.

The mid-piece of the sperm is tightly packed with mitochondria that supply the sperm with the energy necessary for the arduous voyage to the egg. Fertilisation occurs when the successful sperm contacts the egg. At the outer membrane of the egg, the sperm sheds its tail *plus its mitochondrial mid-piece*. Only the head containing nuclear DNA enters the egg to trigger development, while the mid-piece is discarded, like the exhausted booster of an interplanetary rocket ship. All the mitochondria in the resulting developing embryo are therefore derived from the maternal ones that are already present in the egg.

In plants the rate of mitochondrial variation is much less, though still greater than in the nucleus. It is for this reason, perhaps, that plants are more able to undertake continuous asexual reproduction. However, with time, mitochondrial variation will still become too great, so that sexual reproduction once again becomes necessary to allow the nuclear DNA to catch up.

One possible reason why the rate of change of mitochondrial DNA is greater than that in the nuclear DNA is because oxygen is dangerous stuff (Baker and Orlandi 1995). Mitochondria have to interact intimately with oxygen as it is used in energy metabolism. In making ATP (adenosine triphosphate), the ‘energy currency’ of the cell, they transfer electrons to oxygen to yield a molecule of water. In this process, highly reactive intermediate oxygen products that react with almost anything, including DNA, are produced. Damage to DNA is a constant possibility that must be avoided and there are protective molecules ready to scavenge the dangerous oxygen radicals. Even so, some of the highly reactive oxygen compounds do escape to do damage to important molecules and subcellular structures. Plants have to deal with the perils of oxygen in two systems; chloroplasts as well as mitochondria. Chloroplasts once were free-living anaerobic photosynthesisers *producing* oxygen as an end product of photosynthesis, and therefore have a much longer history of dealing with toxic oxygen than mitochondria. Perhaps they are better at it. They too have their antioxidants to deal with reactive oxygen. In any event, modern cells successfully crossed this barrier to symbiosis and the rest is all about you.

Those first great cooperative events that led to the modern plant and animal cells set the scene for the rest of evolution. The next great innovation occurred when two modern cells – two separate but identical cells – started to work together to enhance their mutual survival. This was

the first step in opening up a new range of environments that could be occupied by larger organisms, made up of large numbers of modern cells. The exploration of the advantages of larger size was at last possible.

If the regulatory adaptations necessary for integrating two dissimilar modern cells were too difficult to acquire (after all, that means integrating six or eight different genomes of separate ancient origin), those involved in integrating the activities of two similar genomes were resoundingly successful, and happened at least three times, leading to the kingdoms of animals, plants and fungi. The evidence for this is all around us, and this 'major transition' appears not have been so difficult as you might imagine. 'Snowflake yeast' is a variety of the usually single-celled yeast, *Saccharomyces cerevisiae*. A single mutation enables the cells to stick together to form the 'snowflakes' and thus open up the evolutionary door to multicellular organisms (Ratcliff et al. 2015). This also is the case among algae, where a single gene allows the daughter cells of the alga *Gonium pectorale* to stick together (Hanschen et al. 2016). If only one gene alteration is necessary to create multicellular plants and animals, it becomes a racing certainty.

Once modern cells came into existence, the door opened for the evolution of another layer of symbiosis. Once two or more modern cells successfully collaborated in survival, the scene was set for an explosive adaptive radiation into ecological niches that were not available to single-celled organisms. As the aggregations of cells grew larger, problems of communication within the cluster began to exert their effects. The problems were solved in the first instance by specialisation; the different tasks of survival were allocated to cells that were equipped to deal with them. An early stage of this level of organisation can be seen in modern sponges that have only a few cell types.

Sponge cells, however, have not yet completely lost their individuality. A well-known experiment involves passing the sponge through a fine mesh cloth to separate the cells. The cells survive the experience and return temporarily to an unspecialised condition. With time, they gradually reassemble into one or more smaller sponges. This apparent simplicity may, however, be illusory as sponges have an evolutionary pedigree as long as any of us. One sponge has recently been shown to possess nearly as many genes as humans, about 18,000, suggesting a rather more complex ancestry than originally thought (Mann 2010).

The next level of organisation is found in *Trichoplax*, the only living member of its own phylum, Placozoa (see Srivastava et al. 2008). This tiny animal is barely a millimetre in diameter and has been found only in aquaria. In *Trichoplax*, cells of similar function are grouped together, into two tissues, a sheet of skin-like cells on its top surface and motile and secretory cells underneath. It moves across surfaces and grazes on any ancient cells that it encounters. It has a small genome of 13,000 genes, but quite a few of these are similar to those found in higher organisms.

With greater complexity and size comes a need for greater organisation. In response, tissues of varying sorts that contribute to a single function are gathered into organs. As an example, consider the liver, a very complex organ indeed, with many different, permanently differentiated cells serving the range of functions that all contribute to the property of ‘liverness’. Plants, being modular, never invested so heavily in the specialised organ concept. Cutting off a branch does not kill a tree; removing the liver from a mammal is always fatal.

