CONTENTS

ABOUT THE AUTHORS

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For the millions of people who would not otherwise be here without scientific understanding of the dance of life. For the millions more who are trying to start a new dance. For our parents—we could not have done it without your support and your DNA. To our loved ones too. How did you put up with us?

Praise for
THE DANCE OF LIFE

"An extraordinary, moving and insightful book about human development, science, life, love and motherhood. Mind-blowing science and a moving personal story effortlessly interwoven."
—Professor Alice Roberts

"Magdalena Zernicka-Goetz has written a memoir from the heart. It is a lovely evocation of the triumphs and crushing disappointments on the roller-coaster ride in the pursuit of scientific truth. It is an engaging personal story full of the challenges of negotiating the interface between personal and scientific aspirations from a gifted and successful woman scientist who has managed it well."
—Virginia E. Papaioannou, Professor Emerita of Genetics and Development, Columbia University

"The question of how a gorgeous baby develops from an inanimate, post-coital speck has fascinated humans from the year dot. Highfield and Zernicka-Goetz illuminate this apparent miracle in an entertaining narrative full of scientific insights, human interest and thoughtful reflection."
—Graham Farmelo, winner of the Costa Prize for *The Strangest Man* and official biographer of Stephen Hawking

"A touching, detailed portrait of a life in science. Beautifully written, it's a reminder that scientists are human and their humanity affects every part of their work."
—Angela Saini, bestselling author of *Inferior* and *Superior*

"Of all the biological sciences, developmental biology may be the most complicated, but Magdalena Zernicka-Goetz makes it easier in *The Dance of Life*. An accomplished researcher whose discoveries in this field truly rewrote textbooks, she offers a rich, detailed look

at how humans arise from the union of two cells. In tracing her path as a woman in the male-dominated areas of embryology and developmental biology, Zernicka-Goetz takes the reader with ease through the incredibly complex dance of life that cells undertake in building a human embryo."

—Emily Willingham, coauthor of *The Informed Parent*

"How does a single fertilised egg know how to develop into the trillions of different cells that make up a human? This book provides you with much more than the answer—it is story-telling at its very best. Together with Highfield, Zernicka-Goetz leads us through her life scientific, intertwining the exciting field of twenty-first-century biology with a joyous personal journey of discovery at the cutting edge of research."

—Professor Jim Al-Khalili OBE, award-winning science communicator and broadcaster

"How an entire human can emerge from a single cell is one of the great mysteries of life. This book is a wonderful exposition of that amazingly complicated process and combines Zernicka-Goetz's research and expert perspective with the clear and engaging narrative that is a hallmark of Highfield's science writing."

—Venki Ramakrishnan, President of the Royal Society and recipient of the Nobel Prize in Chemistry

"Part memoir, part mission to touch creation itself, *The Dance of Life* is a candid and gripping odyssey into one of the greatest microscopic scientific mysteries of all—the cellular divisions that spawn human life."

—Samira Ahmed, BBC broadcaster

"Few books succeed as well as this in taking a complex area of rapidly advancing science and turning it into a compelling human story. Rarely will you read such an intimate and personal account of scientific discovery."

—Evan Davis, BBC broadcaster

"Illuminating ... Zernicka-Goetz and Highfield's informative professional memoir has much to engage readers."

—*Publishers Weekly*

"An in-depth journey through the world of the research embryologist.... The story has a memoirlike atmosphere, especially when Zernicka-Goetz turns to episodes of her life. But she is never far from the science.... Meaty and entertaining."

—*Kirkus*

INTRODUCTION

CONCEPTION

How many things in life are more intriguing than the story of how you built your body and your mind all by yourself? The origin and development of a new life is one of the greatest mysteries of biology, yet this is something that all of us have done.

We all know how this story starts: one solitary cell—a fertilized egg—divides into a close-knit family of similar-looking cells. But when examined from the viewpoint of the gene and the cell, there are many paths that development can follow, along with the creation of tissues and organs that escalate in form and complexity so rapidly that, paradoxically, while trying to discern the origins of a human life, one can find oneself staring into what seems to be a pathless future.

When this creation story is examined from the viewpoint of a human, who can struggle simply coordinating calendars to meet a few friends on a Saturday night, it is extraordinary how an embryo with no brain, consisting of a single cell, manages to divide and grow to become the most complex sentient being that we know of.

The development of the human embryo appears even stranger when compared to the familiar things we encounter in everyday life, which tend to be made of simple, immutable units, from Lego bricks to microchips and other elements and components. For flexibility, these basic units come in different types, so that wood can be found in planks, dowels, and doors; metal appears in the form of nails, hinges, and screws; and so on. And yet our bodies go one step further than simply having a repertoire of basic bits and pieces. Their basic units are also malleable. They can change their

character, they can differentiate from parent cells—known as stem cells—into bone, muscle, brain, and other kinds of cells.

