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INTRODUCTION

Nothing Is More Revealing than Movement

Gregor Samsa's transformation into an insect has exerted much fascination in literary history, but of all the riches that "The Metamorphosis" presents for our interpretation, Kafka's precise description of movements has attracted the least attention.[1] The gradual process by which Gregor becomes aware of his new existence is one of coming to know his new corporeality. In practice, understanding his own transformation largely means assimilating the unaccustomed movements, necessitated by an exoskeleton and articulated legs, of a creature that is described only vaguely, but that clearly belongs to an insect species. The execution of these alien movements is what drives Kafka's story on: the definition and interconnection of the characters by their movements, Gregor's inner reconciliation with his outer form through his new body's movements, and the end of his existence both as insect and as Gregor Samsa at the moment of losing the capacity to move.

The movements that Kafka describes are common ones. Yet almost unnoticed, they form the powerful piers between which the story is suspended—being human, being creature, being alive. Gregor's metamorphosis, which begins with his inner, human, and conscious appropriation of his animal body's movements, concludes with a death that is attested by the external world through his absence of movement.

This book takes as its object of study the triad of motion, animal, and life that Kafka wove into a parable on humanity. My theme, though, is not being human, but being alive, and movement that does not aspire to the human, but descends into life itself. When I quote Martha Graham's motto that "nothing is more revealing than movement," then, I do so not in order to highlight the artfulness of the dancer's (or, indeed, the writer's) choreographed movements. Far more simply, and fundamentally, movement reveals life.

Motion, in this book, is the most profound definition of living existence. It is movement that keeps the living alive, movement that organizes life—from the macroscopic to the microscopic to the molecular level. My investigation is anchored in one of our most constant, least questioned observations on the world around us: a being that moves is a being that lives, and how that living being moves tells us much about what it is.

Biological Motion

The term that forms the title of this book, "biological motion," embraces just that foundational relationship between motion and life. I use the phrase, first, to denominate motion *in* the biological world—that is, in the domain of the physical world that we regard as biological. The biology in "biological motion" is a field of scientific inquiry into the living world that has undergone enormous historical changes. In particular, the science of biology has long since ceased to be one in which knowledge is advanced by "unaided sensory experience." Instead, biological knowledge is driven by "artifice," as the American philosopher of science Nicholas Rescher has put it, in the sense of both artful skill and stratagem.[2] What biology brings forth and legitimates as scientifically relevant objects and questions today differs significantly from the biological world that previous centuries saw: technologies, devices, experimental procedures, and digital practices make life newly visible and newly intelligible, continually expanding the parameters for thinking about it.

But "biological motion" also designates the motion *of* the bio-

logical world: movement as the basic characteristic of all things that live. Biological motion in this sense is animate motion, motion within and originating in the organism. The crux of biological motion is that it differs from the motion of physical matter by being active and self-directed. Such motion has been regarded as a sign of life since ancient times.

The fact that I need to introduce the phrase "biological motion" at this stage is itself revealing. The term was coined in the 1970s by the Swedish psychologist Gunnar Johansson to refer to a specific set of experiments in perception that demonstrated the impressive ability of human beings to recognize motion. (I will say more about this later in the book.) I use it here to usher into scientific discourse a phenomenon that is much in need of a name. Indeed, as a conceptual couplet, "biological motion" points to a curious lacuna at the heart of the biological investigation of life: whereas the scientific study of life has prompted much historical research, we know next to nothing about how views of motion evolved alongside it. Put differently, the bond between life and motion in the physical world may be tight, but in scientific studies, the two terms have had unequal appeal, one being as seriously interrogated as the other has been grossly neglected. Yet thinking about biological motion has much to offer. From the perspective of its endurance or transformations, it can illuminate historical shifts in our understanding of life or shed new light on the epistemology of contemporary science. Given that motion bears such enlightening potential, we may ask why it is so manifestly absent from the historiography of life. First, however, comes the question: What is motion in the first place?

On the Science, Knowledge, and Representation of Motion

Motion entered European philosophy, in the fifth century BCE, as an absurdity. In the teaching of Parmenides, there is nothing that is not; in that of Heraclitus, there is only flux.[3] Motion could not exist either with respect to always-already completed and thus inalterable being or with respect to its opposite, the constant transition

and loss of identity of that which moves. Later, Zeno devoted his paradoxes to disproving the existence of motion, whereas Aristotle made motion a cornerstone of his philosophy.[4]

Its epistemic longevity suggests that motion has always enjoyed the privilege of attention, yet motion is by no means one of those concepts that have reliably attracted the interest of philosophers, scientists, or artists (apart from dancers, of course) across the centuries. Though no less indispensable than the notions of space, time, and force, the imaginary expanse of motion does not enjoy a similar status to theirs in intellectual history.[5] The reason may be that motion is not conquered, as spaces may be, does not wither under the dictates of time, does not drive anything except itself. Motion is an unobtrusive magnitude, its essence being to take place without calling attention to itself.

