Introduction

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For more than 30 years, Darwin College Cambridge has been hosting an annual series of eight public lectures taking place on subsequent Friday afternoons during winter and early spring. Each lecture series is assembled around a general theme that reaches out into the Arts and Humanities, the Natural and the Social Sciences, and beyond. In 2015, the theme was 'Development'. This volume contains a series of eight essays that are based on these eight lectures.

Why development? When tasked to define what development is, different ideas come forward from different disciplines. For instance, a biologist would think about the development of an organism from a fertilised egg, a process by which a living organism changes its shape and complexity over time. An athlete, craftsperson, or artist might see development as a personal process of acquiring skills over time through dedicated training and education. Parents would see development of their children as they grow and become unique and complex human personalities. Architects and civil engineers might see it as a process by which their work creates new buildings and structures that change cities and the people living in them. Economists, entrepreneurs, or people working in the finance sector would consider development in terms of the changes to wealth or financial assets over a period of time, often influenced by their ideas or actions. Therefore, the concept of development has many facets; it is interdisciplinary, but has an underlying common principle.

Development is a dynamic process by which things change over time, usually towards greater complexity. The underlying mechanisms bringing about these changes, however, are diverse and not always clear. They can include deterministic internal driving forces that result in predictable results. They can include external manipulations that shape and steer a particular process. Sometimes these two aspects operate side-by-side. The timescales over which we can observe a developmental process stretch over many orders of magnitude. On the one hand, many biological and social developments can be observed in real time during the lifetime of the observer. Astronomical developments, on the other hand, happen over billions of years, and their analysis requires reconstruction from observations made through space and time.

In order to understand development both in the human world and in the natural world, we need to elaborate a mechanistic understanding, in terms of the locus of change, the antecedents and consequents, the shape and the rate of change. We need to ask whether change is linear or non-linear. Are there significant discontinuities, where do qualitative changes happen, is there a clear before and after? Is there a value in development, will it lead to progress? Is it an autonomous process, or is it guided? Individual responses to these questions will be specific to the social and natural sciences. However, sometimes they reverberate back and forth to each other, in the same way as a discursive exchange between different disciplines may be observed in the dining hall over a meal at Darwin College.

Conceptually, development therefore provides an exciting topic for wide and interdisciplinary exploration. When organising the 2015 Darwin lecture series, we brought together eight lecturers from a broad range of disciplines, who approached the topic from their specific vantage points. The following eight chapters in this volume are based on these lectures.

In the first chapter, **John Gurdon** illustrates the fascinating world of developmental biology, and describes the ground-breaking discoveries that led to his Nobel Prize in Physiology or Medicine in 2012. He explores basic mechanisms of animal development first, by which a fertilised egg of a frog turns itself into a tadpole and eventually into a frog, without guidance or support from another frog. He then turns to human experimental intervention in this process and describes how, for instance, the nucleus from a skin cell of an adult frog can be reprogrammed in the laboratory by exposure to the unique environment of the egg, and subsequently develop into a new frog. A consequence of this development is the technological possibility of replacing old and diseased cells in an adult organism by reprogrammed and rejuvenated adult cells, paving the way for cell replacement therapies. The narrative of this chapter is that the autonomous process of animal development can be reprogrammed by human intervention, which in itself constitutes a technological development.

When it comes to the second chapter, **Katherine Grainger** exemplifies the development of an outstanding athlete. She shares an autobiographical account as an Olympian who saw British sport, particularly rowing, develop dramatically during her lifetime. She explores what forces contribute to, or hinder, an athlete's performance. In her experience, the concept of marginal gains was very powerful in achieving successful leaps forward at the highest levels of competition. Her personal story is interwoven with a commentary on the development of a national movement and the multitude of causal agents coming together to support progress, and ultimately to produce individual and collective successes at the 2012 London Olympics.

The third chapter takes an astronomer's perspective on the question of development. **Richard Ellis** explores the development of galaxies and asks how it is possible to know our cosmic history, from our current vantage point looking backwards in time to when our Universe was just about 5% of its present age. Observation of galaxies of different ages, he argues, holds information about their formation and the evolution of the Universe as a whole. The challenge we face is how to reconstruct this story given the technological means at our disposal. Here we see that the development of new technologies on this planet during modern times has enabled us to study the development of galaxies over a cosmic timescale.