The number of cells it takes to build a human body is around 37.2 trillion—three hundred times the numbers of stars in our galaxy—and it was once thought that there were around two hundred basic types, from nerve cells to skin cells.[1] All possess the same DNA code, but they differ from each other in terms of the parts of the code—genes—that are expressed in them, that is, which range of proteins are manufactured to build and run each cell. Depending on the particular "melody" played on the genome, you end up with a different repertoire of proteins and a different kind of cell.

While brain cells "play" one particular repertoire of the twenty thousand genes, cells in the gut use another range of genes from this master set, and so on and so forth. Thanks to new techniques that are able to read the genetic code of a single cell, we now know that there are in fact many *hundreds* of different kinds of human cells in the body.[2] That all this diversity starts from a few cells that appear to be identical to each other is astonishing. To illustrate just how remarkable your origins are, and the extraordinary process of embryo self-organization, let's imagine building a house in the same way as your body built itself.

First of all, there would be no plans, as such, to construct your body. Nor would there be a blueprint or an architectural drawing or design. There are instructions, but if they work in the same way as the twenty thousand genes used to build your body, there would be no simple relationship between these instructions and how the final house appears, just as there is no simple relationship between a recipe and the appearance of a cake.

There is no project manager or site foreman overseeing this construction project. Nor are there any workers. Nor is there the slightest evidence of a hammer, trowel, or paintbrush. Because this house self-organizes, all of its components share the responsibility for its own construction.

If that vision of components having collective responsibility for their own assembly is not strange enough, to build a house in the same way you built your own body you would have to begin with only one kind of building block—a brick—and as the house constructed itself, this brick would then transform into all sorts of

other kinds of building materials, from wood to nails to glass to plaster.

This process of auto-construction has to take place within just nine months, no more, no less. Timing and coordination are everything, yet there is no clock or timepiece in sight. By the end of the first seven days, one kind of building block has morphed into three basic types as molecular structure self-organizes in different ways. After a week, this embryonic dwelling will start to set up its own foundations, burrowing into the ground (in reality, the wall of the uterus), where it will attach itself into the local infrastructure.

At this stage, the embryonic house will look nothing like the finished article. Some kinds of building blocks will destroy themselves, perhaps because they have fulfilled their purpose, while others will morph into many different types. There is complex auto-origami as the elements mold and arrange themselves depending on their individual circumstances. Quite unlike a building, the entire structure remains in working order—in other words, it stays alive—from the beginning to the end of the construction process.

In short, the way the body builds itself is peculiar, strange, and downright alien.

MY SCIENCE

My attempt to understand the nature of our origins is not focused on our evolutionary history but on an individual life, starting with when sperm fertilizes egg and the union starts to divide. For many years, I have dreamed of being able to track the path of each cell in a living embryo from its birthday and throughout the complicated details of its life, until its fate becomes decided or until it dies, as some cells do, as if making space to allow another cell to succeed.

In my laboratory, we focus on the dawn of life. We monitor how the egg is fertilized and how it divides to create a community of cells that change shape, cleave, move to new destinations, and communicate with each other using chemical or mechanical signals. To understand the journey of each cell and how it coordinates with others around it to begin to create a body and make a life, we use special techniques that reveal the invisible world of the embryo.

Before we were able to film development, as we now can do, we devised ways to "paint" cells with specialized dyes or label them with microscopic beads, turning them into sparkling dots of color so we could distinguish one cell from another and their paths as they made an embryo. Today we can also use molecular markers to identify cells and dissect their workings down to the level of genes, proteins, and other molecular components. We try to determine how the embryo constructs itself to the extent that one day we might understand how our body and organs are built and how birth defects arise, and ultimately carry out corrective measures to restore proper functions.

During this first phase of development, this tiny tribe of cells turns from a ball of similar-looking building blocks into a structure with a defined front, back, top, and bottom. Although this is only the start of a life, the processes at work are fundamental. One can already see all the mechanisms at work that will shape the development of the body and mind.

While I have focused my team's studies on the first chapters of the story of a new life, many other researchers have studied subsequent chapters. For example, the heart takes on its characteristic four-chambered appearance in just under two months.[3] After five or so months, the entire group of cells starts to move. During the third trimester, the cerebral cortex of the brain undergoes dramatic surface expansion and folding.[4] By seven months, the fetus can process perceptual information, such as sound.[5] By nine, this group of cells has grown so diverse and so big and so intricate that it starts breathing for itself as it enters a world teeming with unfamiliar sounds, bright lights, and bold sensations.

