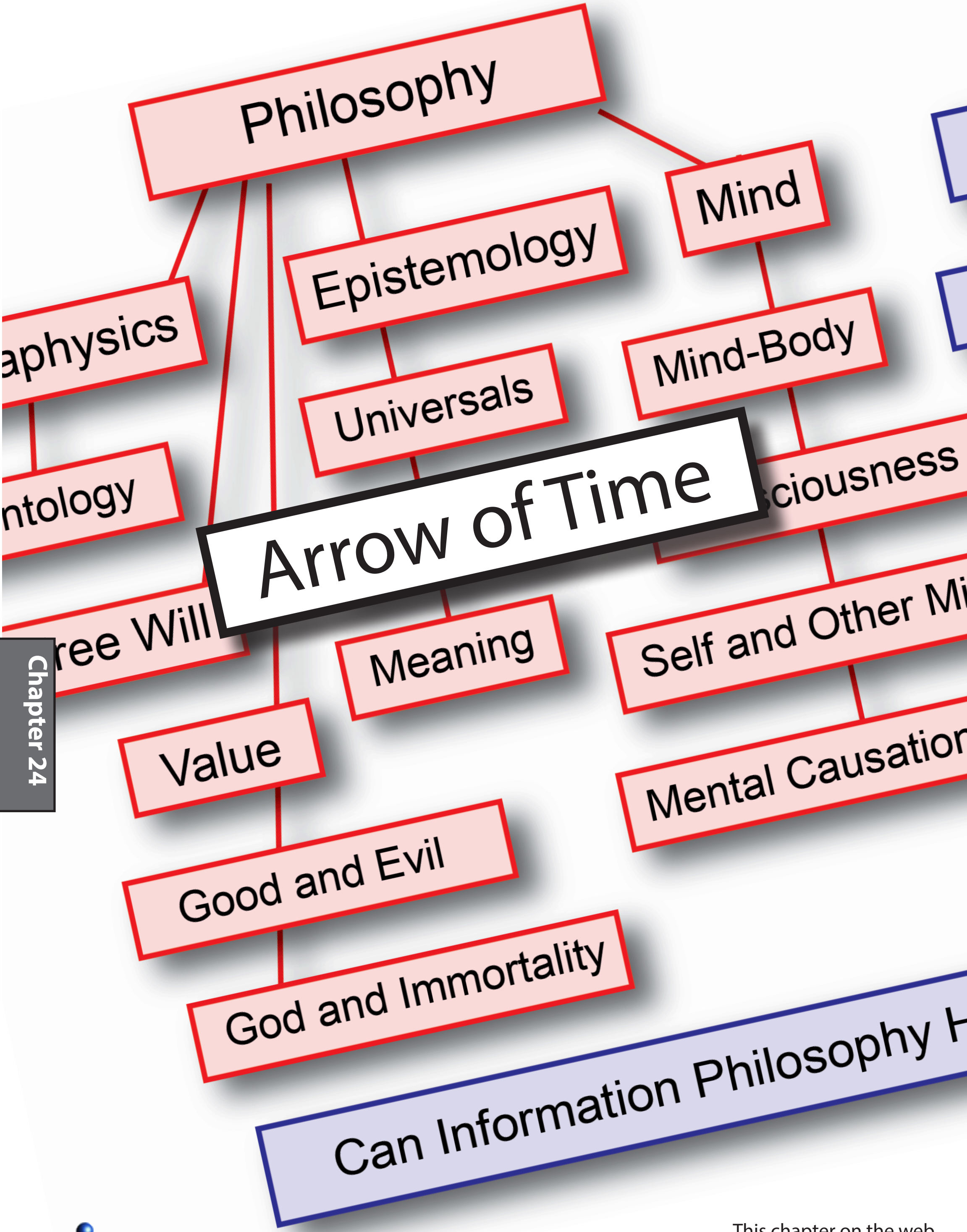
Chapter 24

Arrow of Time



This chapter on the web
informationphilosopher.com/problems/arrow_of_time

The Arrow of Time

The laws of nature, except the second law of thermodynamics, are symmetric in time. Reversing the time in the dynamical equations of motion simply describes everything going backwards. The second law is different. Entropy must never decrease in time, except statistically and briefly, as Ludwig Boltzmann showed.

