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Greedy, Blind, and Stupid— And Not Especially Quick Either

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HIGHLIGHTS

The second law is exposed to be the 'Forrest Gump' and 'Gordon Gekko' of physical principles—but without a Hollywood ending.

INTRODUCTION

Sometimes Nature seems to have personality. One of its core traits, for instance, might be *economy*, as embodied in the *principle of least action*, a foundational idea for both classical and quantum physics. It appears *logical* and *aesthetic*, as shown by its beautifully interlocking laws and mathematical structure. Perhaps Nature is *amoral*, *indifferent to suffering*—maybe even *cruel*—as demonstrated through *natural selection*. When it comes to personal hygiene, however, there's no question: Nature is a slob. Sure, it produces examples of exquisite order (e.g., the symmetry of crystals, the intricate biochemistry of life), but beneath it all, supporting it, there's disorder and chaos everywhere, especially at the molecular level. There's even a law to enable this molecular malfeasance: the second law of thermodynamics. Nature's microscopic messiness is so widespread and universal, so overwhelmingly manifest in almost every action and system that the second law is often called the *supreme law of Nature*. There's no way to escape it, no means to undercut it, no scheme to bend, break, foil, or flummox it. Until now. This special issue of *JSE* is devoted to such systems. For insight into why the second law can be violated, let's look at it anthropomorphically, a tactic often used by scientists to describe and understand Nature intuitively, like one would an old friend. What are the second law's characteristics, propensities, and habits that set it up for failure? (After all, *character is fate*.) The short answer is this: The second law is greedy, blind, and stupid—and not especially quick either. This might seem flippant, but it's true. Let's unpack it.

Greedy

Like the oft-vilified (and sometimes admired) "corporate psychopath" Gordon Gekko in the movie *Wall Street*, with his signature line, "Greed is good," the second law is also greedy when it comes to entropy. Within the constraints imposed by the more foundational laws like conservation of energy, linear and angular momentum, charge, and within the physical limits set by local boundary conditions (e.g., walls, doors, membranes), the second law strives to maximize the entropy in any situation as fast as it can, like a flash trader who lives on short-term gains. The bigger the mess, the better. It just can't help itself.

It's a matter of probabilities. Consider a deck of cards, ordered by standard number and suit. This can be considered (arbitrarily) to be its state of least entropy (least disorder). Any rearrangement of the deck will only increase the deck's entropy. After the deck is shuffled a few times, it almost always ends up more disorganized, that is, less like the original, unshuffled deck. There are no new or special forces at play to make this happen, no conspiracy, no forethought, no malice or planning that goes into this; rather, it's simply a matter of probability: The deck changes its configuration with each shuffling, and there are far more ways for it become more disorganized than for it to become organized, therefore, probability favors disorder. That's it, mindless mayhem.

The condition at which a system's entropy is maximized is called thermodynamic equilibrium. (Distinctions between thermal, diffusive, and mechanical equilibria will not be made here.) Once a system arrives there, it is highly improbable—to the point of being effectively impossible—for it to leave that equilibrium state by itself because there are astronomically more microscopic configurations associated with its high-entropy equilibrium than there are low-entropy states out of equilibrium. The only way to get to a more ordered state involves the use of energy to push it away from equilibrium, but the use of energy generates more entropy. To be clear, almost every macroscopic process generates entropy and any attempt to reduce it by tidying things up inevitably generates more entropy. It's a no-win scenario, a thermodynamic Kobayashi Maru. Anthropomorphically, it's because the second law is greedy for entropy and just can't help itself.

This entropic greediness is quite dependable and, while it seems to guarantee the law's success, it also makes it predictable. This predictability, however, can be a liability under the right circumstances, an Achilles heel, because it's a hidden form of order that can be exploited by clever devices to undermine it. After all, if you can predict an opponent's behavior you have a better chance of defeating him. As Sun Tzu wrote in *The Art of War*, "If you know the enemy and know yourself, you need not fear the result of a hundred battles."

Thus, what is often regarded as the second law's highest virtue, its predictability—indeed, the attribute that elevates it to a law rather than just a handy rule of thumb—potentially holds a key to its own undoing. So, maybe greed is good sometimes, but not always. In the end, it wasn't great for Gordon Gekko—he went to jail—and, likewise, it isn't great for the second law either—it gets broken—just like the Kobayahsi Maru test.

Blind

The second law doesn't apply to individual particles, it's a collective law. The inexorable increase of disorder, ending at an equilibrium state of maximum entropy, emerges through the interactions of many individual particles acting independently. The second law can't be seen in the behavior of a single molecule any more than an ant colony can be understood by watching a single ant. Indeed, analogously to how tens of thousands of ants acting independently can form a highly organized antly society, the independent motions of sextillions of individual gas atoms can constitute a well-defined system called an *ideal gas*. The second law underwrites this: The gas fully fills its container, it uniformly spreads out, and quickly settles down to a uniform temperature, particle density, and pressure. This is the state of maximum possible entropy. The gas has extremely well-defined macroscopic properties, as exemplified by the ideal gas law ($PV = NkT$); however, no individual atom sees to this or even knows that it's part of the gas, or that it's governed by the second law. Likewise, the second law doesn't plan or understand what it's doing, nor can it see this outcome; it simply *does*. The second law is blind.