The volume's fourth chapter moves into developmental psychology and explores what gives rise to the human experience of a sense of self. **Bruce Hood** argues that we develop a sense of self as a consequence of striving for a coherent picture of ourselves and the world around us, even if the picture is a mere illusion. The so-called 'self-illusion' arises in the face of a multitude of influences, factors, and experiences during a lifetime, while early developmental experiences hold a critical importance.

In the fifth chapter, on the development of climate science, **Julia Slingo** explains how advances in human capacity for data capture and data analysis are tightly linked with advances in our understanding of the dynamic climate around us. Her chapter focuses on the development of climate science as a scientific discipline with an enormous impact. Julia Slingo offers her personal perspective as a lead climatologist on how climate science has emerged. It is rooted in meteorology and oceanography, but has now become a means of understanding 'how our climate system works and why climate change is arguably one of the greatest challenges facing us in the twenty-first century'.

The architect **Michael Pawlyn** writes in the sixth chapter about the development of sustainable design. He explores the concept of biomimicry as a design tool, which may become instrumental in shifting mankind from the industrial to an ecological age. Biomimicry uses adaptations in the biological world, which arose during 3.8 billon years of evolution on this planet, as an inspiration to inform and guide sustainable design. This chapter presents examples of the development of designs for office buildings, a data centre, and cityscapes, all based on biomimicry. It concludes with the ambitious Sahara Forest Project as a means to grow crops in desert areas, to generate clean energy, and to reverse desertification. Application of biomimicry, he argues, has the potential for the development of sustainable human habitats.

The seventh chapter in the volume focuses on economic development. **Ha-Joon Chang** calls for a shift in how we describe the mechanisms underlying a country's economic development process. Rather than focusing exclusively on poverty reduction as the main driving force, he argues that production should be viewed as being of central and fundamental importance, with contributions of technological learning and individual developments. His chapter considers key questions about development, such as the extent to which economic development and long-term growth are related, and whether development in financial terms is linked to development in terms of human capital.

The volume concludes with a chapter on technology development by the entrepreneur **Hermann Hauser**. New technologies have already been identified as driving factors of development in several of the preceding chapters. In this final chapter, Hermann Hauser takes this concept further and focuses on computation and information technology as a result of human activity. He explores the development of computing in multiple waves, arguing that there are qualitative changes marking the transition from one to the next. Looking forward, he discusses the development and future implications of machine learning and artificial intelligence for human society, thus concluding his chapter and the discussion of development collected in this volume.

The 2015 Darwin Lecture Series on Development also coincided with the coming of age of the eight United Nations Millennium Development Goals. They comprise a set of priorities agreed by the international community at the Millennium Summit in 2000, notably for reducing poverty and increasing access to education in so-called developing countries. In 2015, the United Nations extended these to the newly minted 17 Sustainable Development Goals, which are to be attained by 2030. These new goals are more inclusive: instead of targeting only so-called developing countries, the new goals apply to all countries around the globe. The new goals are also more integrative: instead of focusing on quantifiers like how many people are completing primary education, there is now also a focus on quality. We can therefore take the opportunity now, on the threshold of these new global monitoring milestones, to reflect on what the chapters in the present volume on development suggest about our future trajectory. Where will we be in 2030, with respect to artificial intelligence, understanding ourselves and our galaxy, stem cell therapy, human athletic feats, the world economy, climate science, sustainability, and harmony with nature? We might look back to 2015 and contemplate new developments that will have led to a changed world, which lies ahead of us.

1 Animal Development and Reprogramming

JOHN B. GURDON

We all start life as a single fertilised egg cell, but that single cell is then converted into the highly complex organism that we all are. In the first part of this essay, I will address how that happens. In the second part, I will discuss how we can make this process go backwards, and eventually provide new rejuvenated cells when our own deteriorate with age or disease. I will also address the question of whether we really can replace old cells with new cells, and, if so, to which extent. I will finally address the ethical and legal constraints of making this procedure more generally available.

