Science and our understanding of the Earth

In 1960 the American meteorologist Edward Lorenz came across a strange result using a simple computer model to simulate weather. Using three nonlinear equations, Lorenz was trying to predict the trajectory of weather scenarios. He found that changing the initial values in the model just slightly yielded vastly different predictions. Divergent solutions would result from what seemed to be the same starting point making long-term weather prediction impossible. Lorenz had come upon what the French mathematician Henri Poincaré discovered while studying the trajectory of three orbiting bodies under mutual gravitational attraction, what was later formalised as chaos theory. The finding that deterministic equations, where cause determines effect, could lead to unpredictable outcomes challenged conventional scientific beliefs and stimulated the development of a new field of mathematics. The study of physical systems has shown that seemingly simple deterministic equations can produce hugely complex behaviour. For a long time (almost as long as we have been building models!) physical phenomena were modelled using linear equations for the simple reason that nonlinear descriptions of the world are often too complex to handle. However, the natural world is full of 'nonlinear' phenomena; in the climate system causes and effects are often not proportional, change is episodic and sudden, and there is more than one equilibrium state. The behaviour of ice sheets, for example, is a nonlinear process. To be able to anticipate future melting of the ice sheets in Greenland and Antarctica, we have to account for their nonlinearity. With the help of powerful computers this is becoming easier, but even in the most advanced climate models today the aspect of nonlinearity is difficult to capture. Understanding and modelling the functioning of the Earth system is a hard task even for those who are most experienced in the field. For most of us the behaviour of the climate system is something we rely on experts to interpret for us.

This last point reflects some important features of our current state of affairs, some of which we explored in Part I. Here it will suffice to point to the fact that the changes in paradigm that have influenced scientific enquiry over the last century have not yet filtered through society at large. According to one scholar *the average person on the street is still a Cartesian*. René Descartes, the brilliant French mathematician and philosopher who invented the Cartesian coordinate system and founded analytic geometry, lived from 1596-1650. Of the many subjects he engaged with the one that may have had the most lasting impact on Western thought was 'the mind-body problem': how can the (nonmaterial) mind influence the (material) body? Descartes believed that the body works like a machine and that the mind controls the machine, much like I control my computer and the software with which I am typing these words (he believed that the mind exerted its influence over the body via the pineal gland). This dualistic view of the mind and body extends beyond Man as Descartes believed that only humans have minds. Animals, plants, and the Earth itself are thus mere machines obeying the laws of physics. Explaining the behaviour of these mechanistic entities was thus a matter of taking them apart and understanding them in terms of their parts, like we do with machines. As should be clear by now this is not a satisfactory description of the world and by no means can it explain how life emerged from matter and how mind emerged from 'machine'. Yet, if we are to believe the scholar, this is how we perceive the world on average. In this light it is not surprising that we need experts and specialists to interpret the world for us. If we are to make sense of climate change we must engage with those areas of our collective knowledge that most accurately describe our state of affairs.

Lorenz's discovery that weather is chaotic proved that it is impossible to forecast the weather beyond a few days into the future. No matter the detail of the model or the capacity of the computer we will never be able to predict the next month's weather accurately. But this does not mean that there is no *pattern* in chaotic systems, chaos is not the same as disorder. Deterministic chaos implies that the state of a system at one point in time depends on the state of the system at an earlier point. Prediction is possible insofar as it is concerned with pattern, or the qualitative features of a chaotic system, rather than numerical, quantitative, values. Chaotic systems operate in quasi-equilibrium states which means that they are always close to this state without ever being precisely at this state (in the language of chaos theory these states are called strange attractors). Thus it is possible to describe how a chaotic system, like the climate system, will behave in the future without predicting the exact weather conditions on any given day. A chaotic system may have more than one quasi-equilibrium state and can switch rapidly from one state to another if it reaches a critical point of instability (a bifurcation point). This is the insight that has led to the assumption that there are thresholds beyond which the climate system will begin moving to a qualitatively different state. We know that the climate system has more than one stable quasi-equilibrium state from observations that the Earth has fluctuated between glacial and interglacial climates numerous times in the past. At the end of a glaciation the climate system is close to a bifurcation point and small perturbations can push the system towards as a qualitatively different state, an interglacial period. Small perturbations can thus lead to large changes in the system, a consequence of the feedback loops that exist between the system's components.

