Physics, Time and Determinism

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Free will and determinism

Some definitions:

1. **Free will is the capacity of an agent to chose a particular outcome**
2. **Determinism is the notion that all events are fixed in one and only one way**

A little thought should convince you that (1) above is rather tricky to specify.

The early notions of free will

Theological origin:

The Problem of Evil

1. God is omnipotent
2. God is all good
3. There is evil in the world

God cannot remove evil → God is not omnipotent

God does not wish to remove evil → God is not all good

Possible answer:

God gives us free will so that we may chose between good and evil

The early notions of free will

BUT this still leaves us with a problem

1. God is omniscient

Therefore God knows everything that we will do (and who will get into Heaven).

If God knows everything that we will do, then everything we will do must be fixed. Thus, we cannot have free will.

Determinism

All things being fixed is DETERMINISM.

Philosophical notions of free will and determinism:

1. **Incompatibilism – free will is incompatible with determinism**
2. **Compatibilism – free will is compatible with determinism**

(2) is rather odd – it appears to rely on the difficulty of defining 'free will' meaningfully.

We shall just concern ourselves with the notion of determinism.

Types of determinism

1. **'Mechanical' determinism – determinism arises through the all physical entities following immutable laws of physics**
2. **'Quantum' determinism – the <u>probabilities</u> of outcomes evolve according to deterministic laws**
3. **Arbitrary determinism – all events are fixed in possibly arbitrary ways**

An example of (3) would be the existence of four dimensional spacetime in which all events (points in the continuum) were fixed.

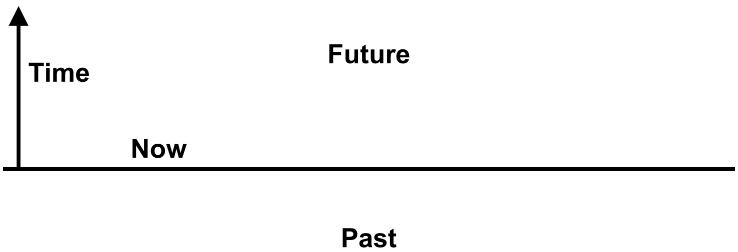
The ‘now’ moment

Our notions of free will are very much tied up with our perception of time

In particular, we continually distinguish a particular time, which we call the ‘now’ moment as being special.

Past, present and future

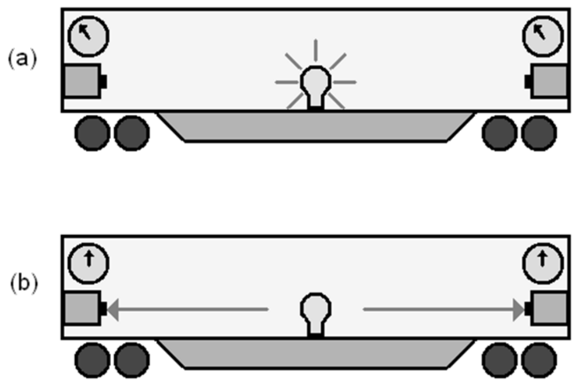
According to our perception, the ‘now’ moment demarks ‘what has happened’ (the past) from ‘what will happen’ (the future).



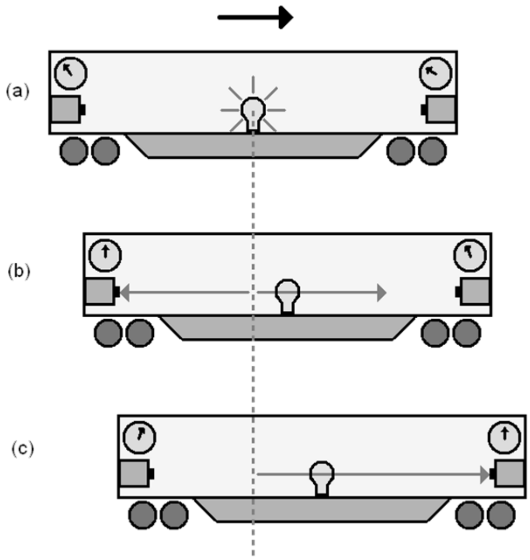
An important point here is that we have direct knowledge (memories) of the past but no direct knowledge of the future.

