The politics of complexity

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As I write, steam is rising from my teacup. Illuminated by morning sunlight, it rises first in a straight column before wobbles and notches appear. These imperfections grow, forming eddies and vortices which spin up smaller whorls and ripples of steam, before dissipating into nothing. Here, in technical terms, the steam has transitioned from laminar to turbulent flow: from order to chaos. These, teacups and rising steam, are the stuff of classical mechanics, a straightforward application of Newton's laws. Yet there's a paradox, too: while the physics that undergirds them can be written in equations dating from the early nineteenth century, predicting the exact path of the steam is almost impossible. The problem with turbulence of this sort is that everything matters.

Physicists like to talk in terms of characteristic lengths: orbits on the scale of millions of kilometres, or nanometre-scale quantum systems. With turbulence, there is no characteristic length. Everything, from the smallest eddy to the largest vortex, affects everything else. Billowing steam is a complex problem, in both the everyday and technical sense of the term. With it, we are in the realm of complexity science, a field that explores how simple, interconnected components—in this case, molecules of water vapor—come together to create something entirely unexpected.

The study of complexity was made possible by computers. Prior to the digital revolution, the only practical way to model the world mathematically was to simplify it into a form that could be solved with a pen and paper, dropping less important terms until scientists were left with something tractable. A billiard ball bouncing around a pool table, for instance, can be described with simple equations because it is okay to ignore things like Jupiter's gravitational field. The analogue tools of thermodynamics will suit you fine even if you have a trillion trillion billiard balls, so long as they are shooting about at random, as physicist imagine a gas. We can think of this case as unorganized complexity.

The turbulent steam from my teacup poses a much harder problem: it exhibits instead what the scientist Warren Weaver called, in 1947, "organized complexity." If the unorganized complexity of a trillion trillion billiard balls admits pencil-friendly statistics, organized complexity cannot be simplified. Pen and paper tricks like dropping unimportant terms fail because, with my teacup, nothing can be ignored. Computers, with their enormous speed, are excellent at not ignoring things. They let organized complexity unfold on its own.

Since the first digital general-purpose computers of the 1940s and 50s, complexity has become an organizing concept in the natural sciences. One of the primary uses of complexity concepts is in understanding weather dynamics. With weather patterns, even a small change in initial conditions—an initial seed of rising air, say, or the location of a crashing atmospheric wave—can lead to a radically different weather system. This sensitivity is what the meteorologist Edward Lorenz famously called the "butterfly effect": with a flap of its wings, even a tiny creature could change the course of weather history.[1] Another field interested in organized complexity is ecology, where the dynamics of species populations is explored using similar math as that used to model the atmosphere. And together, ecology, meteorology, and the complex physics of the oceans are interlinked in the vast computational simulations used to forecast the impacts of climate change: simulations known as Earth System Models, capturing in silicon the coupled evolution of our planet's biosphere, atmosphere, oceans, and ice.

The resulting images of a future Earth, destabilized by climate change, join with images from other complex system fields—swirling fractal geometries, murmurations of starlings, maps of neurons—capturing the minds of the public and intellectuals alike. Where the science of the eighteenth century created an image of the world dominated by clocks and billiard balls, deterministic and described by the laws of mechanics, in the twenty-first, the world is a decentralized network of organized complexity. This popular vision of universal complexity diverges from its roots in partial differential equations: its appeal is not about improving weather forecasts. It's more about a feeling of reverence, even mysticism. This is a mystical complexity that ventures beyond numerical methods, offering answers to ancient questions—solving the mind-body problem, for example, with a soul emerging out of networks of neurons—and speaking to a desire for holism and interconnection, allowing spirituality to enter into an otherwise thoroughly disenchanted world. It is here, at the boundary between complexity science and mystical complexity, that strange and conflicting politics emerge.

Chaos in the air

In the 1940s, Lorenz, the man behind the butterfly effect, was intrigued by the equations of weather dynamics and eager to apply them to computational weather forecasting. Many of his

[1] Lorenz's original animal metaphor was a seagull. The butterfly term came some years later, but neither of these animals were the first creatures in the meteorologist's bestiary: in 1898, physicist W.S. Franklin blamed a "grasshopper in Montana" for turning "a storm aside from Philadelphia to New York."

contemporaries were sceptical, doubting that such complex mathematics would help the working meteorologist. At the time, operational meteorologists relied on linear statistical models, in which the weather in New York today was computed from yesterday's weather plus the weather two days ago in Chicago and so on. Lorenz dismissed this as "a pedestrian approach that yielded no new understanding of why the atmosphere behaved as it did." In the language of complexity science, this statistical approach was reductionist: it failed to capture how the flows of the atmosphere combined into a complex and turbulent whole. So, to humble the statisticians, Lorenz conducted an experiment to demonstrate how such basic math radically underestimated the complexity of the atmosphere. Like the real atmosphere, Lorenz came up with a simple set of equations that behaved irregularly. For such a system, he demonstrated, statistical forecasting failed.