By adulthood, we are talking about tens of trillions of cells, each around a hundredth of a millimeter across.[6] If each cell were the size of a person, the adult body would measure a couple of hundred miles from head to toe. From the viewpoint of arguably the most important single cell of all, the fertilized egg, the choreography that leads to this vast yet intricately organized group of cells is nothing short of astounding: How do all these brainless cells coordinate their actions to create a sentient being?

A big part of my motivation to study the beginning of this cellular odyssey is pure curiosity, typical of any scientist, a passion to understand how we came to be and the extraordinary way we

build ourselves. But I'm also motivated because this knowledge can pave the way for development of new tests and treatments to tackle real problems that affect people's lives. I don't believe we should be defined by gender but rather by the imprint we leave on the world. However, as a scientist who's also a woman and mother, I've discovered firsthand why we need a deeper and broader understanding of the details of human development.

EDGES OF CREATION

So far, we have viewed the creation of a new life from a human perspective, in which scientists like me interpret the behavior of cells in a developing embryo as best we can, thereby enabling clinicians to help an infertile couple have a child and doctors to find insights into a multitude of disorders and devise treatments for some of them too.

But there is a much broader context to the dance of life, where we can view the choreography of a living thing in the most basic terms—the space and time it occupies, the blocks of matter from which it is built, the way it responds to information passed down through generations, and the creation and loss of symmetry to establish form.

If we set the dance in the biggest context, we now know that the time and space required to create a body were born in the big bang some 13.8 billion years ago. As the universe cooled, conditions became just right to give rise to the matter required for life, along with the stuff to build us.

You and I and everyone else exist because the moment of creation was lopsided. As the universe cooled, particles and antiparticles annihilated in pairs, but some kind of asymmetry between matter and antimatter meant that a tiny portion of matter—about one particle per billion—managed to persist. Without this violation of symmetry near the moment of creation, the universe would contain nothing but leftover energy.

But to begin a new life, specific kinds of matter are required. Every one of our cells contains 100 trillion atoms, from light elements that emerged after the big bang to heavier ones made within the hearts of stars by colliding neutron stars and other violent cosmic events.[7] For our bodies to function, the atoms we have inherited from the universe have to present themselves in

the right number and right type and have to be arranged in a precise way. In other words, to create a life we also need information to build a body.

Early insights into the instructions of life came from the physicist Erwin Schrödinger, who in 1943 speculated that the body contained a "code-script" to determine the entire pattern of the individual's future development. This code was not a blueprint, which suggests a static arrangement of atoms, but hereditary information to create a living body that is dynamic and intricate.

Some scientists were critical ("more fiction than science") of the significance of *What Is Life? The Physical Aspect of the Living Cell*, the book in which Schrödinger had outlined his ideas.[8] But his thinking inspired many scientists and among them were Francis Crick and Jim Watson, who uncovered the molecular structure of that code-script in 1953 in their lab at the University of Cambridge, building upon the key x-ray studies of DNA by Rosalind Franklin and Maurice Wilkins in London.[9] Within the twists and turns of the double helix lie many secrets of our inheritance, notably the genes that control development.

The double helix can unzip down the middle and each side can serve as a template for the other, so that DNA's information can be passed to the next generation. While the elements required to make DNA can be found in the aftermath of exploding stars, the order of letters in this genetic code is a blend of the instructions passed through the generations, from our ancestors, which we can pass on to our own children.

All living things on Earth are recent links in a chain of information encoded in the replicating molecule DNA, which itself has been multiplying on Earth for some four billion years. Perhaps the first duplications of the first life emerged in deep-sea hydrothermal vents, aided by amino acids from the ocean crust.[10] But there are many theories and, ultimately, this is yet another blurred edge to life's great story: it remains a mystery how this self-replicating DNA emerged to seed the instructions that evolved into the teeming multitudes of creatures on Earth, first as formless, unicellular life and later the riot of multicellular life around us.

There is yet another dimension to life. The DNA instructions we pass on to our children do not hold a precise plan, like an architect's blueprint, but a recipe for their ingredients to self-

organize in a remarkably coherent way. These instructions kick in during the first few days, beginning a process where a fertilized egg divides and changes to such an extent that these early phases of an embryo's life are given different names: zygote, morula, blastocyst, and—finally—embryo proper.

Like the cosmos, our lives are shaped by symmetry and its violation, from subtle biases within an individual cell to laying down an axis in a group of cells around which the embryo organizes. Ultimately, symmetry breaking shapes your whole body, from the location of your head and toes to the position of your organs, from the symmetric location of lungs and kidneys to the way the heart is on the left. All this, in turn, derives from asymmetries on the molecular scale.

Symmetry breaking is essential to shape many of the most dramatic phases of our development. Due to symmetry breaking, we change as we develop from a rounded fertilized egg to, after five days, a hollow structure of around two hundred cells, measuring one- or two-tenths of a millimeter across. At that point, the embryo is ready to implant into the wall of the uterus. There, the boundary of one life merges with another. The poet and philosopher Samuel Taylor Coleridge once remarked that the nine months preceding a birth "would, probably, be far more interesting ... than all the three score and ten years that follow it."[11] I think the same may well be true when it comes to the first nine days of development.