Special Relativity

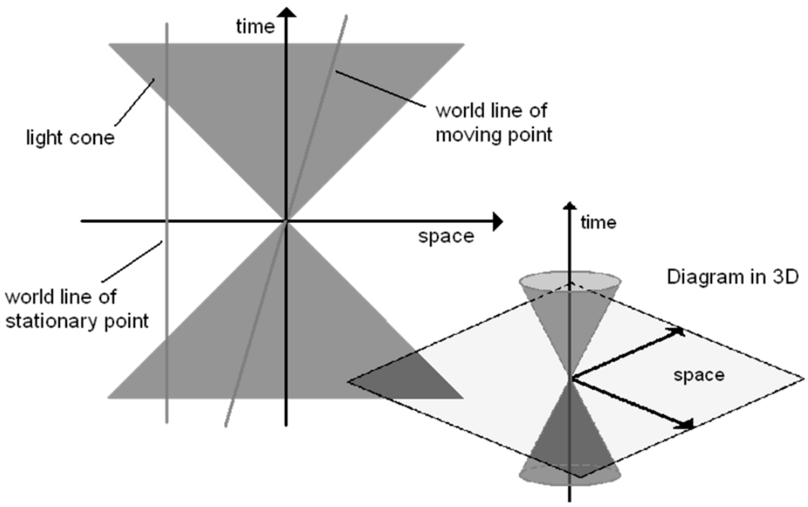
The relativity of simultaneity



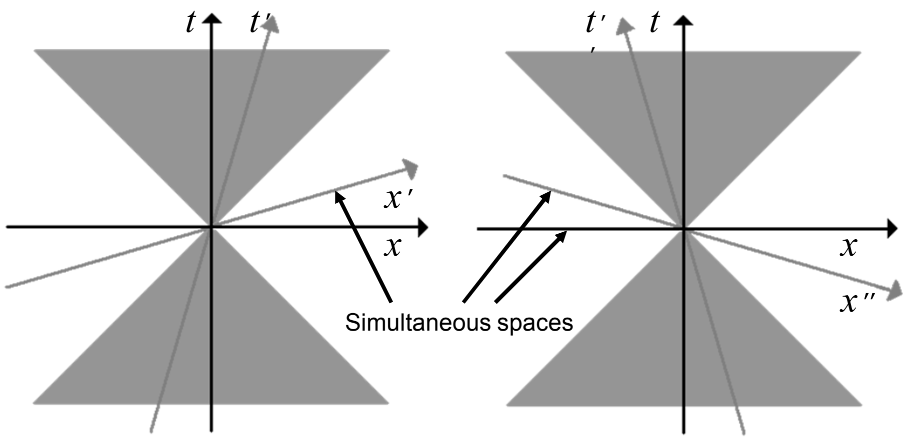
The relativity of simultaneity



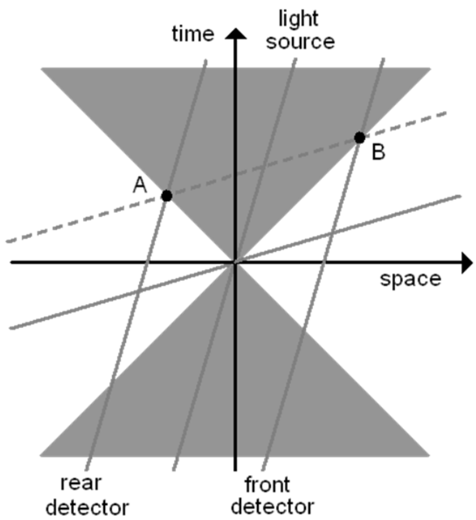
Spacetime diagrams



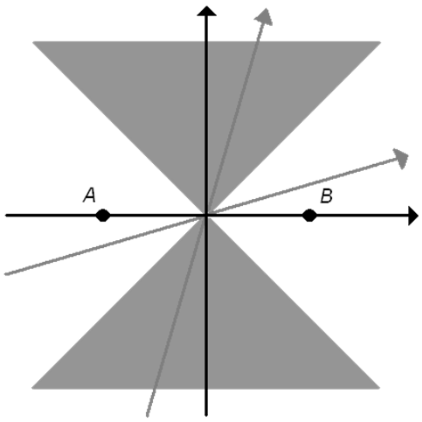
The relativity of simultaneity



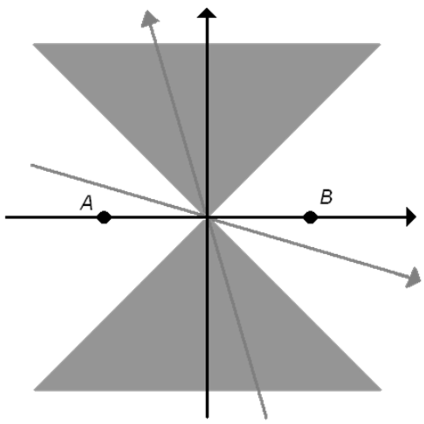
The relativity of simultaneity



The ordering of events



A is in the ‘future’, B is in the ‘past’.