In the process, Lorenz discovered something else. As he reran part of the simulation, just before he left for a long coffee break, he input numbers from an earlier run.[2] When he returned, he found that the results it generated were completely different from the earlier run, even though the computer solved the exact same equations beginning with the same value. At first, he "suspected a weak vacuum tube or some other computer trouble," he later recalled, but he quickly discovered there was no error at all. The differences between the two simulations, he saw, emerged only gradually. When he checked the numbers again, he found that while imputing them a second time he had rounded the initial number, and it was that tiny error that slowly grew, spreading out until it came to dominate the solution. This was chaos, and the implications were obvious almost immediately: "if the real atmosphere behaved like the simple model," Lorenz wrote, "long-range forecasting would be impossible."

These kinds of non-linear dynamics would later find a central role in the work of the philosopher Jean-François Lyotard, for whom they helped usher in a brand-new era: the postmodern age. In his 1979 book, *The Postmodern Condition*, Lyotard saw in complexity science something fundamentally postmodern, associated historically with the rise of the postindustrial knowledge economy. As Lyotard argued, "the continuous differentiable function" – the math of Newtonian physics – "is losing its pre-eminence as a paradigm of knowledge and prediction" gradually replaced by a postmodern science, concerned "with such things as undecidables, the limits of precise control, conflicts characterized by incomplete information, '*fracta*' [fractals], catastrophes,

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[2] Lorenz claims in his memoirs that this world-changing coffee break took over an hour. Perhaps he was picking up a game of chess with Norbert Wiener, the founder of cybernetics and another complex systems legend. As MIT colleagues, the two played often.

and pragmatic paradoxes." Something about the steam rising from a teacup captured, in Lyotard's view, defined the spirit of the age.

Chaos may have been a paradigm shift, but it did not mean the end of science. Lorenz was opposed to the reductionism of the statistical modelers, but his argument wasn't that weather prediction was impossible. Rather, post-Lorenz atmospheric science is about working with chaos, making predictions while remaining aware of the limits of knowledge. Meteorologists today use a global network of environmental sensors, from satellite to aircraft to surface stations, to come up with the best possible guess for the true present state of the atmosphere—as Lorenz predicted, the better the guess, the longer the forecasts remain valid before they dissolve into chaos.[3]

Climate modelers, too, work with chaos, what they call "internal variability"[4], though their goal is to predict broad changes rather than specific weather systems. Climate models transform insights from across the physical sciences into lines of code—dynamicist studies of heat and precipitation, chemists' work on atmospheric constituents, ecologists' the biosphere and soils, oceanographers' the oceans, and so on—and synthesize their findings into software that can demonstrate a complexity and chaos that resembles the real Earth system. Even feedback loops and tipping points show up in the models, just as they do in the real Earth: bright ice melts away, for instance, leaving only dark, light-absorbing ocean, accelerating polar warming in virtual systems as in reality.

Lyotard was right that this is a different kind of science than Newton's billiard balls. Just as classical mechanics was fit for a world of waterwheels, and thermodynamics was tailor-made for the steam engine, the computational study of organized complexity is a natural fit for the post-industrial information age. Even outside the realm of production, Lyotard's linking of complexity in science to a broader cultural shift was to prove perceptive. The world market has transformed the planet into one big network, where individuals—capitalists included—are compelled by a force external to themselves. This is a capitalism as an emergent property of human relationships, mirrored in the scientific conceptions of emergent properties, of atmospheric chaos, that scientists live every day. Complexity is a form of thought native to a capitalism which has conquered the world; as the computer made complexity easier to calculate, the wider world made it easier to think. No wonder Lyotard saw it everywhere.

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[3] True to Lorenz's toy model, when commercial air travel shut down during Covid lockdowns, weather forecasts declined in accuracy because a key data source for the middle atmosphere disappeared.

[4] In other words: the same model, driven by the same emissions estimates, can generate different predictions for future climate depending on its initial conditions.