The concept of feedback is crucial if we want to understand how systems function. Since we are interested in understanding climate change let us take the climate system as an example. The system as a whole is the atmosphere, the hydrosphere, the biota, and the lithosphere (Earth's crust). These components are influenced by, as well as influence, each other. We can conceptualise components in the climate system as sub-systems (e.g. we might say that the ocean is one subsystem composed of further components), attributes (like global temperature), and reservoirs of matter (e.g. mass of carbon or volume of carbon dioxide) or energy (e.g. the latent heat of water vapour). The state of the climate system is all the attributes that characterise the system at a given time such as temperature, air pressure, fluxes of minerals and nutrients, wind speeds, rate of precipitation, albedo (reflectivity of the surface), etc. The flow of matter and energy from one component to another is described as a coupling. This link, or interaction, allows for the regulation of system attributes (and thus the state of the system).

To see how this happens let us consider a simplified version of the global energy balance. The Earth is heated by radiation from the Sun and cools by emitting infrared (IR) radiation to space. The Sun is not part of the climate system because although it influences Earth's energy budget the climate system does not influence the Sun (we say instead that the Sun is an external forcing to the system). But the relationship between surface temperature and outgoing IR radiation to space at the top of the atmosphere is an important part of the climate system. An increase (or decrease) in temperature leads to an increase (decrease) in radiation (i.e. heat loss to space). This is called a positive coupling to denote that radiation is influenced in the same direction as temperature. If one component influences another component in the opposite direction this is called a negative coupling. An example of such a relationship can be found by looking at how IR radiation to space influence surface temperature. As heat loss from the climate system increases (or decreases), temperature will decrease (increase).

These couplings create a loop: temperature influences radiation which influences temperature. Feedback loops are mechanisms of action leading to reaction becoming an action. This particular feedback loop is *negative*, the effects of disturbances are dampened. This relationship between surface temperature and IR radiation to space is one of the fundamental feedback mechanisms that keep Earth's climate stable. *Positive* feedback loops tend to amplify disturbances, which can give rise to a 'runaway' response. A notorious global warming example of positive feedback is the relationship between ice sheets and the ocean. Ice is highly reflective of sunlight and when it melts it turns into sea water which is dark and attracts heat – this in turn pushes up the temperature leading to yet higher rates of melting. The effect of such amplification is captured by the term 'vicious circle', one action initiates a series of reactions which push the system rapidly in a certain direction. A rule of thumb for deciding whether a feedback loop is positive or negative is to count the number of negative couplings. If there is an even number of negative couplings, feedback is positive, an uneven number means the feedback loop is negative.

The whole of the Earth viewed in this way is a great collection of feedback mechanisms between components which interact in countless ways and produce such a great number of processes that we will never know them all (we only know a small minority of them today). What is more, all these feedback mechanisms exert control on the Earth system so as to maintain a stable (quasi-equilibrium) state. A change in one component is sensed throughout the system both 'upwards' and 'downwards'. 'Self-regulation' is a property of the Earth system that emerges once we consider the level of the whole (but self-regulating systems exist in smaller wholes, just think of the system that supports the eyes that are reading these words). An emergent property of a system, like self-regulation, cannot be explained *in terms* of a system's components, it is not a property of any component but something that exists at the level of the whole. A description of the *relations* between components in the context of the whole is also necessary to understand the functioning of the system. Self-regulation in an open system ('open' here meaning that there is a flow of energy or matter through the system) means that it is able to maintain a stable state in a changing environment. But this stability is not static, it is a state characterised by continual change, a state of dynamic balance.

When we consider the Earth as a self-regulating entity with strong couplings and feedbacks between atmosphere, biota, hydrosphere, and lithosphere, a conceptual shift takes place that has to do with our story about the Cartesian perspective on the world: the distinction between the living and the non-living is no longer clear-cut. Living systems and non-living systems interact in a complex network of processes that tie together the evolution of life and its environment in the coupled system of the self-regulating Earth. Exchanges between the biota and the environment affects for example, the cycles of minerals, cloud formation, rock weathering, composition of soils and the levels of greenhouse gases in the atmosphere. This understanding is far from Descartes' view of a fundamental divide between the mind as spirit and the body as machine and the associated division of the human race from the rest of the physical world as well as of the living from the non-living. In terms of physics, living systems exhibit low entropy – they metabolise to maintain high internal disequilibrim far from thermodynamic equilibrium where no more energy is available. The Earth shares this characteristic; it takes in free energy in the form of radiation from the sun, makes transactions within its system, and release low-grade infrared radiation as a waste product. This is not to say that the Earth is alive in the same sense that humans are (or ants or living cells for that matter), it is simply to point to the way definitions and ideas play a fundamental role in shaping our understanding of our world.