A is in the ‘past’, B is in the ‘future’.

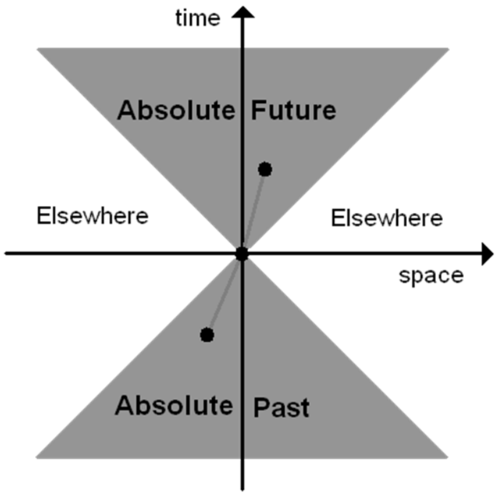
No universal ‘now’ moment

Conclusions so far:

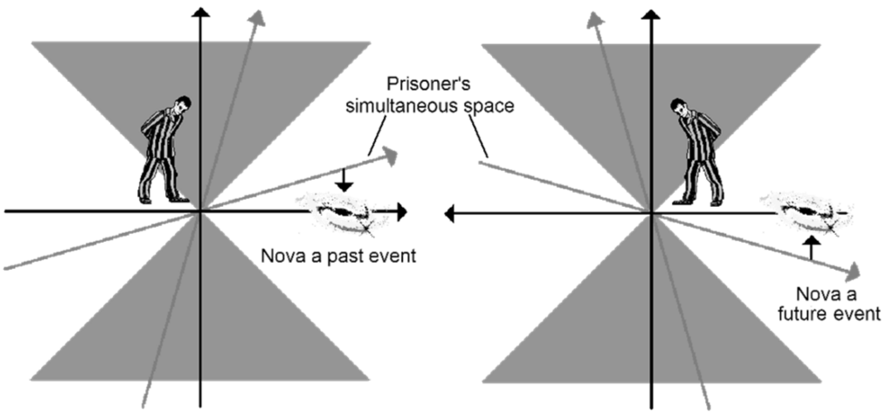
1. **There is no absolute ‘now’ moment common to all observers**
2. **Different observers order events differently**
3. **If the ordering of two events is mutable, they cannot be considered as ‘cause’ and ‘effect’**

Does Special Relativity actually undermine our notion of causality? In fact, NO, since events within a light cone have the same ordering for all observers.

Absolute past and present



The pacing prisoner



Possible explanations

1. All events are fixed – there is only a confusion of language of tense, e.g. ‘has happened’.
2. Some events are not yet fixed – we shall term this ‘open’.
3. Spacetime is not objectively real – it is just a mathematical framework that fits observation.

Case (3) requires rather more thought than we have time for. For now, we shall just consider case (2).

The ‘continuity of existence’

Let us allow that, according to an observer at a particular point in spacetime, other events may be open.

What if there is an observer at this other point? Does this observer cease to exist until there is a causal connection between him or her and the first observer?

Such a situation would describe a kind of solipsism in which there is only one observer. This, in itself, goes against Special Relativity, since it is singling out a particular point in spacetime (or points along a world line) as being special.

The ‘continuity of existence’

If we reject solipsism, then, unless all events are fixed, this seems to imply something like a many-worlds interpretation

We would more typically encounter this as a (controversial) interpretation of quantum mechanics

A Principle of Universality

Let us explore the notion of ‘fixed’ or ‘open’ events a little more systematically.

First we assert a Principle of Universality

No events are special – whatever properties are taken to be true of one event must be true for all events

Transitivity

Let us introduce the notation

$$A \rightarrow B$$

to mean

'B is fixed according to A'

We now assume that this relationship is <u>transitive</u>. That is,

$$\textbf{if } (A \rightarrow B) \textbf{ and } (B \rightarrow C), \textbf{ then } (A \rightarrow C).$$