There are many mysteries that remain in the steps leading to that exquisite pattern of matter that we call a body. Perhaps this should come as no surprise, as the human might well be more complex than the vast structures of light and dark we call the cosmos.[12]

This is the story of my science and my journey to understand how cells in the early embryo arise, how they start to recognize and interact with one another, how they organize step by step to form us with stunning precision, how they direct their own development, how they sense when this process goes wrong, and how we can detect this and determine the reasons why.

There has to be some kind of clock for important events in development to happen on time and in the right sequence, but how does this cellular timepiece work? In other words, what mechanism does an embryo use to mark the passing hours and

days? Why, after two and a half days, do all cells develop different ends, so-called outside-inside polarity? Why does a pregnancy take nine months rather than five or a year? Within a developing embryo, that most basic unit of life, the cell, multiplies and changes in a way that is highly choreographed in space and time. Can we understand this most stunning, intricate, and overpowering dance of life?

These are just a few of the questions prompted by research at the current boundaries of scientific understanding, all utterly fascinating. Despite my best efforts and those of many other scientists, there is a limit to what we have managed to answer so far. Even so, we—as a field—have made dramatic progress in recent years.

CHAPTER 1

WHITE DRESS

When I took the phone call, I was standing at my desk in my University of Cambridge office, looking toward the gardens of Downing College. Whenever I was struggling with a problem that seemed without a solution, I would look across the road at Downing with its wide-open lawns and trees where squirrels jumped between the branches and, just below my windows, students wheeled their bikes to their next lecture. Spending a minute or two on my own this way would often help me to think more clearly. And would sometimes reveal solutions too.

Spring was turning into summer, and the trees were dappled with green and gold as sunlight penetrated their leaves. I was wearing the sleeveless white cotton Indian dress that I had owned since I was a student. I remember it vividly because when I was in this dress, you would not notice that I was pregnant at all. And at that point, I still didn't want anyone to know.

The voice on the phone was concerned. She asked if I was alone and then directed me to sit down.

She explained that my pregnancy screening test had revealed genetic abnormalities in a quarter of all the cells the doctors had tested. The doctors found that chromosome 2, the second-largest package of DNA to be found in human cells, was present in three copies instead of the usual quota of two. This test used cells from my placenta but it suggested that my baby might be abnormal too.

The voice on the phone said that I should return to the hospital to discuss what to do next.

I did not suspect at that moment that my life and work were about to lock together. This experience would affect me personally and professionally. It would change the direction of my research, guiding the experiments I would conduct for years to come. Even as I write these words, my team is doing research that is in part influenced by the shock of that day.

By the time I took that call, I had studied so many embryos like the one growing inside me that I knew them inside out. As a scientist I have spent decades trying to understand the beginning and nature of life and what happens when it goes wrong.

I have always been fascinated by the journeys of the individual cells in an embryo from the moment a life begins, trying to understand their behavior, from how they act individually to the way they cooperate with each other, and, most importantly, how their eventual fate is decided. I have also tried to identify the basis for their behavior and fate, starting from even a slight molecular difference—you can call it a bias—that would encourage them to establish or change their direction in development.

When I was growing up, I was fascinated by how the mind works, by its ability to make decisions, and by its plasticity that enables it to learn. As a result, I planned to study medicine or psychology at first. But today, I think about decision making and plasticity from the viewpoint of a developmental and stem cell biologist. How do cells make decisions on the long road from embryo to adulthood? Cells don't have minds, and yet they do make choices, often complicated ones, that are often not fixed either and can be reversed.

Even though many details of embryology were so familiar to me, I felt as any mother-to-be would have when I realized the potential impact of what I was told during that phone call: it wasn't easy news to take. Certainly not. And yet ... I felt hopeful too, as I knew that embryos possess a remarkable plasticity that allows them to respond to their circumstances as they develop, just as we can respond and adapt to changes in our environment. I had been studying this plasticity in my scientific life, but now it had become unexpectedly personal as well.

MY TEST

When I took that phone call, it had been just another normal day in my lab, busy with many simultaneous projects. But in the days that followed, the test results never left my thoughts as I wondered what they really meant.

I should stress that doctors always provide counseling, explaining that there is no certainty when it comes to interpreting such test results. As a developmental biologist who had spent years studying embryos, I was able to weigh up the different ways this genetic abnormality could have arisen. Whether conscious or not, my attempts to map out the details of my unborn child's development to better understand the test results would help me keep my equilibrium.

