1 Arrows of Time

There are roughly 7 arrows of time: 1) Entropic: destruction of macroscopic order in a closed system increases the entropy, 2) Cosmological: the universe is expanding, 3) biological: life begins at birth and ends at death, 4) psychological: we remember the past not the future, 5) radiative; EM radiation is determined from the source not the target, 6) black holes: there are no time reverse equivalents of black holes, known as white holes, that exist, 7) weak nuclear force is not reversible. Simply stated, the arrow time problem is stated in the following syllogism: A.) Natural processes have natural explanations, B.) 1-7 are all natural processes, C.) Hence, 1-7 have natural, that is, law-like explanations. All of these processes is irreversible and hence, there must be some sort of natural explanation that accounts for them. Let's see if we can deduce this from the laws of physics.

- Classical Mechanics $F = ma$ is perfectly reversible because the acceleration depends on the second derivative of the position with respect to time. Since the time is squared, $t = -t$ causes no change.

- Electricity and Mechanics

  The basic equation for the magnetic force is $\mathbf{F} = \mathbf{v} \times \mathbf{B}$. Since $\mathbf{B}$ is linear in the velocity $\mathbf{v}$, the magnetic force is perfectly reversible in time.

- Quantum Mechanics

  The basic equation is the Schrödinger's.

  $$H\psi = i\hbar\partial_t\psi, \tag{1}$$

  with H the Hamiltonian, and ψ the wavefunction, which is in general complex. Time reversal in quantum mechanics is obtained by sending $t \to -t$ and taking the complex conjugate. Since the Hamiltonain is invariant subject to complex conjugation, nothing changes in Schrödinger's equation.

- Nuclear Forces The theory of subatomic particles, quantum field theory, makes a rather extraordinary claim: the laws of nature should be invariant under the combination of three operations: change the sign of all the charges or more generally convert every particle to its anti-particle (C) , invert space, known as parity (P), and time reversal (T). This is known as CPT symmetry. Nonetheless, there are some cases in which CP can be violated. Hence, if one adopts the CPT theorem, then T invariance is only approximately true. This effect is weak, however. Nonetheless, elementary particles can tell left from right. Does this manifest itself on a macroscopic level? Probably not.

- Weak Interaction

  Any asymmetry here is traced to the initial not to the final state. So the answer lies elsewhere.

So where does the asymmetry in time come from? Why is it that when we run a movie backwards, we can distinguish it from the forward version? This is the arrow of time problem?

2 Boltzmann

Boltzmann claimed that our intuitive sense of the arrow of time is grounded in the entropic asymmetry. That is, because

$$\Delta S \geq 0 \tag{2}$$

for an isolated system (S the entropy) we have an ability to distinguish past from future. Precisely what this means and what Boltzmann had in mind is the subect of this lecture. Boltzmann attempted to prove this using the kinetic theory of gases. There is a problem, as pointed by Loschmidt, in doing this. Consider two equilbrium states a and b. Let an isolated system evolve from a to b. By Boltzmann, it must be the case that $S(b) > S(a)$. But by reversibility, there must be an antithermodynamic pathway in which the system evolves from b' to a' but the entropy at b' is $S(b)$ and the entropy at a' is $S(a)$. This contradicts the increase of entropy rule. The problem is that irreversibility cannot be proven from equations that are strictly reversible. There is no law-like basis for it. Boltzmann assumed that the motion of the gas particles was uncorrelated. There is no basis for this.

So what does Boltzmann's statement mean? Consider two options: 1) TIme is asymemtric and 2) Systems in time behave asymmetrically. As Sklar points out, those who argue for the latter point to the deep nature of the asymmetry, in particular examples in which the asymmetry is not generated by laws of nature. Only a law-like asymmetry could lead to asymmetry of time itself. None seems to be available except CPT violation. However, this asymmetry really has nothing to do with the macroscopic asymmetry of time's arrow. Or at least , it is highly unlikely that this law-like nature ofthe asymmetry of time has anything to do with time's arrow. However, we could just posit asymmetries of spacetime itself. In the context of inertial frames, one of the options was simply to posit that certain inertial frames are brute facts of nature. In this case, it is unclear what this would entail.

What we need to do is understand what Boltzmann has in mind by grounds our understanding of the asymmetry of time and that ground being the entropy. Rarely do we tell the time by checking the entropy. So what does Boltzmann have in mind? Consider up and down and gravity. Every fact of up and down is captured by gravity. Subtract gravity and there is no distinction between up and down. Hence, gravity is both necessary and sufficient to explain up and down. That is, the gravity offers a compete explanatory account of up and down. Now is this the sort of equivalence that exists between entropy and the arrow of time. This is similar to the issue of handedness and parity conservation at the atomic level but quite different from a theory of light and a theory of electricity and magnetism.

Boltzmann claims that when there is no local entropic asymmetry, no future-past distinction exists. Does this make sense? In fact, Boltzmann would maintain that our memory is always of the events that have the lower entropy regardless of the direction of the arrow of time. So according to Boltzmann, the future direction of time is simply the direction that we label the increasing entropy direction to be in. Reichenbach shifts the emphasis to macroentropy. Macroentropy is associated with the kind order that distinguishes an orderly arrangement of objects from a disorderly one. So if you walk into a room and see a mess, you know that at some point in the past , the room was orderly or at least not in its present state. He argues that low macroentropy is likely not to be a spontaneous change in an isolated system but some sort of intervention by an outsider. This is similar to the argument for intelligent design. Footprints on the beach imply someone was there. This formulation is a bit problematic because thinking about the macroentropy involves categorizing parts of the system into natural and unnatural parts.

So what do we make of Boltzmann? Really what Boltzmann is saying is that the increase in entropy and the future are synonymous. Now do we make an identity statement here? Recall when we say A=B we must be equating items of the same kind. Edington argued that whatever the relationship between increase in entropy and future directions cannot be one of identity because we know what it is for one event to follow another and we know what it is for entropy to increase. The two do not feel the same. More explicitly, we know what 'afterwardness' is like. We also know what is entailed by one state having more entropy than another. These two relationships do not seem to be the same. Hence, they are not . This is similar to the consciousness debate. We know what mental events are and we know what physical events are . The two do not seem to be the same. To quote Sklar, 'the temporal relations among events in the world is a genuine feature of the events involved. This is the same kind of temporality that relates the events of imediate experience to one another.' Hence, any explanation of the arrow of time based on the entropy is a non-starter because it does not have the temporality of events as an intrinsic feature. Rather, it is a secondary property.