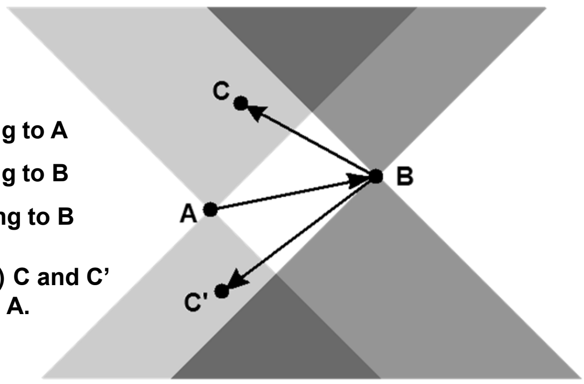
'Fixed' and 'open' events

B relative to A

Case	abs. past	abs. future	Elsewhere	transitive?
1	O	O	O	✓
2	O	O	F	
3	O	F	O	
4	O	F	F	
5	F	O	O	
6	F	O	F	
7	F	F	O	
8	F	F	F	✓

‘Fixed’ and ‘open’ events

Assumption: events in Elsewhere fixed



1. **B is fixed according to A**
2. **C is fixed according to B**
3. **C’ is fixed according to B**

Therefore (transitivity) C and C’ are fixed according to A.

Since we could pick *any* point B in elsewhere such that any point in the light cone of A was fixed, we conclude that

If events in Elsewhere are fixed, then all events are fixed.

‘Fixed’ and ‘open’ events

B relative to A

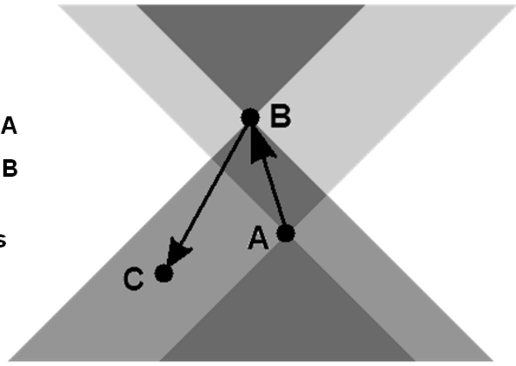
Case	abs. past	abs. future	Elsewhere	transitive?
1	O	O	O	✓
2	O	O	F	X
3	O	F	O	
4	O	F	F	X
5	F	O	O	
6	F	O	F	X
7	F	F	O	?
8	F	F	F	✓

‘Fixed’ and ‘open’ events: case 7

Assumption: all events in light cone fixed

1. **B is fixed according to A**
2. **C is fixed according to B**

Therefore (transitivity) C is fixed according to A.



Hence, if all events in the light cone of an event are fixed, then all events are fixed according to it.

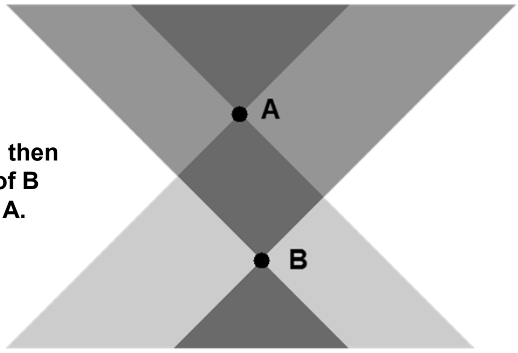
‘Fixed’ and ‘open’ events

B relative to A

Case	abs. past	abs. future	Elsewhere	transitive?
1	O	O	O	✓
2	O	O	F	X
3	O	F	O	?
4	O	F	F	X
5	F	O	O	?
6	F	O	F	X
7	F	F	O	X
8	F	F	F	✓

‘Fixed’ and ‘open’ events: case 7

Assumption: only events in the absolute past are fixed



If B is in the absolute past of A, then all events in the absolute past of B are also in the absolute past of A.

Hence, any event fixed according to B is also fixed according to A, so transitivity holds.

(The same consistency with transitivity is also found if only events in the absolute future of an event are fixed).

‘Fixed’ and ‘open’ events

B relative to A

Case	abs. past	abs. future	Elsewhere	transitive?
1	O	O	O	✓
2	O	O	F	X
3	O	F	O	✓
4	O	F	F	X
5	F	O	O	✓
6	F	O	F	X
7	F	F	O	X
8	F	F	F	✓

‘Fixed’ and ‘open’ events

Four possible scenarios:

1. **All events open (no causality at all)**
2. **All events fixed (complete determinism)**
3. **Only events in the absolute future of an event are fixed**
4. **Only events in the absolute past of and event are fixed**

Case 1 represents an unobservable Universe, since nothing determines anything else.

Cases 3 and 4 would seem to require multiple universes

‘Fixed’ and ‘open’ events

Of the four possible scenarios, consider:

1. **Only events in the absolute future of an event are fixed**
2. **Only events in the absolute past of and event are fixed**

The fact that both of these scenarios pass the test of transitivity may be taken as an example of the time symmetry of Special Relativity. That is, the physics works just as well in one temporal direction as the other.