To be sure, many disciplines have tried to throw their snares over motion, with physics leading the way. Motion has always been a fundamental concept in the exact sciences, and physics effectively co-opted motion as an exclusively physical object, framing it with the instruments of geometry and algebra. The early historiography of science, itself largely anchored in the field of physics, located motion's historical and philosophical emergence primarily in the mechanist thinking of the seventeenth century. Where biological disciplines have studied living movement at all, they have virtually never begun to contemplate it outside of those parameters. The criteria were set by the Scientific Revolution, which the history of science has made its founding narrative and nothing less than a "supernova" of the human intellect.[6] Accordingly, they have become the constraints on biology's examination of animate motion while also accounting for the almost total neglect of the issue in the history of biology.

Instead, animate motion remains coterminous with physical motion, whether in the heights of the universe or the depths of the animal domain. Locomotion studies—broadly, the study of how animals, including human beings, move—is thus devoted to animal

anatomy and the physical environment in which legs, fins, wings, or cilia are used for movement. Locomotion is the concern of kinematics, biomechanics, and bioengineering or of autonomous motion research on intelligent systems that collapses the boundary between the world of old-fashioned animals and man-made "snail-o-bots."[7]

Where animate motion is not clearly incorporated into the cosmos of physics, it has mainly featured in the science of animal behavior. In a standard definition by the *Encyclopaedia Britannica*, this encompasses "everything animals do, including movement and other activities and underlying mental processes."[8] In the long and diversified history of research into animal behavior, animate motion is subsumed under behavior, absorbed into a general notion of "doing" that places individual movements in the context of stimulus-response and instincts, objectives and intentions, or social interaction and evolution.

The movement behavior of humans, though, is what most of all marks thinking on motion and makes it the object of genuinely multidisciplinary endeavors. In the 1930s, the French anthropologist Marcel Mauss (1872–1950) introduced the notion of "techniques of the body" (*techniques du corps*), founding the French tradition of anthropological and sociological interest in the body. Mauss saw the gestures and other movements of the human body not as something natural, but as a normatively loaded, cultural legacy. In this view, walking, climbing, or jumping — no less than techniques of sleep, techniques of care for the body, or techniques of reproduction — are distinct "ways in which . . . men know how to use their bodies." Being "specific to determinate societies," they demonstrate that not only did non-Europeans swim differently than Europeans did, for instance, but that earlier generations jumped or climbed trees differently than later ones.[9] Since Mauss, the movement of the human body has been parsed in every possible academic direction. Just a few examples are the anthropology of upright gait, the literary figure of the flaneur, and the customs and measured movements of the art of dance;[10] bodily culture from care and crisis, to sports and

exercise, to discipline and deprivation;[11] and facial expressions and gestures in physiognomy, theater, and social perception.[12]

But it is not just within and across academic domains that motion is everywhere present and nowhere at home. Constitutively fugitive, motion is hard to portray. It is not a tangible object. Evading perception and representation alike, it slips from being inconspicuous, acting everywhere in the background, into being invisible. Despite this virtual invisibility, however, motion has been present in every epoch of art and picture making and has never ceased to challenge the intellect. Art, technology, and the mind have been taxed by the question of how to capture, freeze, pick motion out of flux, given that ephemerality is its essential property.

Across the centuries, motion has appeared in a movement depicted in a painting and the affects conveyed by that movement, in architecture as measured out by human steps, or more generally in a reality that is accessed bit by bit along the movement of the eye and only successively opens up to perception. Not least, motion in art finds its resonance in the beholders, in the feelings and processes that art provokes in them.[13] This is why Leonardo da Vinci (1452–1519) regarded as "most praiseworthy" the figure that "best expresses through its actions the passion of its mind." The double movement is what makes a representation seem alive. If it fails, Leonardo concludes, the picture seems "twice dead, inasmuch it is dead because it is a depiction, and dead yet again in not exhibiting motion either of the mind or of the body."[14]

Like no other, Leonardo approached "the representation of the *concept* of movement," as opposed to confining himself to the "mere evocation of its physical manifestation."[15] The lively movements he captured on paper arise from a virtuoso use of graphic resources; as art historian Martin Kemp remarks, this wealth of resources was unprecedented and went on to influence virtually every area of graphic art. The repertoire that Leonardo assembled for the first time embraces all the important representational resources available before the invention of moving images.[16]