In the beginning, when an embryo consists of a handful of rapidly dividing cells, it is surprisingly resilient. We can, for example, remove one cell and the remaining cells will often go on to grow and develop into a complete adult. When I first arrived at Cambridge to carry out my postdoctoral studies, I myself had carried out such experiments on mouse embryos. I wanted to uncover the limits of this plasticity and how it works. We generally expect the same to be true for human embryos, given that all mammals develop in a reasonably similar way at this early stage of life.

Baby and placenta start off as one and the same at the beginning of our lives—the very earliest cells can give rise to either the fetus itself or the tissues that support its development. As the embryo grows into a ball of cells, only a tiny group of cells within that ball will go on to make the embryo proper, and then the baby. Meanwhile, the outer cells go on to burrow into the wall of the uterus and become the placenta.

The screening test was on cells from the placenta that united me with my unborn child, so it was possible that the abnormality might have arisen only in those placental cells, and *after* they had separated in the early embryo from the cells that were destined to be the baby. This would be a most happy outcome, as it would mean that my child would have a high chance of being normal. Of course, at that time, I couldn't possibly be sure.

On the other hand, the abnormality could have appeared *before* the separation of the cells giving rise to my placenta and those giving rise to my baby, in which case the baby would be at risk. I thought this second possibility was quite likely: the test showed

that so *many* of the placental cells were found affected with exactly the same abnormality that it seemed things had probably gone wrong very early in development. Not good.

And yet ... I kept thinking that the situation was not hopeless. The abnormality must have occurred during development, rather than in the unfertilized egg. I could deduce this because many cells had normal numbers of chromosomes. Abnormalities that occurred during the formation of the egg itself would leave the embryo with an abnormal number of chromosomes in all of its cells. This would have been catastrophic, leading to early pregnancy loss or abortion.

But there was another factor to consider. I knew from experiments by many of my colleagues and in my own laboratory that mouse embryos, and most likely human embryos too, have an ability to readjust after damage. In a very real sense, we make ourselves. We self-direct our own development. When I thought therefore about the fate of my own embryo, I hoped that even if the abnormality had taken root very early in its development, it might have self-corrected to sideline the cells with the genetic abnormality or eliminate them. It would be extraordinary, but then embryo development *is* extraordinary. That was the day my research took a new turn. I decided to test this idea in my own laboratory.

At the heart of what follows is a story about the life of embryos, and about my life and work devoted to them, framed by my thinking, questioning, and choices. It's about my concern for the fate of my child and so many human embryos that might appear to be "not perfect," and about how the plight of other mothers and fathers who face a similar dilemma would drive me to study this particular mystery of development, though there were always other questions to tackle and resolve on the way.

This is a story about my decisions, and my search for deeper understanding of the events that begin a life that bear upon these choices. This is the story of a journey to find my own scientific voice, my way of searching for insights into how a life begins and evolves. This is also a story about dealing with powerful emotions, not just my own but the feelings of those closest to me.

I have been surrounded by many talented people in my research and I value their scientific intellect. But in building my team of embryo and stem cell biologists at Cambridge it has been equally

important for me to create an environment where there is a strong bond of shared values and friendship, passion for and devotion to solving problems, and the ability to enjoy the simple things of everyday life.

Several of our results challenged the prevailing dogma that said the seeds of symmetry breaking occur relatively late in the development of the mammalian embryo. I must have been either too brave or too foolhardy because I still put forward these unfashionable findings and concepts at that time. But like any other human being, I am not free of doubts. I have had to deal with more failure than success in many aspects of my scientific and personal journeys. They have led me into difficult situations but also paved the way to unexpected discoveries.

Careers and reputations are founded on new ideas. But confronting existing thinking does not always go down well, and it has perhaps been even more difficult for women to take up such challenges. I believe that progress in science depends on being creative, being open and fearless in questioning well-established wisdom along with one's own preconceptions when you have evidence that these are wrong, and yet being thoughtful and modest too. And it would flourish if pursued by even more women.

My story makes a case for not giving up on your dreams and discoveries, however unpopular they might seem; for keeping a tight hold on hope; and for enjoying the quest for insights. Despite my team efforts and those of hundreds of biologists worldwide, there are still many more mysteries left to tackle if we are to tell the whole story of a human life.

But with the help of new techniques, clever experiments, talented peers and colleagues—both women and men—and my wonderful students, who are serious about science and yet make it fun, we can at least sketch out the fundamentals of the dance of life. What I am about to reveal is intricate and unexpected. But it is also truly epic.

lived in the institute I was brought up collectively by many of his friends, who also happened to be scientists. Even when we eventually moved out of the institute into an apartment, the stream of scientific visitors continued, not least because my father loved to issue impromptu invitations and organize ad hoc dinners. I would be enlisted by my mother and grandmother to turn flour and white cheese—among the few provisions we could reliably obtain from the local corner shop—into *lenive pierogi* (lazy dumplings) to feed any last-minute visitors.