Time symmetry

Why, then, do we have the subjective sense of the 'present' moment?

Why do we have the sense of the past and future being different to one another?

Are all of the Laws of Physics time symmetric?

(Quick answer: No!)

Entropy

The perception of time

Our subjective sense of the 'present' moment has one obvious explanation: memories.

We have information about the past (i.e. memories) but no (experiential) information about the future.

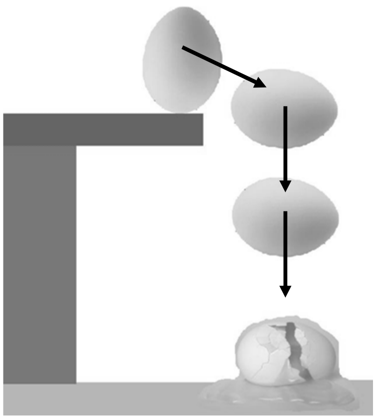
The 'now' moment demarks the two realms – what we know of from what we do not know of.

So why don't we have memories of the future?

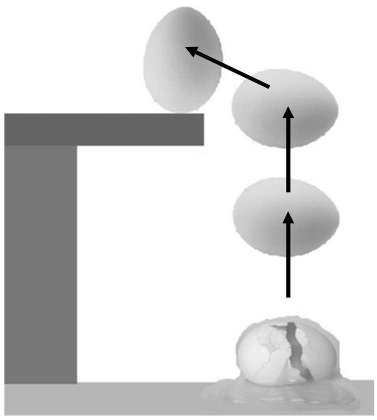
(speculative explanation to follow! First, a little thermodynamics...)

Time's arrow

Despite the time symmetry of the Laws of Mechanics...



Common sequence of events



Never happens!

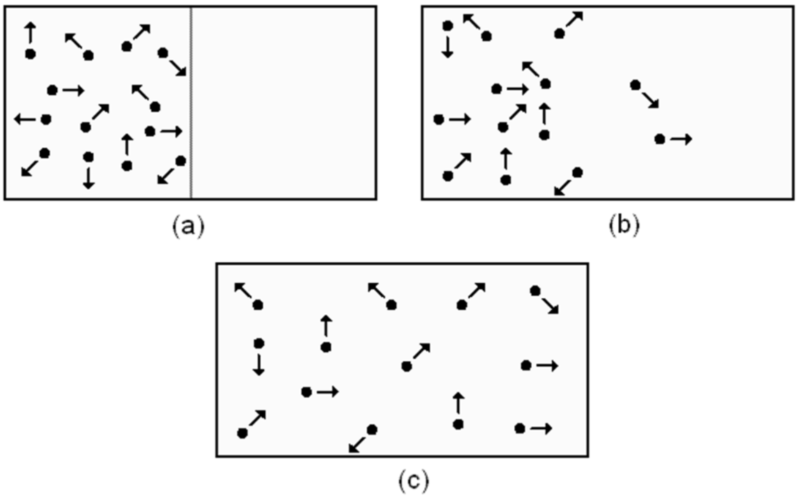
Irreversible processes

Processes that occur in one temporal direction but never in the other are called

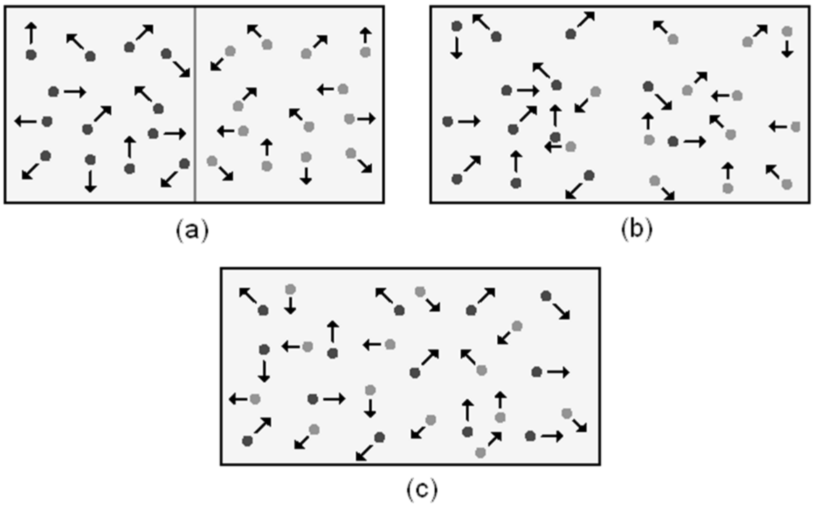
Irreversible processes

The breaking egg is one example. More examples to follow...

