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C. Anastopoulos: Particle or Wave

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INTRODUCTION

Perhaps Universal History is nothing more than the history of a few metaphors.

—Jorge Luis Borges, *The Sphere of Pascal*

If we ask individuals from a Western society to ponder the meaning of the word “matter” (in the sense of material), they will probably come up with many different images. They may think about the atoms and all the tiny particles that have been discovered by modern science. Or perhaps they will think about the successes of technology in controlling and manipulating all different types of material processes and then consider how this affects their everyday life. They may also realize that they are themselves material beings and will inevitably remember the oldest of contrasts, “mind vs. matter,” or perhaps “mind over matter.” Or they may be quick to think in moral terms and focus on the distinction between the “person of spirit” and the “person of matter.” One way or another, the word “matter” will have a meaning for them—perhaps not a unique or an unambiguous one, but they will definitely conclude that it refers to something so fundamental as to be really important.

We may next imagine asking the same question to people of other cultures and times. We will have to find an appropriate word in their language to translate “matter.” It is rather remarkable—given the immense

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diversity of living and dead languages—that most of the time we will be able to find an adequate translation. The corresponding word may not have exactly the same connotations—the idea of atoms would hardly come into the mind of a person unfamiliar with modern science, or at least with a developed philosophical tradition. There may also exist fine differences of meaning between these words. Still, any person who understands the question will not fail to think of matter as the substance manipulated with one’s hands, however primitive the technology may be. After all, humans are and have always been toolmakers and tool users. And neither will the person fail to grasp the distinction between matter and mind because this is akin to a distinction familiar to every human being, that between the things of the outside world that we perceive through our senses and the emotions and thoughts of our internal life.

It follows, then, that “matter” is an abstraction common to people of different times and cultures. It arises out of the one single thing that a modern person shares with a Greek of Plato’s times, a tribesman of New Guinea, and a courtier of the Forbidden City: our common humanity in the way we sense, feel, act, and live our lives in the world. Matter is therefore a universal concept. A magician of old times would not hesitate to call it a “word of power”; a modern psychologist would perhaps prefer the word “archetype.” Of course “matter” is not the only such word: time and space, emotion and reason, divine and profane, multiplicity and unity, flux and immobility, cause and effect, psyche and matter—all these are ideas that resonate in the thoughts and languages of all times, and their significance is explored in the people’s philosophies, myths, religion, songs, or dreams. There exist differences of meaning, of course. One concept may be understood differently in different cultures. But no matter how important such differences may be, they do not affect the essence of the fundamental concepts. These concepts are perceived at a deep level of the human psyche, before any association to words, logical definitions, or social practices. At that level, they are the same everywhere because they refer to an experience of reality common to all people.

In modern societies, however, the study of matter is perceived to be a prerogative of the sciences, mainly physics. Indeed, the development of

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physics during the last couple of centuries has provided deep insight into the deepest structure and organization of matter. The success of the scientific method has been so overwhelming that by the end of the twentieth century many scientists did not hesitate to make an astonishing claim that it is only a matter of time before we construct a “theory of everything.”

The scientific description of the world, however, does not grow in a vacuum. It is equally impossible to detach the concepts of science from ideas, perceptions, and feelings that arise in other fields of human culture. Scientific concepts may be presented in their final form detached, self-contained, and logically complete, but this is mostly an outward appearance, similar to the precise, clean-cut, and orderly performance given by a military unit during an inspection by their commander in chief. In reality, the concepts of science and the thoughts of scientists are immersed in the ocean of the society people live in, and their origins are blended with a myriad of other ideas, images, and thoughts. This is the reason that even an account of the scientific theories of matter cannot be restricted to the scientific theories themselves but has to seek their roots in other fields of human activity.

History also plays an important role. Hermann Weyl, one of the greatest mathematicians of the past century, has remarked that it is impossible to understand the character of modern mathematics unless it is considered in the perspective of its history over the last two thousand years. The same is also true for modern physical theories, and even more emphatically so. Mathematical concepts are abstract by nature, while the physical ones have a more earthly character. They are more closely related to the concrete experience of the senses and the way the world is perceived in different times and places. Indeed, mathematical purists are often exasperated with the ambiguous character of the physical concepts, which still seem to carry the “dirt” of their lowly origins.