Back then, I must have felt that this life was perfectly normal: scientists were ubiquitous, and everyone lived in a lab. I think it is fair to say that while my exterior, everyday life in a socialistic Poland was gray, my interior life was fun and full of encounters with the wonders of discovery. I was one of those little girls who would do handstands at unexpected moments. Life was not predictable.

So although I never thought explicitly about becoming a scientist, I spent my childhood surrounded by people in white lab coats, along with my father's and mother's friends, colleagues, students, and visitors from all over the world. I felt that scientists were super-exciting and almost childlike people. This perhaps influenced my future choices.

When I look back, I am sure that my father and grandmother bore the emotional scars of war, but these were invisible and never discussed. Instead they focused on what is beautiful in life. They made it clear to me that life is inspiring, but also that finding solutions to problems thrown up along the way is not optional. They taught me that physical possessions do not matter much, as they can be lost in seconds, while what does matter is that I remain true to myself and speak up for what is right. This was rarely easy.

As a child, I found it so much easier to express myself through art than by writing. Writing didn't come naturally to me and I would skip some letters, as if they had been lost somewhere between my mind and the page. Most embarrassing of all, I would sometimes muddle my words while writing and speaking, sowing confusion. Some of those who didn't know I was dyslexic thought I was doing it for fun. I wasn't.

Health care was free during my childhood in Poland, as in other communist countries, but provided by an outdated infrastructure, where the finest medical facilities were reserved for the topmost

ranks of the Communist Party. There was a feeling that life was better if you joined the party. But my parents did not want to belong to the party elite. By the time our medical system figured out I was dyslexic, I was seventeen. By then, the school had discovered that although writing and reading took me longer, I excelled at mathematics and expressing my ideas and feelings through any kind of art.

When it comes to science, my husband thinks I might actually owe my lateral thinking to dyslexia. I am not so sure, however. I think that my dyslexia led to self-doubt, which can sometimes be helpful, but not always. My mother still remembers that as a child I was always surprised when I succeeded in something.

And even now, when things go wrong, I respond by creating something new or reinventing something old. I have reworked one painting so many times in response to dramatic—both happy and disturbing—events that if I had taken a picture of each of its incarnations, I could make a movie of my life.

During my teenage years, art was more than art per se. Art was a way to express your freedom under the communist regime and escape to a world of powerful complexities and possibilities of color, light, and form.

In those days of empty store shelves and shoddy raw materials, school uniforms were made of synthetic fabrics, fashion was centralized, and we all dressed in pretty much the same way. We all had to learn Russian and admire portraits of Lenin.

I found it so unnatural that we all had to look and be the same that I couldn't conform. My grandmother, the mother of my father, was extraordinarily creative and able to conjure up divine food and clothes out of nothing. And since at one point in my childhood she gave up her job to take care of me while my parents worked, I started to design, sew, and knit my own clothes, and made jewelry with beads, leather, and a rainbow of threads. All this color energized my life. Unlike today's Warsaw, which vibrates with energy, back then it was a monochromatic metropolis of concrete apartment blocks.

Everyday commodities were in short supply, so scarce that people would often have to spend part of their day standing in lines. As both of my parents worked all day, I spent a share of my time in lines to buy food for us, sometimes for hours, often with a girlfriend to make the time pass more quickly. I was told that one

could make money by being a *stacz*—a person who would stand in a queue for somebody else.

The regime was oppressive. Before the rise of Solidarity, the first independent labor union in a Soviet bloc country, everyone was expected to go on parade for the Polish United Workers' Party. During school art lessons, we would pin red flowers on a stick to carry with us. I don't remember my family ever taking part in a parade, however. I liked my decorated stick but it always stayed in my bedroom. As the parades marched past, I would watch them through the windows.

On December 13, 1981, I woke up to a day more gray than normal. There were soldiers outside my bedroom window. I saw posters everywhere declaring that Poland was under martial law in an attempt to crush political opposition. Tanks had rolled into Warsaw. Borders were sealed, airports closed, and road access restricted. I had just turned eighteen and was preparing for my university entry exams. The feeling was so intense that I remember everything about that day. Tens of thousands of Solidarity supporters were dragged from their beds and arrested that morning. Many were reported killed. There was a curfew, so we couldn't go out in the evenings. Prodemocratic Solidarity was banned (but continued to flourish in the underground). Martial law was so oppressive that the protests and strikes intensified. A year and a half later, it was lifted.