Free expansion



Heat transfer



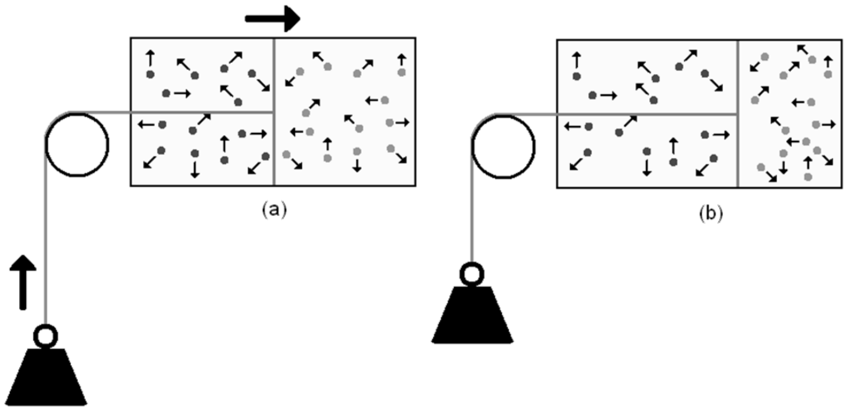
Entropy

The entropy of a system may be defined as

A measure of the unavailability of the system's energy to do work

Let us see why...

Work



Entropy and probability

Entropy is often described in terms of 'disorder' – an association fraught with misconceptions!

Instead, let us consider entropy in terms of probability.

First, we need to define a couple of terms:

1. **The macrostate of a system is the state of the system that can be specified in terms of macroscopic observables (such as pressure and temperature)**
2. **The microstate of a system is the state of the system that might be specified in terms of microscopic observables (e.g. position and momentum of each atom)**

Macrostates and microstates

One conclusion may be drawn with only a little thought

1. **The same macrostate (i.e. a state with the same values for the macroscopic system observables) may manifest from many different microstates.**

We might define the probability of a particular macrostate *i* **along the lines**

$$P_i = \frac{\textit{No. microstates of i}}{\textit{Total no. microstates of system}}$$

Macrostates and microstates

From this definition, we can may say

1. **Entropy is a measure of the probability of a macrostate.**

(Using the term 'disorder' we would say that a state of high disorder has a high probability).

For two macrostates *i* **and** *j*, **we would have**

$$\frac{P_i}{P_j} = \frac{\textit{No. microstates of i}}{\textit{No. microstates of j}}$$

which we may interpret as a measure of the change in entropy between *i* **and** *j*.

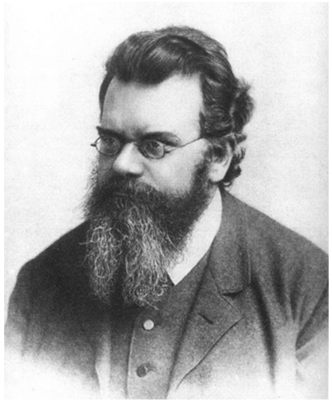
Boltzmann's Equation

Denoting the change in entropy by ΔS, we might then render this in the form

$$\Delta S = k \ln \frac{P_i}{P_j}$$

where k is a constant. This is in the same form as Boltzmann's equation for entropy

$$S = k_B \ln W$$



Ludwig Boltzmann

(1844 – 1906)

where k_B is a Boltzmann's constant and W is the number of microstates associated with the macrostate.

Entropy and the arrow of time

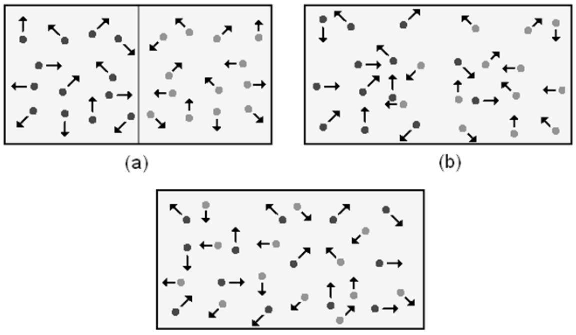
We now arrive at a very important observation. It is so important, that it is enshrined as the Second Law of Thermodynamics. Roughly, this may be expressed as*

The entropy of a system never decreases with time

***we would have to introduce a little more jargon to make this a truly accurate statement of the Second Law.**

Entropy and irreversible processes

We should note that, in particular, the entropy after an irreversible process has always increased.



For example, there are more microstates associated with macrostate (c) than macrostate (a) (this may require some thinking about).