Starting in the mid-nineteenth century, innovations in optical technology such as flip-books, phenakistoscopes, and chronophotography prepared the human eye to grasp a rapid sequence of images. These new visual habits paved the way for science to deploy an entirely novel set of possibilities of representing nature, and the new media opened up fresh access to motion. Cinematography, video, motion capture, and the computer are all successor technologies that enabled movement to be visually generated as a reproducible event beyond its immediate execution. In recent decades, they have attracted a great deal of attention in art, philosophy, and the history, theory, and archaeology of media, and as the computer has come to prevail as a pictorial tool, "animation" has become a transdisciplinary buzzword in research. Now that computer-generated and computer-animated images dominate our visual culture, their aura of aliveness intrigues those disciplines as the apparently natural obverse of their technicality.[17]

Even the most artful of such movements, however, are bound to remain only representations. This is true of artistic representation in pictures, buildings, and sculptures, but it also applies to the manifestation of motion in equations, notations, films, or computer programs. Descriptions of motion are not and cannot be motion itself; they serve at best as imitations, analyses, or instructions on how to reproduce it as event.

Biology on the Move

All this gives us little guidance in our exploration of movement in the living world. Yet a book about biological motion seems timely, for a glance at scientific journals and websites suffices to show that motion is a crucial or even the crucial theme of basic biological research in the twenty-first century. At the very beginning of the millennium, the journal *Science* proposed, not without dramatic flourish, that movement is the "root of all existence."[18]

Far-reaching advances in visualization technology, fluorescent marking, and the rise of systems biology have meant that processes

deep in the body's interior, at a cellular and subcellular level, can now be made visible. A new iconography of the body has taken the place of the external gaze, shaped for centuries by the practices of anatomy, that intrudes into a body dismembered and denuded. Now the body intact, revealing itself from the inside out, guides the gaze as a participant through the darkness of its own interiority.

In this body, nothing is still; everything moves. Indeed, the body's task seems to consist solely in sustaining motion. Pivotal physiological processes are now studied by scientists everywhere in terms of the movements they make possible: the metastasis of cancerous cells, the migration of axons, the movement of neutrophils to the site of injury, the migration of cells during ontogenesis, intracellular transport, the walk of motor proteins in the cytoplasm. Scientists and lay people alike take delight in picturing how "a migrating cancer cell trails sticky appendages as it rolls through a blood vessel and attempts to squeeze through the vessel wall" or "a fiery orange immune cell wriggles madly through a zebrafish's ear while scooping up blue sugar particles along the way."[19]

It is surely impossible to deny the special relevance of motion for biology today. But how exactly does the movement of proteins, leukocytes, or tumor cells take place? When we talk of sperm that "swim" and immune cells that "roll" or "wriggle," does the nuanced language used to describe movements define them scientifically, or only metaphorically? Historically, how did this descent into ever greater depths of the organism's interior result in the unstoppable ascent of motion as a concept? Finally, is the current pertinence of the topic really new?

Siting Movement

My project began from the observation that watching the movements of living organisms is among the most mundane and self-evident ways in which human beings assure themselves that they and the other members of their world are alive. Movement is not an object to be found: it happens. As a phenomenon manifesting

itself in continual change and momentary consummation, it is performance and reiteration that gives shape to movement. Movement thus occurs within a situated interplay of place, time, and viewer.

This book, first, examines how biological motion is produced in particular scientific interplays of conceiving, perceiving, and producing biological motion. It offers signposts to mark the sites where researchers, technologies, ideas, and practices set off on new paths in order to constitute the phenomenon of motion.

Drawing inspiration from art history, I describe the situated interplay in which motion is made as a "site." The art historian Peter Gillgren has given a very valuable definition of the site as a "conceptualized place with strong internal and external relationships" and "explicit openness of meaning."[20] In the 1960s, artists started to make art specifically for a site and its context in the natural environment, the urban cityscape, or the museum.[21] Art historians have studied such artworks by asking how the beholder's movement and perception engenders the artwork at its specific location as an ensemble of place, work, and viewer. Today, that method is no longer confined to art of the modern era, but is applied much more broadly to artists and their works.[22]

