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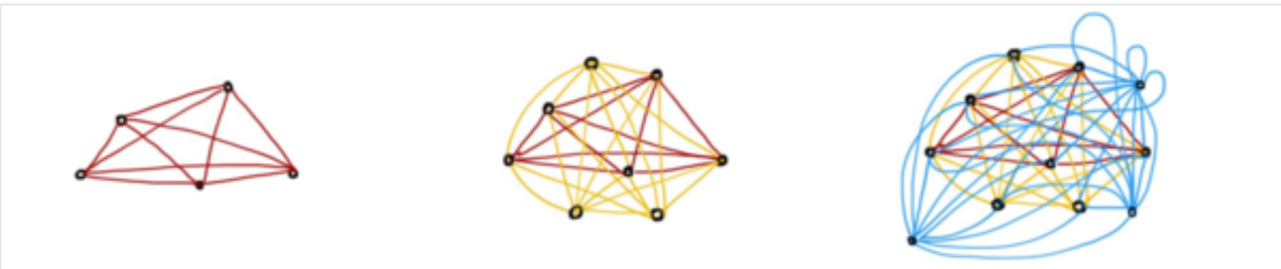
More Is Different

by Tasneem Zehra Husain

Emergence is a word deep enough to lose oneself in. It alludes to realities appearing, not suddenly or out of nothing, but slowly dissolving in to our consciousness - like a fuzzy picture, coming into focus. It refers to a gradual process, one that is smooth - not jerky - and yet results in an outcome that could not have been predicted, given the origin.

Examples of such behavior abound in the natural world. In stark contrast to human mobs, there are groups that exhibit increasing coherence and/or intelligence as they grow (In fact, intelligence too, is said by some to be an emergent phenomenon.) When birds or fish amass in large numbers, they move in ordered flocks, exhibiting a degree of synchronization and structure that is lacking in smaller groups. The organization of ice crystals is not hinted at in the molecules of water, any more than the structure of hurricanes is stamped onto individual air molecules, or instructions for avalanches are coded into grains of sand. So long as objects are studied in isolation, they display no hint of what becomes possible in groups that exceed a certain threshold. Emergent behavior is a property not of individuals, but the collective; it arises naturally, out of multitudes - a perfect illustration of a whole being greater than the sum of its parts.

In science, a phenomenon is deemed emergent if it cannot be attributed to the properties of the constituents of a system, but instead arises from the connections between them. It is an ability that resides not in the nodes themselves, but in the network they create. Think of that childhood game of join the dots. With each new dot that is added, the possibilities are multiplied manifold; a new dot can potentially connect to every single dot that already exists, forming bonds that both strengthen, and transform, the system. A network grows exponentially faster than the number of its nodes.

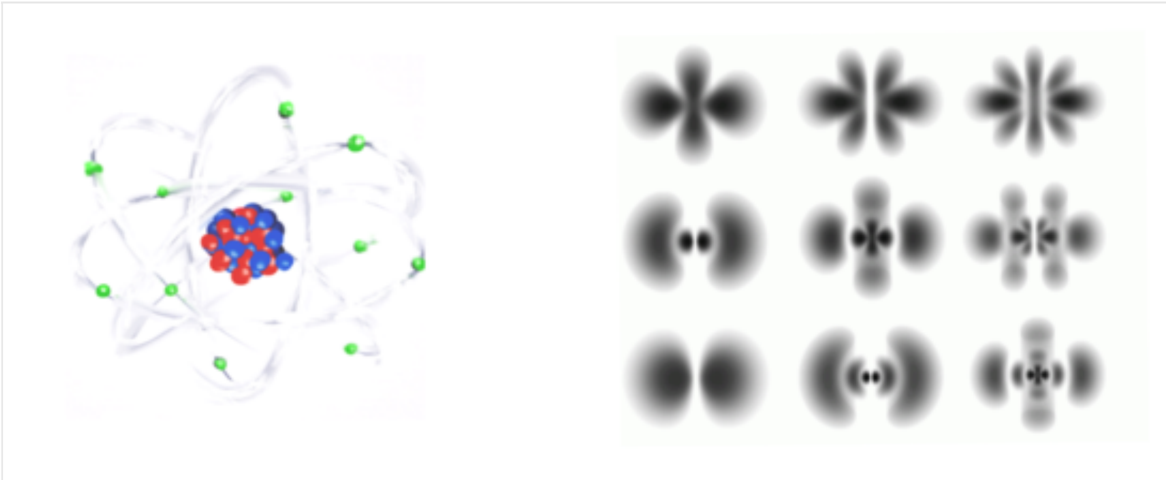


It so happens that in physics, there are many cases where macroscopic and microscopic behavior are best described in different vocabularies. One oft-quoted example is that of classical mechanics ‘emerging' from quantum mechanics. At the turn of the last century, the reluctant revolutionary Max Planck was forced to declare a resolution to a set of problems that had plagued physicists for years. All these contradictions would disappear, he grudgingly said, if one assumed that energy could only be radiated and emitted in discrete blocks - he called these quanta. Barely was the quantum unleashed that it spread like a forest fire throughout physics. Suddenly, it became apparent that many quantities we had considered infinitely divisible, existed instead in multiples of a smallest basic unit. Zeno's paradox finally had a solution - you could simply not keep covering "half the remaining distance" between yourself and something else, because beyond a certain point, even space can no longer be subdivided. The quantization penetrated down to the very structure of the atom, which seemed to allow only certain well-defined orbits in which the electrons could revolve around the nucleus.