If we follow Weyl’s advice in the context of modern physics and attempt to trace back in time the origin of the modern physical concepts about matter, we see that they arise from two conflicting theories, whose seeds in art and myth are probably lost in the mists of prehistory. These theories were first explicitly stated and rationally analyzed in Greece during the fifth century B.C. The first of these theories is the

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atomic theory; it describes matter as consisting of discrete, indivisible pieces, which move in the void and through their motion create all things that come into our perception. Indeed, even the human soul consists of such particles, finer in their form than the ones of ordinary matter. The motion of these *atoms* is due to a necessity external to them, which determines precisely and unambiguously how and toward which direction each atom will move. Everything that we see in the world may be analyzed in terms of the distinctive properties of the atoms and their motion in the void; nothing else exists—all other images are simply figments of our imagination.

In opposition to the atomic theory stands the *theory of the elements*. Matter, it proposes, consists of elementary substances (the *elements*), which are distinguished from each other by means of their intrinsic qualities. The elements are pure and simple; they represent elementary qualities and cannot be analyzed in simpler components. Initially only four such substances were postulated: Earth, Water, Air, and Fire. All material things that appear to our senses arise from the elements being blended together, and what we perceive as creation and decay is nothing but the change of the analogies in the blend. This change is due to powers that are inherent in matter (originally denoted as love and strife), whose effect is to bring elements together or take them apart. Since the elements refer to qualities, and qualities are seemingly preserved when we divide matter in pieces, it is more natural in the theory of the elements to postulate that matter can be subdivided indefinitely.

These two theories not only differ in their details but also represent very different attitudes toward the world. The atomic theory has the ambition to explain all material phenomena through the motion of undivided entities in space. If the human intellect succeeded in understanding the specific rules that guide the atomic motions, it would be able to explain and describe every single process of nature. The atomic theory then lends itself to an image of predictability and control, a demystification of matter. The theory of the elements is the exact opposite. It places quality at the center of its explanations—and qualities, however much abstracted, are by their nature closer to sense perception than to logical calculation. Moreover, the theory of the elements attributes the cause of

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change to the intrinsic forces and powers of matter. It emphasizes the spontaneous character of matter, its mutability and aversion to control.

But as opposites flow to each other, the two conflicting perspectives were destined to a marriage. A third party was needed to bring them together, and this had appeared about fifty or sixty years earlier. A rather shadowy figure of antiquity, Pythagoras, had come up with an idea that may perhaps appear self-evident to a modern person. *Reality is structured upon symmetry*, and symmetry—the proper proportion—is something that subsists in number and figure, the subject matter of mathematics. The two conflicting theories for matter together with the realization of the mathematical character of reality were the germs of subsequent ideas about the structure of matter, to which we may trace the lineage of even the most complex theory of modern physics.

We follow somewhat the development of these theories in antiquity and the Middle Ages, but we shift our attention to the sixteenth century A.D. At the westernmost corner of the Eurasian continent, we encounter a young culture that had a deep fascination with number and shape; a love for the rediscovered ancient traditions mixed with a curiosity for the new worlds that lay open before them; an unprecedented strong inclination toward precision of observation and logical deduction; and a strong desire for the power bestowed by the unraveling of nature's secrets. That intellectual environment needed only one single spark before it caught fire. It took thirty-six years of inspired work by a single person to produce that spark. That person was Nicolas Copernicus, the Polish monk who resurrected the then obsolete idea that Earth and all planets move around the Sun. He expressed a deep conviction that the language of mathematics captures nothing less than the whole "System of the World." Copernicus's spark became fire, and the fire brought revolution—what we nowadays describe as the era of the Scientific Revolution was born.

It took almost a century and a half for the revolution to reach its apex in the work of Newton. His creation, unprecedented in scope, united "the things of the heavens and the things of the earth." They were all subject to the same laws, which were expressed unambiguously in a powerful mathematical language. The new theory kept the old atomic theory's vision of

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particles moving in the Void, but, influenced by a specific emphasis on precision and strict logical succession, the necessity that caused all motion was so strict, unyielding, and ever present as to be beyond anything that had ever been dreamed up before. The new theory was named mechanics. This name brings forward the image of matter as a machine, an object whose motion is governed by strict, unambiguous rules that apply separately to each of its parts. The image of the machine was so well attuned to the new theory that it slowly assumed its powers—in spite of the misgivings of its creator and loud protests from every direction.