The concept of the site brings to the fore the constantly renewed perceptual, cognitive, and participatory dimensions of art as an event. Siting involves attentiveness to perception of place and circumstance with all the senses, by all actors in their own moments of time. The scientific investigation of biological motion is likewise a specifically situated interplay. It entails observers encountering a sensory event that usually they themselves produce as an event, using the instruments of analysis, experiment, or computers under the mandate of a particular scientific question. By capturing motion visually or as data, they make it into an object. The phenomenon, the beholders, and their instruments and data form an ensemble that only as such can constitute "motion." Methodologically, thus, siting movement expands the investigation of movement, bringing into play the confluence of the fleeting event's sensuality, its

perception, and its intellectual analysis that together make up the motion event. Siting thus highlights, on the one hand, the changing external relationships that constitute motion, thwarting completeness and closure. On the other, it treats motion, like the artwork, as independent in itself, a regulated, orchestrated interplay and sovereign pattern of strong internal coherence. It is this duality, I hold, that biological motion shares with a site-specific work of art: self-contained, yet existing only in relation to its environment, being simultaneously in itself and in the world.[23]

Second, the concept of site allows me to look at the biological organism itself as a site of movement and the organism's dynamics as an interplay between motion and environment. The processes that constitute the organism, keep it alive, and renew it again and again are always movements, but they are produced by particular situations, in specific ways, in diverse micromilieus, each with its own constraints. Never static, the physiology of the organism is what motion makes of it, new at every moment. If, as Nicholas Rescher put it, events have little or no "fixed nature in themselves," neither do their effects.[24] Observing a movement event, and thus the workings of the body, will always be only a snapshot, a momentary impression in every sense. It is momentary for the viewer who participates in it; it is a momentary excerpt from the flow of motion, a momentary instantiation within a specific experimental setting, and a momentary use of the artifices available to snatch movement out of ephemerality.

Elusive and protean, motion is difficult to pin down. Its story resists narrative. It cannot be told in terms of an ending and conclusive analysis, as narrative necessarily is. Instead, and this is my third point, this book makes siting its method in following biological motion through history. I pursue movement and the arrival of thinking about biological motion on the historical stage by means of movement's own devices—by striking out on a journey. Journeys generate events with every step; they construe motion out of motion. Siting is just such a process of "gradually be[ing]

choreographed into learning about the site." As Peter Gillgren has elegantly described it, "with every step, new features and new constellations appear."[25] In the same way, this book identifies historical moments when thinking on animate motion takes new turnings, steps off established paths, steps onto new ones. As it moves along its route, the book notes some of the waymarks that locate biological motion at the intersections of knowledge domains and scientific and cultural practices—the animal machine, modeling in mathematics, or the human gait in the chemistry of molecules.

These movement events are neither unalterable nor arbitrary, but the outcomes of my own, mobile positioning. They form a choreography of the phenomenon of biological movement as, both historically and analytically, it glides between the most varied fields of knowledge, regroups at the boundaries of questions and methodologies, shape shifts along with the technical media that bring it forth and the experiments that make it visible. Motion thwarts not only closure, but also the interpretive power of narrow, static approaches, traditional paradigms, and established conventions.

Movement, in other words, shows us the "mental sculpting" (to borrow Martin Kemp's term for Leonardo da Vinci's method of drawing with its multiple revisions) that is performed by our own labor of thinking.[26] For the confrontation with motion is always also a confrontation with the observer's own movements of perception and understanding. Movement challenges the observer to engage with the phenomenon rather than pinning it down, to seek rather than to find, and to give form to something that is unfinished and inaccessible.

Stepping into the Book

Attention to life moving on screens may be a recent phenomenon, but moving matter never escaped notice or scrutiny. On the contrary, it was always part and parcel of the scientific study of life and had profound epistemic consequences for the whole of biology from the start. It has been the driving force for research that seeks the

foundations of life, or at least the foundations of its own knowledge. *Biological Motion* uncovers that secret life of movement—eagerly explored throughout the centuries by a veritable crowd of monks and microscopists, botanists and bacteriologists, taxonomists and cytologists while hidden from historiography in plain sight.

Animate motion entered the microscopic world as a mystery, captivated Enlightenment audiences as a curiosity, overturned the notion of life in the nineteenth century, and has recently become the key to framing molecular existence. Over the centuries, the locus of animate movement migrated from animal to matter, from the organized to the inchoate, from the organ of locomotion to the contractility of all living matter. Descending from the whole to the part, from outside to inside, movement became the determining feature and essential explanation of the inner workings of life, whether reproduction, physiology, or protein action.

In the seventeenth century, Antoni van Leeuwenhoek's discovery of animalcula in a drop of rainwater—tiny animals that became visible only under the strong magnification of his lens—opened up a new realm for biology, which would only much later begin to recognize its true luxuriance. In the visible world, motion was what was obvious; with the discovery of movement in the microscopic world, motion was what was extraordinary. Yet Leeuwenhoek entertained not the slightest doubt that this new world was full of life.