How blind? To get an idea, consider the following hypothetical scenario. Imagine a 10,000-megaton thermonuclear bomb. (This might be hard to imagine given that the largest bomb ever detonated, the USSR's Tsar Bomba, was 'only' about 60 megatons—yet still 3000 times more powerful than the ones that obliterated Hiroshima and Nagasaki—but in fact, the father of the US H-bomb, Edward Teller, did imagine building a 10,000-megaton thermonuclear bomb. Fortunately, no one else thought it was such a great idea.) Now let's say someone has their trembling finger poised a few microns over the bomb's detonation button—and let's hope it's not Edward Teller. The detonation of this 10,000-megaton thermonuclear bomb would certainly generate a hell of a lot of entropy—enough to truly overjoy some versions of the second law, while annihilating an area the size of Southern California—and all it would take would be for there to be a very slight fluctuation, a nearly imperceptual twitch of one little finger, to bring this about, perhaps just a few extra ions crossing an ion channel controlling a single muscle fiber. The potential entropy production hanging upon this tiny twitch is tremendous, but the second law is incapable of conceiving of it or affecting it. Instead, it just dithers about, making sure the air molecules around the finger are well mixed. This is because the second law cannot see more than one molecular collision ahead, one molecular vibration or energy transfer beyond where it currently is; it's fumbling about in the dark.

In summary, the second law is blind and cannot see the possibilities beyond the immediate, local microscopic domain of individual molecules. And it doesn't even bother to look. Flaw number two.

Stupid

The second law is dumber than a bag full of hammers—and Forrest Gump is its hero. It's so dumb that sometimes it's hard to tell whether it's being willfully ignorant, blind, or just plain stupid. (See H-bomb example above.) What is meant in this context, however, is that the second law has no memory, no ability to learn from mistakes, and no capacity to plan for the future. It lives and acts in the *eternal now*, which means that it can be tricked again and again—and again and again—by the same simple ruse. It never learns. As my mother used to say: *Fool me once, shame on you; fool me twice, shame on me*. Considering the second law's memory, this becomes: *Fool me once, shame on you. Fool me once, shame on you. Fool me once, shame on you. . . .* If thermodynamics were a chess game, the second law would be a player who moves his pieces about randomly, making a mess of the board, never plotting a strategy, never looking ahead or behind. Sure, for mindless molecular mayhem the second law can't be beat, but in organized games—like ones intelligent beings such as ourselves might cook up—the second law plays at a disadvantage. For us thermodynamicists, it's a matter of finding those games.

The second law's flaws—that it's dependably and predictably greedy for entropy production, that it can't see what it's doing, doesn't know what it's doing, can't remember what it's done, and can't plan what to do next—open the door to its manipulation and makes it an easy mark for scheming thermodynamicists.[1]

Not Especially Quick Either

Topping this off and making violations possible, the second law has another useful characteristic: It's not very quick. By this is meant not that it's stupid—we already know that—but instead that by most physical standards the second law achieves its ends relatively slowly as compared with other physical laws. Consider, for example, conservation of energy, momentum, or electric charge. These quantities are conserved in every known microscopic process down to sub-nuclear levels, as well as by every macroscopic process up to at least the scale of galactic superclusters. Because they are conserved at the very smallest length scales, they are conserved down to the smallest time scales, too. Not so with the second law.

As we've learned, the second law is a collective law, it is manifested only through the interactions of many particles. These collections can involve countless particles—quintillions of times more than the number of all the grains of sand on all the beaches in the world—and be spread over vast distances. (For example, electrical systems can be thermodynamically connected over thousands of kilometers by copper wires, or stellar nurseries might come to equilibrium over many light years distances over millions of years.) What this means is that significant time (and distance) scales can sometimes be involved for full satisfaction of the law, during which time (and space) the system is not at equilibrium and, therefore, is potentially ripe to have a bit of its energy siphoned off by a fast secondary process. Thus, if one operates cleverly within these nonequilibrium time (and distance) windows, the second law can be cheated. (It's like setting a trap for an opponent in chess—a game the second law can never master because it has neither the mind nor inclination for it.) In effect, you can steal a bit of energy *before the devil knows you're there*. You pick the second law's pocket so fast that it doesn't know it happened. Given how blind it can be, it might not notice, and even if it does, so what? It would forget its loss instantly. Thus, you can go on to cheat it again and again with the same thermodynamic ruse.

Many of the second law challenges documented in this special issue of *JSE* take advantage of these flaws. It is my belief that there are countless other possible devices that might foil it by such means. What has held us back thus far has been our collective scientific timidity and lack of imagination.[2] But these things can change, as the second law itself teaches. Now that we're in the throes of the Anthropocene Era, the stakes have never been higher that they do.

Come, Watson, come! The game is afoot!

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NOTES

1 For example, most second law violators run in thermodynamic cycles, converting ambient heat into work. Because such a device consumes thermal energy (heat), it cools relative to its environment. But as the Clausius form of the law states, heat runs from hot to cold, therefore, the environment naturally supplies heat to a violator to keep it warm—and running. (This also maximizes entropy production.) To my knowledge, every violator relies heavily on the second law—right up to moment that it bamboozles it, and usually even after. Thus, with its thoughtless, blind, and forgetful greed, the second law abets its own undoing.

2 Those who read between the lines might see that this essay is as much a critique of the scientific community as it is one of the second law.