One after the other, the physical phenomena succumbed to the lure of mechanical explanation and description. The machine moved eventually from the realm of science, and rational explanation into the realm of practice and everyday life. A new revolution—the industrial one—materialized, and it transformed not only people's perceptions of the world but the world itself. The new world brought wealth, comfort, and the promise to fulfill all material needs. However, progress came through the machine, and it had its price. It made people fear losing their humanity: many artists, philosophers, and scientists attempted to provide a different view of the world, but their efforts seemed at that time to be in vain.

Then came the twentieth century, bringing with it war and revolution. To the new generation, the comfort and security that progress had promised them appeared more and more like an illusion. Consequently, the perception of the world was radically transformed. In particular, the image of the machine was dealt two strong blows. They came from the same realm of thought from which the image had originally appeared: physical theory. The first blow was the work of a single person—Albert Einstein and his theory of relativity. The other—the more powerful one—was the theory of quanta, which was delivered through the efforts of a generation of physicists. All of a sudden the world looked different. Matter seemed to have been dematerialized, its mechanism dismantled and substituted by an uneasy abstraction, while the old but never forgotten ideas of inherent powers in matter returned to complement the atomic perspective. But the same moment that matter seemed more uncontrollable and uncertain, control over it increased rather than

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lessened, and technology moved in directions of greater promise and power, and of greater destruction.

The story above provides the background of the issues addressed in this book, namely, the images of matter in modern physical theories. The key principle of modern quantum theory is the remarkable assertion that the elemental and the atomic aspects of matter coexist. In technical language, this principle is referred to as the *field-particle* (or wave-particle) duality. I argue that the field description of matter is obtained from the development and refinement of basic insights of the theory of the elements, and in a similar way the atomic theory carries the conceptual germs of the particle description.

However, such identifications are neither simple nor straightforward. Even though a central thesis of this book is that the complex concepts of modern physics can trace their origins to simple and intuitive ideas, we cannot ignore the fact that modern physical theories weave these ideas in a distinctive and complex pattern that cannot be perceived unless one follows the twists of every single thread. If the atomic perspective of particles moving in the Void remains fundamental to modern physics, the three words “particle,” “moving,” and “Void” involve so many more associations and properties than their traditional counterparts that they appear substantially different. And whereas some scientists have seen in modern physics the rebirth of ideas about intrinsic powers of matter, the carrier of this idea is a mathematical object, the *quantum field*, which is so abstract in its character that its true essence, if such exists, remains hidden from our eyes.

For this reason, I found it necessary to expand on some of the intricate details of modern theories about the motion and structure of matter. Keeping the wave-particle duality and its implications in focus, I survey the state-of-the-art understanding of the structure of matter, namely, the theories of *quantum fields* and *elementary particles*. I place particular emphasis on identifying the limits of the present theories, and hence on determining the boundaries beyond which our present knowledge is not secure.

I hope I have been able to communicate the scope of this book and the main ideas that motivated it. The story narrated here is hardly

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exhaustive, and the choice of what to include and what to leave out reflects largely my personal tastes and preferences. My main guideline in the choice of the material was to look for the components that form the images of matter in modern scientific theories.

As far as the description of physical theories is concerned, I have tried to include all important concepts and ideas, and to present diverse and even conflicting attitudes and opinions. Still, the emphasis reflects inevitably my personal perspective. The balance of the presentation was another criterion in the choice of material. As the book deals primarily with the properties and structure of matter at the fundamental level, I have practically ignored specific fields of modern physics that deal with the larger-scale organization of matter—such as the theory of condensed matter or the physics of stars and galaxies. Clearly, I am solely responsible for any omissions, errors of fact or judgment, partiality of perspective, or mere ignorance. I can only ask for the reader's patience with any such inadequacies.

Finally, I wish the reader as much enjoyment in reading this book as the pleasure I have had in writing it.