From Egg to Adult: How Does It Happen?

In most species, excluding mammals and humans, the very early stages of development can be seen. During the development of a frog, a fertilised egg first develops synchronously, and within only a few hours the egg has turned itself into a ball of several thousand cells. Soon after, some of the cells on the outside start to move to the inside of the ball and, within a day or two, the future brain, nervous system, and other parts of the embryo can be seen to form. In mammals, early development takes place in the mother, and the mother's cells help to guide the embryo as it forms. But in all other animals early development takes place entirely independently of the mother. The different kinds of cells of which we consist appear progressively. At an early stage new embryo cells take a decision whether to go in the direction of brain and skin, muscle or intestine. Later, those that have gone in the first direction take another decision and follow separate pathways to reach their eventual fate (Figure 1.1). Once a cell has embarked on a pathway leading to a particular fate, it and

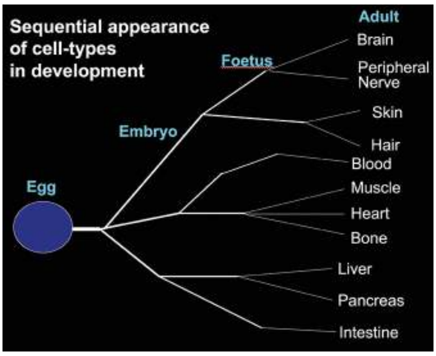

FIGURE 1.1 From egg to adult. As embryo cells divide, they and their daughter cells become progressively restricted in terms of the kinds of cells that they can form.

its daughter cells do not change or go backwards. Therefore, as an embryo grows and differentiates, its cells become progressively committed to particular pathways, leading to specific cell types.

How Does the Embryo Know What to Do?

We are familiar with frogspawn in a pond. Initially, each egg is a single cell, and in a few days each one has turned itself into a swimming tadpole. How does it know how to do this? The parent frogs have long since disappeared, and give no guidance to the eggs on how to develop.

Before powerful microscopes were invented, it was thought that each egg or sperm might have a little creature inside it, dubbed a homunculus, and it just had to grow (Figure 1.2). Later, in the nineteenth and early twentieth centuries, the very influential German embryologist Ernst Haeckel (1834–1919) was impressed by how, in early life, the embryos of many different kinds of animals look similar. He made the proposition that 'phylogeny is the mechanical cause of ontogeny'. Many people revered Haeckel's global view of development, but the phrase I have quoted did not give any meaningful explanation of how development works. At the time, Haeckel's position as a very senior German professor led others to accept his pronouncements without questioning them. However, later commentators treated him often as what, I think, we call

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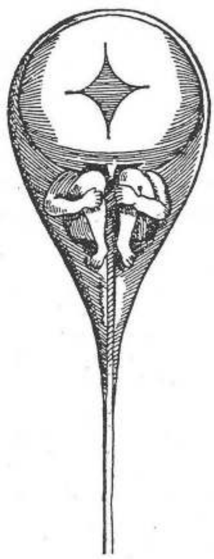

FIGURE 1.2 An early idea that a human sperm might contain a miniature man, a homunculus, which could grow to an adult once in the fertilised egg. (From Hartsoeker (1694).)

the 'whipping boy'. When something did not make sense, they blamed it on Haeckel. For example, to quote one very highly regarded later commentator: 'Haeckel's greatest disservice was not his total ignorance of exception to his rule, but his emphasis on his irrefutable explanation of the mechanical cause of development. He thereby distracted those who might otherwise have made a valuable contribution to this whole field.' (Hamburger, 1988).

But what have we learned about the principles of development, what can we say now about how an egg can turn itself into a complete organism? If we look at the inside of a frog egg, there is no indication of any kind of organism, or type of cell, inside. All we can see is a tiny nucleus at the top in a huge mass of the so-called cytoplasm, most of which is yolk platelets, a source of nutrition for the embryo (Figure 1.3). We now know that there are two fundamental mechanisms by which this mass of apparently disorganised cytoplasm turns itself into cells of different kinds.