Entropy and probability again

So why should entropy increase with time? Let us address the simpler question of why the entropy increases with change.

1. A system evolves from one microstate to another spontaneously
2. We assume that the probability of any particular microstate is the same
3. Therefore the system is more likely to evolve to a macrostate with many microstates than one with few. In other words, the system evolves to the macrostates with the highest probability.

Note that this does not explain the particular direction of time that entropy increases in. We shall address this shortly...

Tendency to lower potential energy

Another related observation is that

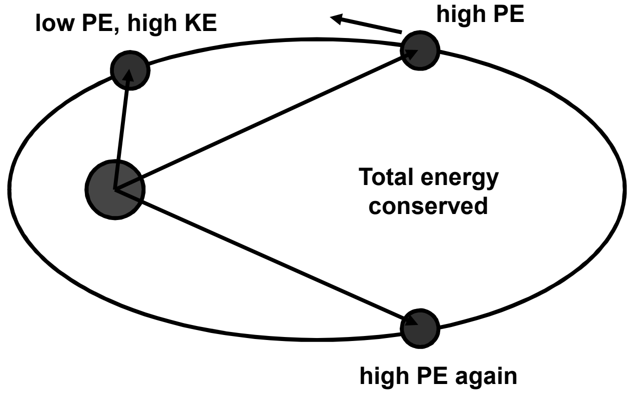
Systems have a tendency to lower their potential energy with time

Why should this be?

Is this related to the Second Law and, if so, how?

Example from Classical Mechanics

Planetary orbit



In this system, there is no overall lowering of potential energy

Example from Classical Mechanics

But if this were always the case, how would planets form in the first place?

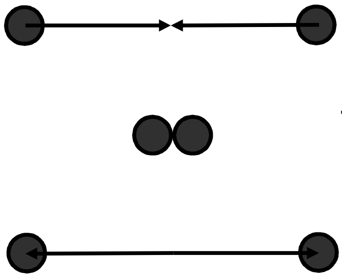
Consider an elastic collision

initial PE

minimum PE

Total energy conserved

PE = initial PE



Again, no overall lowering of potential energy. Moreover, no <u>aggregation of the matter</u>.

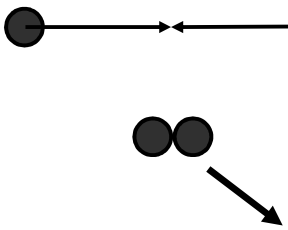
Example from Classical Mechanics

Consider now an inelastic collision

initial PE

minimum PE

Energy dissipated to environment

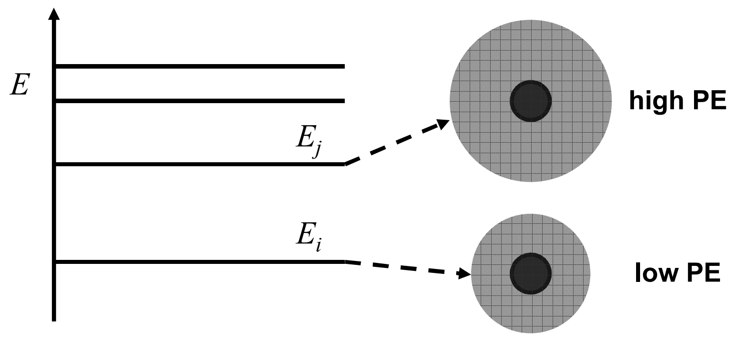


In this process, there <u>is</u> an overall lowering of the potential energy, with the difference being dissipated to the environment

Note also that this is an irreversible process.

A little Quantum Mechanics

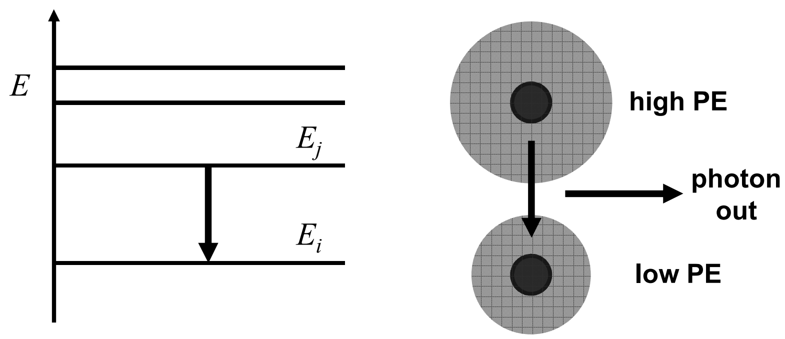
Consider the electronic energy levels in an atom



We have discrete energy levels corresponding to different electronic configurations.