Many natural processes are apparently irreversible. Irreversibility is intimately connected to the direction of time. Identifying the physical reasons for the observed irreversibility, the origin of irreversibility, would contribute greatly to understanding the apparent asymmetry of nature in time, despite nature's apparently perfect symmetry in space.[1]

The Thermodynamic Arrow

In 1927, Arthur Stanley Eddington coined the term "Arrow of Time" in his book *The Nature of the Physical World*. He connected "Time's Arrow" to the one-way direction of increasing entropy required by the second law of thermodynamics.[2] This is now known as the "thermodynamic arrow."

In his later work, Eddington identified a "cosmological arrow," the direction in which the universe is expanding,[3] which was discovered by Edwin Hubble about the time Eddington first defined the thermodynamic arrow.

There are now a few other proposed arrows of time, including a psychological arrow (our perception of time), a causal arrow (causes precede effects), and a quantum mechanical arrow (electroweak decay asymmetries). We can ask whether one arrow is a "master arrow" that all the others are following, or perhaps time itself is just a given property of nature that is otherwise irreducible to something more basic, as is space.

Given the four-dimensional space-time picture of special relativity, and given that the laws of nature are symmetric in space, we may expect the laws to be invariant under a change in time direction. The laws do not depend on position in space or direction,

---

[1] See chapter 25.

[2] Nature of the Physical World, 1927, p.328-9

[3] New Pathways in Science, 1937, p.328-9

they are invariant under translations and rotations, since space is seen to be uniform and isotropic. But time is not just another spatial dimension. It enters into calculations of event separations as an imaginary term (multiplied by the square root of minus 1). Nevertheless, all the classical dynamical laws of motion are symmetric under time reversal.

So the basic problem is - how can macroscopic irreversibility result from microscopic processes that are fundamentally reversible?

Long before Eddington, scientists asked deep questions about the direction of time. Perhaps the first to explore the connection with physics was Boltzmann, who with JAMES CLERK MAXWELL investigated the statistical motions of the atoms and molecules of gases.

If the laws of nature are time symmetric, perhaps the "arrow of time" is to be found in the "initial" conditions, although this may be a circular concept, since "initial,"current," and "final" states are all defined with respect to time. Since the dynamical laws are time reversible, scientists as early as ISAAC NEWTON understood that one could calculate all the motions of a system by assuming "final conditions" and working backwards in time.

Nevertheless, many if not most physicists have assumed the universe must have begun in a highly ordered (low entropy) state and it has been "running down" (entropy or disorder increasing) ever since. In the nineteenth century, this was called the "heat death" of the universe. This view has the unfortunate implication that all the information in the current universe was present at the beginning, which is friendly to some theological ideas like predestination, but distinctly unfriendly to ideas of human free will.

Boltzmann assumed that the universe was infinitely old and that our current state is the consequence of a massive statistical fluctuation away from equilibrium and maximum entropy, a condition to which we must ultimately return.

Would time itself be reversed if we could make the entropy decrease? That is unlikely, since entropy decrease anywhere (creating negative entropy or negentropy, a term coined by LEON

Brillouin) must be accompanied by an increase elsewhere, to satisfy the second law. Otherwise we could use the local reduction in the entropy to build a perpetual motion machine.

Put another way, if we could reverse the time, would entropy decrease? What can time reversal really mean? A thought experiment suggests not. Consider a closed perfume bottle inside a large empty container. Remove the bottle top and what would happen assuming that time is flowing backwards? It seems likely that the perfume molecules would leave the bottle whatever time is doing.