The way that evolutionary complexity has occurred emphasises the inherent capacity of living systems to cooperate, both with each other and then at a higher ecological level. In each case, the evolutionary process works with what has gone before to create novelty. If ancient cells can work together to produce a viable unit, why not try aggregating modern cells? If some cells are all doing the same thing, why not clump them together into tissues? If tissues are combining to serve a single complex function, why not gather them into organs? Perhaps even whole animals and plants can be clustered to provide additional novelty to make an ecosystem. Perhaps ecosystems can be clustered to make ... Gaia?

And that, of course is what has happened. There are many examples of animals and plants that have adopted a colonial or social lifestyle. *Dictyostelium*, the little slime mould that we have already met, has been used as an experimental model for development and differentiation (Durstion 2013). It is a member of a very successful group of protists that have adopted a cooperative lifestyle. JT Bonner, a world authority on slime moulds, describes them as follows (Bonner 2010):

No more than a bag of amoebae encased in a thin slime sheath, yet they manage to have various behaviours that are equal to those of animals who possess muscles and nerves with ganglia – that is, simple brains.

So, becoming a social organism works for the slime mould; then what about higher animals? And what about humans? Well, the evolutionary muse might have remarked to herself, what worked once will work again.

‘Go to the ant, thou sluggard; consider her ways, and be wise’ (Proverbs 6.6, King James version). Deborah Gordon (2010), no sluggard she, of Stanford University, has been going to the red harvester ants and considering their ways in Arizona for 30 years. She is particularly interested in their capacity for self-organisation in the absence of central control. The queen is merely a reproductive machine – ‘the ovaries of the whole colony’ – and does not give orders. The worker ants have at least four different jobs. While doing a particular job, they produce a job-specific type of pheromone. These are volatile hydrocarbons that change the behaviour of other ants in the same nest.

Ants use these pheromones to communicate with one another. Wherever they go, they leave pheromone traces. When an ant encounters another ant, it samples its pheromone by touching it, and so receives a cue for the exhibition of a particular type of behaviour. The pheromones do not last long, as they quickly evaporate – indeed, this is one of their most important properties, because it clears the slate, as it were, for the next day’s activities.

The ratio of the numbers of ants doing different things is maintained more or less constantly. Obviously, ants cannot count, but what they can do is secrete different types of pheromone, depending on the task they are doing. Thus, an ant that is foraging will spread forager pheromone on all the ants it meets. If an ant bumps into a large number of foragers within a certain time frame, and into very few cleaners, it will change its job to cleaning. Thus, the different sorts of ants within a colony can carry out a variety of tasks that maintain the colony in a high degree of order. ‘Overall,’ says Gordon, ‘the red harvester ant demonstrates a remarkable ability in social cognition, cost-benefit analysis, and behavioral economics’.

The nest self-regulates. It does not matter if an ant with a single objective marches straight by a food source to which it has not been directed. It is an imperfect system, but then it doesn’t need to be perfect, as resources are continually renewed by flood and wind.

Many organisms have crossed the line towards social behaviour. Bees and wasps belong in the same taxonomic group as ants. Bees in particular have a rich palette of pheromones that allow them to maintain a highly

organised hive. They do better than ants in foraging because they fly and their behavioural transmission of information – the waggle dance – gives information about direction, distance and quality of a food source. Termites belong to a different group of insects altogether, but their organisation is also based on pheromones.

Many vertebrates, and especially humans, are social animals. Compared with the insects, they have greater degrees of intelligence and consciousness. Humans have high levels of both, which gives us flexibility in ways of doing things. In spite of this, there are so many, many similarities in the ways different groups of humans construct societies that this suggests that our biology is unconsciously dictating how we go about things.

The extended family, to take one example, is an institution that greatly facilitates the rearing of offspring whose continued immaturity is measured in years. Humans are far from unique in this. Cooperative breeding is common in birds – cooperative breeders include Australian magpies, white-winged choughs and blue wrens, where there is one breeding pair bringing up the young assisted by uncles, aunts and siblings. It is a characteristic of birds that live in a harsh environment (Stacey and Koenig 2006).

The human evolutionary journey from the origin of the first cell to the struggles of modern humans is part of the vast interconnected weave of Gaia. As for any species, it is story of boundaries crossed and collaborations established. In following this line of inquiry, the principal difficulties arise, ironically, from the social boundaries imposed by current ways of thinking in this, the second decade of the twenty-first century. One of these impediments is the tendency for dichotomous thinking – either this one *or* that one, not both – that has resulted from the 300 years of the scientific Enlightenment.

It is the Western reductionist tradition of separating the parts from the whole, the physical from the social, the rational from the creative and the individual from society that has created many of the boundaries encountered by humans on their journey. These are boundaries that have impeded the unearthing of the coherent and fully integrated story of life.

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