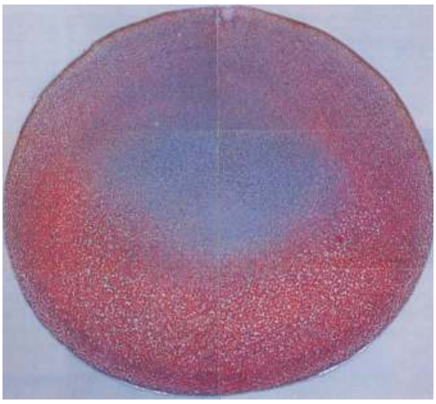

FIGURE 1.3 The unfertilised egg of a frog. Most of the egg consists of yolk (red), and apparently structureless cytoplasm (blue) in the middle. (Plate 8 of Hausen and Riebesell (1991). With permission of Springer Nature.)

Asymmetric Distribution of Parental Molecules

As long ago as 1905, Conklin made a detailed description of the marine mollusc Styela. He could see that the yellow-coloured cytoplasm of the undivided egg gradually became localised in one part of the egg, and subsequently in some of the cells derived from that region of the egg (Figure 1.4). This yellow material eventually became part of the muscle of the embryo. The basic concept that resulted from this observation is that the undivided egg has various substances in its cytoplasm and that these are gradually distributed in the early embryo so that each of them goes to different parts of the future embryo. The yellow pigmented material happens to mark those substances that become muscle, though the yellow pigment is itself only indicative of other muscle-forming substances (Figure 1.4). As development proceeds, these formative substances, originally present in the undivided egg, gradually become localised to those parts of the early embryo which will turn into various kinds of cells. Various external influences cause these substances to move to where they need to be. These include the exact position in which the sperm enters the egg, and the movement of substances under the influence of gravity. As a result of the progressive localisation of these formative substances, cells

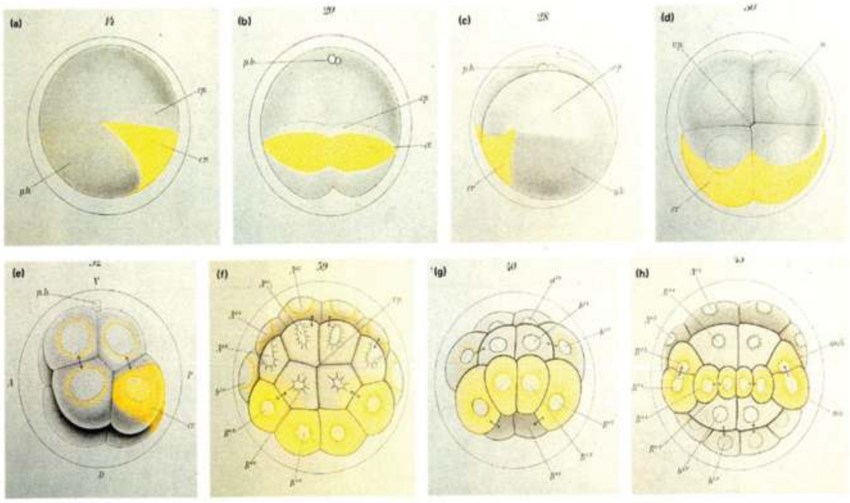

FIGURE 1.4 Localised substances in the early fertilised egg become progressively localised to the part of the embryo that will form a particular kind of cell. The muscle-forming substances of the egg of the mollusc are occupied by a yellow pigment. (From Conklin (1905).)

gradually become committed to their eventual fate, and alternative pathways are eliminated (Figure 1.1).

Signalling between Different Cells

We now know that cells of one kind in one part of an embryo send signals, in the form of molecules, to other cells elsewhere in the embryo. In the frog embryo, for example, the earliest distinction is between those cells at the top end of the embryo and those at the bottom (Figure 1.5). Substances which originated at the top end of the undivided egg, seen in yellow, become localised in the cells which will eventually form skin and brain, whereas substances at the other end of the egg, seen in blue, are localised in cells which will form the intestine and internal organs. After only a few hours, the blue cells send signal molecules upwards to the nearby yellow cells and cause the yellow cells to change their fate by making different substances, seen in green. These commit those cells to