Human action, not human design

There is a tension here, however, between the urge to take complexity as a theory of everything, and the fact that complexity science is still, fundamentally, a natural science—one that makes predictions both useful and boring about the world.

One of the writers for whom complexity played a central role in their totalising vision of the world was the conservative economist Friedrich Hayek, who argued that out of the complex interactions of billions of individuals the spontaneous order of the market emerges, an order that works only so long as no one interferes by introducing distortions like regulations or the welfare state. Hayek was one of the "neoliberals", a term now often used as a catch-all for conservatives like Ronald Reagan and Margaret Thatcher and their associated vices—privatizations, tax cuts and the valorization of selfishness. But for Hayek and the other neoliberals, they had something more specific in mind, at the heart of which is a philosophy built upon the almost mystical complexity of market society.

For Hayek, markets were complex systems capable of "discovering" new things. The market, he wrote, "brings about the reduction of costs to the minimum discoverable" through competition, which is then communicated to the world via the price system. A new, low-cost method of producing shirts, for instance, would rapidly dominate the fashion market, in the same way that an invasive species might remake an ecosystem. Or, as Hayek argued in his 1945 essay "The Use of Knowledge in Society," if somewhere in the world a tin mine closed tin prices would rise, and purchasers of tin would adjust their behaviour accordingly. No one needed to know why prices rose; instead, purchasers responded to a signal like an individual neuron responds to an impulse.

Adjusting his arguments as he learned more about complexity science, Hayek later used the metaphor of the crystal. "We could never produce a crystal by directly placing the individual molecules from which it is built up," he wrote in 1964. "But we can create the conditions under which such a crystal will form itself." Planning, even in the guise of the welfare state, was as foolhardy as manually arranging a trillion trillion molecules, though this did not mean that the state should be eliminated. Instead, states were to create the conditions for spontaneous self-organized complexity, leaving the market to crystallize on its own. At the same time as the crystal metaphor praised the complexity of markets, it degraded the role of human beings and human agency. Hayek imagined humans as molecules, obeying simple laws and giving rise to a complex and ultimately unplannable social order. Forms of systematic resistance to the crystalline order—whether union organizers or would-be planners—were an impurity to be expunged.

In a later essay, Hayek went further still. Because the world "is only very partially understood," he argued, humans for millennia have evolved "certain inhibiting rules" over time through trial-and-error to avoid unknown consequences. When one deviates from inherited tradition and rules, the world "becomes frightening", and so superstition was therefore "probably older" than religion, more like a species-wide instinctive behaviour. For Hayek, superstition, from the perspective of species survival, was at least as important as efforts "to understand the rules on which this world operates"—science, in other words. In fact, for Hayek science was worse than superstition: biologically ancient and sub-rational impulses were not threats to social order. The real danger for Hayek, as historian Quinn Slobodian has written, was "not so much the law of the jungle as the law of the engineers": the rule of those who believe they can rationally order society better than the market.

If a complex society is only to be cohered by market signals, then other kinds of knowledge are a threat to what Hayek called *catallaxy*—the spontaneous order of the market. This even stretches so far, as the historian Philip Mirowski has argued, as content-driven processes like the peer review of state grants: neoliberals, Mirowski writes, "look forward to the rapturous day when all knowledge (and not just science) is comprehensively funded and coordinated by the market." They are even hostile to the kind of science practiced by such seemingly benign institutions as pharmaceutical safety agencies: Milton Friedman, another neoliberal Nobel laureate, argued against the licensing of doctors and regulation of drugs on the logic that the markets would themselves select for safe practices.

Hayek may have liked the aesthetics of complexity, with its imagery of crystals and fractals, but he was hostile to much of the science that produced it. He was particularly sceptical of computer models, especially those that tried to capture the organized complexity Lorenz encountered on his coffee break. In his 1974 Nobel Prize speech, Hayek cited Weaver's concept of organized versus unorganized complexity. The social sciences, he said, were, like complexity science, also concerned with the former, but he vociferously criticized attempts to use computers to explore this organized complexity. The only sort of knowledge that could be obtained from organized complexity was, he said, "mere pattern predictions." Atmospheric scientists, who each day forecast the evolution of organized chaos on a rotating sphere hurtling through space, would be surprised to hear that their efforts to make "precise predictions" are in vain. Unless, of course, Hayek's goal was to use the language of complexity, not its methods, to valorize his preferred complex system: a market-driven planetary brain.