PLASTICITY

My life, like the cells in a developing embryo, could have taken quite a different path in other circumstances. As an example, one idiosyncratic aspect of my father's approach to my upbringing was to tell me not to bother with homework too much and enroll me from the age of seven in a professional tennis club, Legia, host of the Warsaw Open. While my friends were having fun on the playground after school, I would take an hour-long bus drive, initially supervised by my grandmother, to the club on the other side of Warsaw to train on court and to compete in tournaments that often took me out of school. I took this journey every day for nine years. Eventually I fell in love with tennis and it became part of who I was, but when I was fifteen I injured my back and had to

endure a year of physiotherapy. To the regret of my coach and my father, eventually I quit competitive tennis when I was seventeen.

Perhaps my focus, although far from perfect, can be traced back to my demanding tennis training. It taught me the importance of taking one ball at a time rather than thinking about winning the match, and about putting all my energy into the present. My close friend from my tennis days, Ewa Gajewska, now Lewanowicz, remains one of my best friends. Unusually, our bond was created when we played against each other in the Warsaw Tennis Championship. Our match had endless tie-breaks and neither of us remembers now who won.

The mind is as susceptible to fate as the body. Late one summer in the mid-1980s, I went to a concert while on a short seaside holiday on the Baltic coast. Afterward, I met Waldek Miszczor, a drummer who wrote the smart, politically engaged songs of Mr. Zoob, a chart-topping alternative group at that time. It was love at first sight. Even though we studied in different parts of Poland—Waldek studied culture at the University of Poznan and I biology at the University of Warsaw—he became my fiancé. It was an extraordinary and magical time, but after three years I broke off the engagement. With that, my future took a new path, though it was far from straightforward.

My grandmother, who had brought me up, suddenly died. It was devastating. I lost all my energy, had to stop my studies, and put my life on hold. It was at this fragile moment when Krzys Goetz, whom I'd first met when I was seventeen, would come back into my life, after he'd spent three years in Ghana. He became my husband.

Accidents and circumstances can alter the course of a life; in the same way, the course of embryonic development can be shaped by random influences, such as the buzzing noisiness of the molecular innards of the embryo's component cells.

Education is one key influence, though it was not school but my discussions with my father and his friends and upbringing in a lab that gave me an abiding passion for biology and a fascination with the brain and its plasticity in particular.

The plasticity of our brain is why we have an amazing capacity to learn new skills, deal with complexity, and adapt to novel environments. But as a student at the University of Warsaw in the 1980s, I would become fascinated by another kind of plasticity,

which took place during embryo development. I can remember exactly why that interest really came alive, thanks to one certain professor. During a lecture, Andrzej Tarkowski single-handedly inspired me to fall in love with developmental biology. Today he is regarded as one of the fathers of what is called classical experimental mammalian embryology, before the field was changed by the rise of molecular biology and our ability to read and edit genes.

Despite the difficulties of doing research in communist Poland during the 1960s, when scientific materials and modern equipment were in short supply, Tarkowski made many important advances. He was the first to create chimeras, blending together cells of two different embryos so that they developed as one organism, which I will discuss later. He also had a sense of fun and, like me, a love of creating things—in his case, expressed in the form of nature photography.

I can still remember the precise moment when I realized that I wanted to understand how embryos develop. During a lecture, Tarkowski had described a pioneering experiment he had done decades beforehand, in which he had come up with an elegant demonstration of the plasticity of the mouse embryo.

At a very early stage, when the mouse consisted of just two cells, Tarkowski had destroyed one yet found that the remaining cell still possessed the ability to grow into an entire mouse. The remaining cell had the same potential to grow into a living thing as it had when accompanied by its sister cell—"totipotent" is the term that scientists use to describe this capacity. In 1959, he described this feat in one of the world's most prestigious journals, *Nature*.[1]

Little did I realize that his experiment would haunt me in the years to come as my team gathered evidence that questioned not Tarkowski's experiment but how it had been interpreted since the sixties. But all that lay in the future.

Just as he altered the fate of cells, so my encounter with Tarkowski would alter my fate too. He redirected my interest in brain function and psychology toward the allure of embryology. I applied to do the master of science degree necessary to complete my studies at Warsaw University in his laboratory. He accepted me and I found myself in Tarkowski's lab on the top floor of one of the few historical buildings used by the school. The Department of

two eminent scientists who would become important characters in my own story.

Tarkowski suggested that I apply but stressed that, if successful, I would need to return to his laboratory afterward. I wrote up my scientific idea into an experimental plan and applied for a fellowship. A few months later I was short-listed for an interview by a group of Oxford scholars. To my delight, I was awarded a Soros Fellowship.

By then, I was married to Krzys Goetz, the engineer I had first met at age seventeen while skiing, a sport at which he excelled. Bright, quick, with a huge sense of humor, Krzys was the kind of person who lit up a party as soon as he walked through the door, and was the first true love of my life. Even though we were reluctant to part, we both knew that the opportunity to study at Oxford was irresistible given the political and economic situation in Poland at that time.