A little Quantum Mechanics

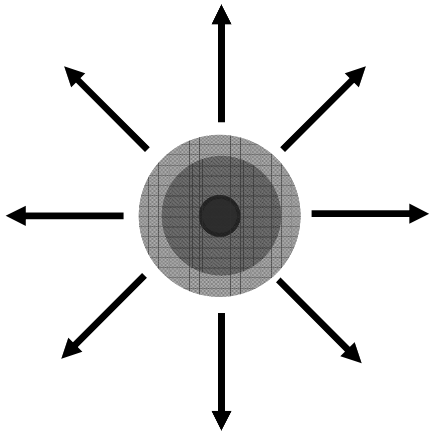
An atom can lower its energy by spontaneously emitting a photon with the energy difference of the states



We may also have stimulated emission or absorption.

A little Quantum Mechanics

For spontaneous emission, the direction of the photon will be random



Potential energy and entropy

Now

1. A system of particles spontaneously emitting photons will emit in all directions, carrying energy to the environment
2. The probability of an equal number of photons converging on the system at the same time from the environment is extremely low
3. Therefore the system is more likely to drop in total potential energy than remain constant or increase
4. Because it is more likely that the PE will drop than remain constant, the former state implies greater entropy

This explains the tendency for a system to reduce its potential energy in terms of the Second Law.

Storing memories

Let us ask a simple question about memory: How do we store memories?

1. A memory is required to be robust – that is, it must not be subject to being erased spontaneously
2. Such a state of affairs may be arrived at by lowering the potential energy of a memory storing system in such a way that it is unlikely to be increased spontaneously
3. Cutting to the chase, this means that a stored memory implies that the entropy of the storage system must have increased

What do we store memories of?

A slightly more difficult question is what do we store memories of?

1. First, we need to sample information from the rest of the Universe
2. For this to meaningful and not just random noise, this must be some net transfer of information from one system to another
3. Such a state of affairs implies that the system we are recording must also have evolved to a state of higher entropy (there are subtleties here we must skirt over)

Thus, we store memories about systems of increased entropy.

The perception of time

Returning to our perception of time in terms of memories, we are now in a position to assert that

1. The storing of memories implies an increase of entropy
2. We perceive the passage of time because we have memories
3. Therefore, our perception of time is one in which entropy is always increasing

Thus, our perception of the 'arrow of time' is because storing memories always increases entropy.

Does the 'future' exist?

It may be the case that all events are fixed in the fabric of spacetime. If this is the case, do our discussions about entropy still hold water?

1. If events are truly fixed, one event follows another with certainty
2. If this is the case, the probabilities associated with the evolution of microstates are 1 for the determined event and 0 for all others.
3. In this case, Boltzmann's description of entropy would appear not to hold

Is this actually the case or is the Boltzmann equation compatible with determinism?

Does the 'future' exist?

The use of probability can be used to skirt over our lack of complete knowledge about a system.

Even if the 'real' probabilities are either 1 or 0, we may still use values in between when we do not know what the exact state of the system is.

In this case, entropy may be interpreted as our lack of knowledge.

Does the 'future' exist?

Alternatively, we might argue that the future (defined as that half of spacetime we have no direct knowledge of) is open.

In this case, the microstates of a system <u>do</u> require probabilities.

To address this issue properly, we need to involve quantum mechanics, which tells us how probabilities evolve.

However, we are still faced with a lack of knowledge about future events. It may be that this lack of knowledge comes from quantum theory itself (i.e. the Uncertainty Principle)

A speculative step further

- Time is a manifestation of the Second Law – our perception of time is that of a path through configurations of greater entropy
  - Needs some formal justification
  - Almost certainly needs a quantum mechanical treatment

Conclusions

- We have investigated the problem of the Relativity of Simultaneity
  - Determinism is the easiest answer to this problem
  - However, it does not appear to be the only possible answer
- Our perception of time relies on the storing of memories
- We have discussed entropy and concluded that we will always perceive entropy increasing
- This relies on Boltzmann's description of entropy
  - The simplest interpretation allows future events to be open
  - However, fixed determinism is not ruled out and remains consistent with Boltzmann's entropy

Some further thoughts

- Connection between information and entropy
  - Information is physical
  - Analogue between Shannon’s (information theory) and Boltzmann’s (thermodynamics) entropy
- Connection between entropy and knowledge
  - Does knowledge of a system change its physical state? (consider Maxwell’s Demon and work)
  - The ‘Erasure Principle’
- How does quantum mechanics tie in with thermodynamics?
- and other questions...

The End / Beginning /
Could be either