For champions of the free market like Hayek, then, complexity is political: it allows a social structure to emerge from atomic, isolated individuals. In this, libertarian complexity overlaps with complexity mysticism more than it does with the daily work of atmospheric science, offering a totalizing vision of an order that emerges from the chaos of the world. Unbound by the sober circuits of the meteorological supercomputer, complexity gives both hippies and union-busting economists a shared metaphysics.

Green markets

The conflict between complexity science and the complex system of the Hayekian ideal is clearest in market-driven policies to address environmental problems. These most commonly work through offsetting: carbon markets that generate credits to "offset" polluting activities. The issue of complexity here is resolved by coordinating environmental protection entirely through a market system, rather than by having scientists making apparently outrageous and elitist statements (for instance, that destroyed stream A shelters an ecosystem that is not at all like the ecosystem in stream B, and they cannot therefore be interchanged in a market-based manner).[5]

In this way, we can see market creation as inherently a process of information loss: tin from distinct mines become interchangeable, mediated by a world market, such that the closure of one mine is anonymized and ripples out to the world as a price change, a single number summarizing change in a complex world. The problem with this for the climate and for ecosystems is that airborne greenhouse gases, to take one example, are impossible to summarize in a single number, which is the first requirement of carbon markets, whose aim is to make unlike gases tradeable with one another in a unified metric of pollution. Carbon dioxide lasts for centuries in the atmosphere before it is removed by a variety of processes, from weathering rocks or the churning ocean, but molecule-for-molecule it is a relatively weak greenhouse gas. Methane, by contrast, lasts about a decade before it is oxidized to carbon dioxide, but in that decade captures an extraordinary amount of heat. Carbon markets render these interchangeable through the metric of "carbon dioxide equivalent" (CO_2e), which measures the amount of heat captured by the gas in a given period and compares it against carbon dioxide. On a twenty-year timescale, methane is worth about eighty

[5] Scientists are often uncomfortable with the procedures required for knowledge markets: Stream mitigation banking, for example, relies on a classification system devised by a private consultant who has been vociferously criticized by academic scientists. David Rosgen's system classifies streams based on their geomorphology but leaves aside their biology and ecology. Geographer Rebecca Lave summarizes the system's ecological view with a quote from the baseball film *Field of Dreams:* "if you build it, they will come."

CO_2e, capturing eighty times more heat than an equivalent amount of carbon dioxide. On a hundred-year timescale, however methane is worth only about thirty CO_2e as it has oxidized to carbon dioxide for most of those hundred years.[6] These striking differences raise a tricky question for the market-loving regulator: is methane worth eighty or thirty carbon dioxide molecules?

To the atmosphere, the question is meaningless. There are really two climate crises: the overall *magnitude* of long-term warming, caused mainly by carbon dioxide, and the *rate* of climate change, which is strongly influenced by potent but short-lived greenhouse gases like methane. The rate of climate change has its own biophysical signatures on the Earth system—rapid changes in temperature may disrupt the Gulf Stream, which keeps Europe temperate despite its high latitude, as well as degrade slow-changing ecosystems—but cutting methane will do little to mitigate the long-term magnitude of global warming.

Yet markets require simplifications, and those simplifications come with perverse but entirely "rational" consequences. Take fluorinated gases, found in refrigerators and air conditioners. These gases, which capture large amounts of heat, have CO_2e in the thousands, which historically made their control highly lucrative: in 2005, HFC-23 destruction accounted for two-thirds of all the credits in the Clean Development Mechanism of the Kyoto Protocol, because it was worth 11,700 CO_2e. As a result, individual industrial facilities responded to the price signal by first intentionally producing fluorinated gases as waste, then reducing that waste to generate carbon credits, ultimately selling their invented efforts to polluters who found real mitigation too costly and leaving behind an atmosphere laden with more greenhouse gases than before.[7] The situation is hardly better when carbon dioxide is traded for carbon dioxide. The signature trade on carbon markets is regrowing forests to offset burning fossil fuels, but a 2023 *Guardian* investigation found that 90% of rainforest carbon credits issued by the largest certifier do not correspond with real removal.

Good complexity

Slavoj Žižek once pointed out that Beethoven's Ninth Symphony was endorsed by everyone from the Red Guards of the Chinese cultural revolution to the upholders of Rhodesian apartheid, from Nazis and Soviets to the bureaucrats of the European Union. Almost as universal is a hatred of

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[6] The idea of CO_2 equivalents was first proposed by scientists in the original 1990 IPCC assessment report, where it was offered as a simple way to think about greenhouse gases at time horizons of 20, 100, and 500 years, periods given as "candidates for discussion" that "should not be considered as having any special significance." Later carbon markets took up the idea as settled fact, typically taking the century figure for their accounting.