As far as I remember, nine of us were selected for the honor of studying at Oxford. We were a colorful group and although scattered among different colleges, would meet regularly in the evenings, mainly for parties. Our mentor was the iconic Polish philosopher and writer Leszek Kolakowski, who was one of the key inspirations for the Solidarity movement and had to leave Poland for political reasons. Since then he had spent most of his career at All Souls College. My memories of Oxford are strongly linked to my time spent at Exeter College. The college dated back to medieval times and I felt like I had walked into the pages of a history book.

When my scholarship ended, as a farewell present Kolakowski gave me a talisman, a glass bird that I still have, and stayed in touch by writing letters of encouragement. However, although Kolakowski was inspirational, and we discussed philosophy most of the time, my own studies would remain focused on the field of experimental embryology.

OXFORD CLONES

In my new home, I began to work with another father of mammalian experimental embryology, Chris Graham. Chris was the first student of John Gurdon, who would himself become a central influence in my life. At that time, I didn't have any idea about Chris's scientific heritage or, to be honest, know much about

John Gurdon either. But after a little while I came to learn that John had done pioneering frog-cloning experiments to probe a basic question that had loomed over cell biologists for decades: Are the cells of an adult organism genetically identical to the fertilized egg from which they are derived?

Chris Graham had been inspired by John's success in cloning frogs in the sixties and would try a variant, based on research at Oxford by Henry Harris, who had used a virus to fuse human and mouse cells to form "heterokaryons" containing genetic material from both species. The virus offered a way of easing a nucleus of a cell, the part that contains its genetic instructions, into an egg without the trauma of an injection needle. In 1969, Chris made waves with what he himself admitted was an outrageous paper that suggested successful nuclear transfer in mammals—cloning—was imminent. By the time I arrived at Oxford in 1990, Chris Graham was preoccupied not with cloning but imprinting, when genes that have come from one or the other parent are selectively switched off and left unused.

Oxford was different from Warsaw in every way. I was able to work in a well-equipped Western laboratory, which was great, but I was far away from my family, husband, and friends, which was not. Nevertheless, I found everything so exciting and had an out-of-body feeling, as if I were watching a movie in which I appeared.

Fortunately for me, Chris was kind and patient. At that time, my English was weak and it must have been difficult to communicate with me, which was not made any easier by Chris's tendency to turn almost every sentence into a joke. I often had to guess what he said and politely laugh along. Hmm ...

He had allocated some space for my experiments close to where laboratory animals were kept, so during the day I was often on my own as the molecular biologists were two floors above me. But although I spent only a year there, my experience in Chris's lab influenced me deeply, not just in terms of my science and the wonderful people I met there, but also in giving me a taste of life outside the communist bloc.

What kept me at work in the laboratory for long days was an attempt to understand genome activation, one of the critical first events in life when the instructions held in the DNA of the fertilized egg itself start to be used instead of the legacy instructions passed down from egg and sperm in the form of the

genetic material RNA and protein. I wanted to find out how the DNA of the rat embryo becomes activated to direct the subsequent development of the embryo.

It was at Oxford that I was able to address this question as the technology wasn't available at that time in Poland. We thought that it was not possible to create rat-mouse hybrid embryos because their genomes activate at different times during their development, and at Oxford I was able to test this idea directly. We knew that the mouse embryo genome is first activated when the embryo has only one cell, and a major wave of activation of genes happens when the embryo has cleaved into two cells. I needed to find out when this critical moment took place in the rat embryo.

I found that the rat genome activates a little later, toward the end of the two-cell stage.[2] Perhaps that was one reason why a rat genome would not be activated properly in a mouse egg. But I never got the opportunity to explore whether that really was the reason it was impossible to create rat-mouse hybrids. My fellowship and time at Oxford had come to an end, and I returned to Tarkowski's lab.

During my year at Oxford, my husband had built a house for us in Michalowice, a village near Warsaw where his family lived and where his grandfather, an architect, had designed many other houses. It was the first home of my own and even had enough space for a studio so I could do more painting and, perhaps, forget about my science too. In a certain way, it was like being in heaven. I loved that house, and it was tempting to remain in that secluded family paradise.

Paradoxically, around this time my life was changed in a good way by an accident. In 1993, while wearing smooth-soled horse-riding shoes (for no reason), I slipped on the first unexpected snow of winter and broke my right arm. With my heavy old-fashioned plaster cast I wasn't able to drive to the lab to carry out my experiments. Suddenly I was faced with long days and time to explore other interests. Painting was difficult without my right hand, but I could write. I started to write poetry (it was so bad that I destroyed it, I am glad to report). Then I realized I could use the time to write up my experiments in my PhD thesis, and when I asked Tarkowski, he agreed. By the next year, I had my doctorate.

My life didn't initially change much because of my new qualification. My position in Tarkowski's lab was tenured, so I