But tiny animals with unlikely behavior were only the beginning of an investigation that by the nineteenth century had shaken some of science's most deeply rooted beliefs about the organic world. Simple as they were, infusoria presented a series of mind-boggling puzzles. First of all, they posed the question of what constitutes an organism. If infusoria moved like animals, and consequently were animals, one might expect that on closer inspection and experimental scrutiny, they would prove to be organized with similar complexity. If they did not, would they still be animals?

The self-evident analogy, based on motion, between higher animals and infusoria began to crumble in the nineteenth century.

Motion took on a new role as the criterion for redrawing the frontiers between animal and cell, plant and animal, dead and alive. In protozoology, taxonomy, cell biology, botany, and physiology, animate motion expanded from being the signum of the animal to defining protozoa and plants, then organic matter itself. By the end of the century, the activity or contractility of organic substance, and this alone, was what indicated the property of being alive. Yet in order to track down organic matter's contractility and understand how all the various physiological functions of growth, nutrition, and development arise from, work through, and are perpetuated in motion, a world full of vitality had to be studied while it was still alive.

The microcosm glimpsed through the lens faced its beholders with visual and epistemic challenges that lost none of their appeal for the curious-minded over time. The effortlessness with which life exudes vitality is matched only by the arduousness of biology's search for ways to bring the hidden life of biological motion into the realm of perception and analysis, its struggle with the practices, methods, and devices it must employ.

Even in Leeuwenhoek's day, projections using light and lenses offered a space of experimentation for a new, sensual experience of microscopic life as it lived. Performances and spectacles featuring the camera obscura, magic lantern, or solar microscope were well known, as was their potential for studying movement. In the seventeenth and eighteenth centuries, watching insects and infusoria was not only an intellectual challenge, but a pastime. In the nineteenth century, solar microscopes and special illumination methods were still being used to make motion visible and thus open to investigation, even if the motion was so delicate it could hardly be perceived or else took place in material that was itself almost invisible and formless.

Well into the twentieth century, scientists continued to work on a broad repertoire of inscription formats and visual methodologies that enabled movements to be recorded and measured successively

on paper, played forward or backward on celluloid film, or studied three-dimensionally and back-to-front through prisms—at times in a resolution high enough to register the individual cell.

The discovery of vitality that arose from microscopic exploration brought with it the wonderment, unbroken for centuries, at how perfectly mysterious this world in motion is. Leeuwenhoek's tiny organisms were animals by virtue of their movement, but the nature of that movement remained difficult to grasp. Some characterized it as spontaneous, voluntary, instantly recognizable; others likened it to acting on the stage and found in it a spectacle equal to anything that the opera and street performance could offer the pampered eighteenth-century Parisian theatergoer. To no small extent, the epistemic challenge of understanding moving life—fleeting but vital, unremarkable but fundamental, ubiquitous but easily overlooked—has been a source of aesthetic pleasure. However much it is parceled and partitioned into ever tighter scientific grids, movement has never lost its imaginative allure. On the contrary, the modern life sciences seem to have fallen entirely under its spell.

As research has pried more deeply into the subcellular domain and microscopy has become nanoscopy in the past few decades, enormously sophisticated experimental apparatuses and biochemical knowledge are paired with the computer and mathematical modeling. While animalcules wriggled visibly beneath the seventeenth-century microscope, the new microscopy also sees cells, nanobots, and proteins that walk or limp. When single molecules are drawn into the visible world, it takes mathematics to make the invisible move under the conditions of visibility. Now that motion is visible in new places, is it also visible in new ways that help us to understand it differently?

Aristotle established motion as a fundamental category for thinking about, perceiving, and organizing the world. The body is alive because the soul lends it life, and living existence maintains itself solely in movement—the precondition for its constant

transition and transformation. Motion in Aristotle's work projects organic existence toward its future, its preservation in mutability. From this intellectually powerful enigma, motion descended into the more prosaic conceptual space of the machine in the seventeenth century. Now animals moved according to the same rules as projectiles or planets, whether in Pisa or in the firmament, and machines could copy and perform motion in the place of animals. In the twentieth century, technical experimentation relocated motion into the perceiving observer, and movement became a phenomenon of ascription. Today, synthetic robots and biohybrids move organically in ways that play with our perception and erode the Aristotelian equation of being in motion with being alive.

The critical question we face in the twenty-first century is no longer whether what we see moving is natural or an artifact or both, but the inverse: whether or not we wish to define the motion we see as animate. Does biology's mathematical turn finally liberate biology from the problem of how to explain aliveness or, quite the contrary, does it strip life of its very essence, its vitality?

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