[7] To give the green capitalists some credit, fluorinated gas mitigation was removed from carbon markets in the 2010s.

seventeenth century French rationalist René Descartes. To intellectuals in the complexity-loving present, whether on the left, right, or centre, Descartes is taken as a representative of the mechanical world of Newton's billiard balls: a reductionist enemy of all things complex. Eco-feminist Carolyn Merchant saw in Descartes a reduction of the living Earth into dead, extractable matter, while the geographer Jason Moore, like many others in environmental studies, argues against "the prison house of the Cartesian binary," the unnatural separation of humans from the environment of which we are all a part. Hayek, too, held Descartes responsible for ill-advised attempts to control the market: "The belief in the superiority of deliberate design and planning," he argued, came "only through the rationalist constructivism of Descartes."

Progressives are often heard calling for a politics of complexity, set against the binaries and mechanistic reductions of Cartesian thinking. For Marxist biologists Richard Lewontin and Richard Levins, for instance, a complex system approach in medicine would run counter to capitalist health systems, which reduce disease to disconnected symptoms treatable by small molecules. The biomedical settlement simplifies the world by leaving social conditions to the side: treating tuberculosis in the individual with drugs alone, rather than treating the unsanitary conditions which incubate the bacteria in the first place. Likewise, anti-racist and feminist scientists have long wielded complexity to contest biological determinism. In the 1970s, the Black Panthers campaigned against a proposed research centre at UCLA, which would have studied violence as a biological phenomenon, one essential, perhaps, to Black people.[8] The Panthers argued instead, as historian Alondra Nelson puts it, that "violence was a symptom of societal dis-ease," a complex expression of racial capitalism rather than something biologically (or racially) essential. Ecologists and climate scientists, inheritors of the scientific mantle of complexity, have in turn been forced into the realm of politics by right-wing attacks on their work, and have pushed back against oversimplified carbon markets. There is a structural similarity between carbon markets and scientific racism and sexism: Hayek's complexity only works when it is built precisely out of the reductionisms critiqued by scientists and progressives alike.

Calling for complexity in the abstract, however, is not enough. Complexity is an idea that fits its time, one which everyone from Marxists to market fundamentalists find appealing. This makes it slippery. Though a Cartesian separation of nature and culture may be wrong, what replaces it could be worse. Hayek would be more than happy to kick the Scientific Revolution to the curb and resolve

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[8] The center, supported by Reagan, would have been led by an author of the 1970 book *Violence and the* Brain, which argued that psychiatric surgery could address irrepressibly violent tendencies in some (Black) individuals.

the nature-culture binary with his One Weird Trick to Complexify Anything. Far more important than critiquing the billiard-ball-world of the seventeenth century is making the case for the complexity we want, something more than obedience to markets.

What progressives usually mean when they talk about complexity is that the world is not set in stone. What we have inherited can be changed. Inequality, racism, and sexism can be confronted because they are not the results of our genes. The climate problem may be hard, but, if we transform the world, it can be solved. Progressive complexities tend towards liveliness, a vision of the world as energetic, unruly, exploding with possibilities radically different than what exists at present. This complexity is opposed to Hayek's image of a crystal, a vision of complexity that demands submission and obedience to market emergence.

In this way, and against Hayek, we must insist that planning and complexity are not opposed. In fact, planning is the original point of complexity. From Lorenz's coffee break insight, meteorologists have developed a system of planetary knowledge, where data from global networks of satellites, sensors, and models all feed into your phone to tell you, in real time, if you will need an umbrella. Complexity science has also developed tools, using the same global networks of information, that run the atmosphere backwards in time, detecting who is responsible for dumping new pollutants into the air. From this, much more is possible. Imagine something like a weather app but for social movements, alerting communities to airborne hazards in their neighborhoods, pointing a finger at who is responsible. Something like this already exists: a pilot initiative at the UN uses satellites to trigger methane alerts, with officials calling operators they suspect are responsible for major gas leaks within hours of detection. New forms of economic planning can emerge from this experiment, new possibilities of governing complex interactions between human and nonhuman systems that bypass markets entirely.

Predicting the transformations that could emerge from this vision of complexity, from this linking of complex natural and human systems, is impossible. But that is the point. Complexity science is not billiard ball science: it cannot promise perfect knowledge or tight control. As with the turbulent steam from my teacup—anything can happen.