This pixelization of Nature was universally unwelcome, in a culture grown used to the smooth continuity bequeathed us by Newton, but perhaps even more disturbing than this choppiness was the fact that physicists were no longer allowed to deal in definite statements. Quantum mechanics came along and claimed that probabilistic answers were the best we could do. For large enough ensembles, probability works very well, and so on the macroscopic scales where we operate, the numbers work out in our favor and we seem to have firm answers - but when we descend to a subatomic level, all we can do is to enumerate possibilities, and calculate the odds of them coming to pass. Nothing can be claimed for certain.

This confusing world they had unwittingly ventured into, both fascinated and troubled the physicists of the time. They wondered where, in this crazy space, lay the innocent realm in which they dwelled before the quantum interrupted. In answer, Niels Bohr came up with his famous correspondence principle. The classical laws we are familiar with might not be applicable to microscopic realms, he said, but whatever else quantum mechanics does, it should - for large enough collections of atoms - replicate the behaviors we are used to - just as Einstein's special theory of relativity effectively reduces to Newtonian mechanics, when the velocities under consideration are much slower than the speed of light.

My favorite description of the correspondence principle comes from Arthur Stanley Eddington - the astronomer who led the eclipse expedition that provided proof for the general theory of relativity. Eddington talks about the discrepancy between Bohr's model of the atom, where an electron is constrained to move in (one of many) fixed, predetermined orbits (each corresponding to a particular quantized energy) and Schrodinger's wave equation for the same system. Bohr's model is full of the new unexplained discreteness, but is at least visualizable; Schrodinger uses smooth, continuous, familiar waves - but forbids them from having any familiar, or even tangible, interpretation - they are waves of probability, he claims. One hardly knows which is the lesser of the two evils!



To understand probability waves, Eddington suggests we picture a medium that oscillates so fast that we cannot resolve the individual ripples on its surface; at times, waves converge and coalesce and "conspire to create a disturbed area of extent large compared with individual ripples but small from our own . . . point of view." It is exactly such a "stormy area" that we recognize to be a material particle; in other words, what we think of as an individual particle is, in fact, a superposition of many waves, each of which may be moving with a different velocity. This amalgamated group of waves obeys the classical equations of mechanics, but as Eddington points out, "we should have gained very little if our theory did no more than re-establish the results of classical mechanics on this rather fantastic basis." The virtues of this construction become visible when we deal with nonclassical phenomena. Thus far, we have supposed our stormy area to be small, so that it could correspond to a particle, but if the wave picture is true, there is nothing that keeps the area from expanding.

As this wave-group "storm" spreads out, there is no boundary it crosses, no line that separates "small enough to be a particle" from "too large to be called a particle," and so we can imagine it spread over a wide region. The naive conclusion would be to think, "Aha! So particles spread out and become larger and more nebulous!" If only it were that simple! In Eddington's words, it is not that concentrated particles melt into diffused matter. "That is not Schrödinger's theory. The spreading is not a spreading of density; it is an indeterminacy of position, or a wider distribution of the probability that the particle lies within particular limits of position. Thus if we come across Schrödinger waves uniformly filling a vessel, the interpretation is not that the vessel is filled with matter of uniform density, but that it contains one particle which is equally likely to be anywhere."

Speaking of how classical laws materialize from quantum, Eddington writes: "In Bohr's semi-classical model of the hydrogen atom there is an electron describing a circular or elliptic orbit. This is only a model;

the real atom contains nothing of the sort. The real atom contains something which it has not entered into the mind of man to conceive, which has, however, been described symbolically by Schrödinger. This ‘something' is spread about in a manner by no means comparable to an electron describing an orbit." As we excite the atom to higher quantum states, the Bohr model would have us picture an electron jumping into higher orbits, but "in the real atom Schrödinger's ‘something' begins to draw itself more and more together until it begins sketchily to outline the Bohr orbit and even imitates a condensation running round."

At yet higher quantum numbers, the pictures meld into each other. Schrödinger's "something" appears as a compact object, moving with the same velocity and in the same orbit that Bohr had decreed, and obeying the classical laws of radiation expected of an electron. "And so when the quantum number reaches infinity, and the atom bursts, a genuine classical electron flies out. The electron, as it leaves the atom, crystallizes out of Schrödinger's mist like a genie emerging from his bottle."

In countless other physical scenarios, we find new properties surfacing on macroscopic scales - more is different, as Philip Anderson famously claimed. Take radioactivity, for example. The half-life of a radioactive element is well known. We can say with remarkable confidence how long it will take for any given sample to decay to half its size (the time taken is known as the half-life of the element), but when asked about one specific atom, we are immediately silenced. It might decay in the next second, or the next millennium - we cannot say. The behavior of an individual atom is unpredictable, even while the evolution of a large enough collective is reasonably deterministic. That might be a bit shocking at first glance, but if you stop to think, isn't this, in fact, a strength? Isn't it marvelous that the system is orderly and predictable, without being fixed and mechanistic or devoid of surprises?

I find it a lovely metaphor for the process of science. The rules and laws that form our canon are exact, dispassionate and objective statements that have emerged from the collective work of a large group of passionate, creative, and unique individuals.

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