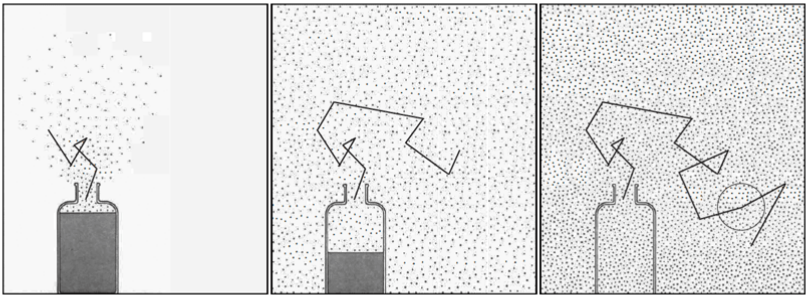


Figure 24-29. Information physics has shown that at each collision of a gas particle with another particle, the path information of where that particle has been is erased, so that time reversal would not return all the perfume to the bottle. .

For Aristotle, time was a measure of motion and change and for practical purposes, many scientists have thought that time reversal can be approximated by the reversal of all the velocities or momenta of material particles at an instant, starting from their current positions.

If we could perfectly reverse the motions of every material body (a practical impossibility, and perhaps a violation of Heisenberg's uncertainty principle), would that make the entropy decrease? Boltzmann agreed that it might, but only for a while. His intuition was that a system could not return to a highly ordered original state, such as every molecule getting back in the perfume bottle.

J. Willard Gibbs thought otherwise, if the detailed path information in all the macroscopic motions is still available as microscopic information (if information is a conserved quantity), then reversal of all the motions should be exactly like a movie played backwards.

The fundamental question of information philosophy is cosmological and ultimately metaphysical. What is the process that creates information structures in the universe?

Given the second law of thermodynamics, which says that any system will over time approach a thermodynamic equilibrium of maximum disorder or entropy, in which all information is lost, and given the best current model for the origin of the universe, which says everything began in a state of equilibrium some 13.75 billion years ago, how can it be that living beings are creating and communicating new information every day? Why are we not still in that state of thermal equilibrium?

It is perhaps easier for us to see the increasing complexity and order of information structures on the earth than it is to notice the increase in chaos that comes with increasing entropy, since the entropy is radiated away from the earth into the night sky, then away to the cosmic microwave background sink of deep space.

DAVID LAYZER is a Harvard cosmologist who in the early 1970's made it clear that in an expanding universe the entropy would increase, as required by the second law of thermodynamics, but that the maximum possible entropy of the universe might increase faster than the actual entropy increase. This would leave room for an increase of order or information at the same time the entropy is increasing![4]

Layzer pointed out that if the equilibration rate of the matter (the speed with which matter redistributes itself randomly among all the possible states) was slower than the rate of expansion, then the "negative entropy" or "order" (defined as the difference between the maximum possible entropy and the actual entropy) would also increase. CLAUDE SHANNON identified this negative entropy with information, though visible structural information in the universe may be much less than this "potential" information.

---

[4] See appendix B for more on Layzer's work.

The Historical Arrow

Layzer called the direction of information increase the "historical arrow." In a 1975 article for *Scientific American* called “The Arrow of Time,” he wrote:

> the complexity of the astronomical universe seems puzzling. Isolated systems inevitably evolve toward the featureless state of thermodynamic equilibrium. Since the universe is in some sense an isolated system, why has it not settled into equilibrium? One answer, favored by many cosmologists, is that the cosmological trend is in fact toward equilibrium but that too little time has elapsed for the process to have reached completion... I shall argue that this view is fundamentally incorrect. The universe is not running down, and it need not have started with a marked degree of disequilibrium; the initial state may indeed have been wholly lacking in macroscopic as well as microscopic information.
>
> Suppose that at some early moment local thermodynamic equilibrium prevailed in the universe. The entropy of any region would then be as large as possible for the prevailing values of the mean temperature and density. As the universe expanded from that hypothetical state the local values of the mean density and temperature would change, and so would the entropy of the region. For the entropy to remain at its maximum value (and thus for equilibrium to be maintained) the distribution of energies allotted to matter and to radiation must change, and so must the concentrations of the various kinds of particles. The physical processes that mediate these changes proceed at finite rates; if these "equilibration" rates are all much greater than the rate of cosmic expansion, approximate local thermodynamic equilibrium will be maintained; if they are not, the expansion will give rise to significant local departures from equilibrium.[5]

This is Layzer's seminal theory of the *growth of order* in the universe These departures represent macroscopic information; the quantity of macroscopic information generated by the expansion is the difference between the actual value of the entropy and the theoretical maximum entropy at the mean temperature and density.

---

[5] Scientific American, December, 1975, p.68

In his 1989 book *The Emperor's New Mind*, Roger Penrose speculated on the connection between information, entropy, and the arrow of time.

> Recall that the primordial fireball was a thermal state — a hot gas in expanding thermal equilibrium. Recall, also, that the term 'thermal equilibrium' refers to a state of maximum entropy. (This was how we referred to the maximum entropy state of a gas in a box.) However, the second law demands that in its initial state, the entropy of our universe was at some sort of minimum, not a maximum!
>
> What has gone wrong? One 'standard' answer would run roughly as follows:
>
> True, the fireball was effectively in thermal equilibrium at the beginning, but the universe at that time was very tiny. The fireball represented the state of maximum entropy that could be permitted for a universe of that tiny size, but the entropy so permitted would have been minute by comparison with that which is allowed for a universe of the size that we find it to be today. As the universe expanded, the permitted maximum entropy increased with the universe's size, but the actual entropy in the universe lagged well behind this permitted maximum. The second law arises because the actual entropy is always striving to catch up with this permitted maximum.[6]

Penrose's "standard" answer is a clear reference to the pioneering work of David Layzer.

The Radiation Arrow

Whether they be electromagnetic waves or waves in water, we only observe wavelike disturbances that propagate outwards in space away from the disturbance. These waves are described by what is called the retarded potential. In his 1909 discussion of waves and particles, Albert Einstein described the very remote possibility of incoming spherical waves:

> According to our prevailing theory, an oscillating electron generates a spherical wave that propagates outwards. The inverse process does not exist as an elementary process. A converging spherical wave is mathematically possible, to be sure; but to approach its realization requires

---

[6] *The Emperor's New Mind*, p.328-9

> a vast number of emitting entities. The elementary process of emission is not invertible. In this, I believe, our oscillation theory does not hit the mark. Newton's emission theory of light seems to contain more truth with respect to this point than the oscillation theory since, first of all, the energy given to a light particle is not scattered over infinite space, but remains available for an elementary process of absorption.[7]

In 1945, John Wheeler and his student Richard Feynman attempted to symmetrize Maxwell's equations for electromagnetic fields with an "Absorber Theory of Radiation," that combined retarded potentials (outgoing spherical waves) and advanced potentials (incoming spherical waves) for radiation. They later described the theory as a mistake. There are no incoming spherical waves.

The Cosmological Arrow

We can define a cosmological direction of time as the direction in which the universe is expanding. There are excellent reasons for seeing this as the most fundamental of all arrows, even the one driving some of the others. Without expansion, a static universe would settle into thermal equilibrium and there would be no changes. There would be no entropy increase to show Eddington's thermodynamic arrow. There would be no information increase, as seen in Layzer's historical arrow.

Without the cosmological arrow, the thermodynamic, radiation, and historical arrows could not have been realized.

---

[7] "On the Development of Our Views Concerning the Nature and Constitution of Radiation," *Einstein Collected Papers*, vol.6, p.213