Quantum Theory and Reversibility

Reversible, irreversible and irrepeatable events

Physics is the study of *events*. Events which are worthy of study are those that happen within an *isolated system* in a *finite period of time*. If and when we are in the happy position of being able to *predict* the course of an event and its outcome by applying a *theory* to a complete description of the *initial conditions* of the system, then we are entitled to conclude that our theory is a good one and that it helps to explain why the system behaves as it does. Newton's theory of Gravity and Motion is such a theory. Given the positions and velocities of all the major objects in the Solar System, it is possible to predict where those objects will be in 100 years time to a remarkable degree of accuracy. It is also true to say that, given the positions and velocities of the objects in 100 years time, it is equally possible to run the equations backwards to deduce where they are now. In other words, events which occur in the Solar System are *reversible*. An important conclusion from this is that the *information content* of the system must remain constant; there is enough information present in the initial conditions to determine the outcome – and, equally. there is enough information in the description of the outcome to determine the initial conditions. In fact we can make this observation the basis of a definition of reversibility.

A reversible event is one in which information is neither lost nor gained.

A direct consequence of Newton's laws of Motion is the law of conservation of momentum. When two snooker balls collide on a snooker table, there is an exchange of momentum between the two balls – but knowledge of the initial momenta of the balls (i.e. knowledge of their masses and velocities) is insufficient to calculate the momenta of the balls after the collision. Something is missing. In order to be able to calculate the outcome of the collision we need another equation. This is provided by another law which is not deducible from Newton's laws of motion, namely, the law of conservation of kinetic energy. But this law can only be applied to perfectly rigid – or perfectly elastic – bodies. Fortunately, snooker balls are pretty elastic and the results of the calculation agree well with reality. In addition, since kinetic energy is conserved, we can run the equations backwards and calculate the initial velocities from the final ones just as easily as the forward direction. Collisions between perfectly elastic bodies are therefore reversible.

But what about the collision between a snooker ball and a lump of putty? Suppose that we know that the two objects stick together after the collision. This gives us another equation which we can use to complete the calculations. Given the velocities of the ball and the putty, it is now perfectly possible to calculate the velocity of the combined object after the collision.

All well and good.

But suppose we are told the latter data and asked to calculate the former. What then? We know that the combined object splits apart into a ball and a lump of putty but when we come to write down the relevant equations we find that *there is insufficient information* to perform the calculations. It seems that vital information about the system has been *irretrievably lost*. We can use this fact to define what we mean by an *irreversible event*:

An irreversible event is one in which information is irretrievably lost.

Now it is currently fashionable to claim that, in fact, this information is not lost – it simply becomes inaccessible. As is well known, in a collision between inelastic bodies, some of the kinetic energy is turned into *heat* – i.e. random motion of the molecules of the putty and if you were to be told all the positions and velocities of all the molecules in the putty you would, in principle, be able to predict exactly when and with what force the putty sprang apart from the ball and you would consequently be able to calculate the velocities of the ball and the putty before they collided. In short, so it is claimed, irreversible events do not exist and that, in principle, the information content of the universe remains constant. It follows that, given the sum total of all the information in the universe at the present moment, it is, in principle, possible to predict the state of the universe at any moment in the future and to retrodict the state of the universe at any moment in the past. This assumption is known as *determinism* and has been the default position of the the great majority of scientists and philosophers ever since Newton.

Obviously the claim that information is never actually lost can only be upheld if it works at the microscopic level so let us have a look at the interactions between two molecules – let us say, two nitrogen molecules in a litre of air at standard temperature and pressure. Are there any ways in which a nitrogen molecule could absorb energy internally, as it were, in a way that causes information to be irretrievably lost?

One possibility is that, after the collision, one or both the molecules might be rotating or vibrating. If this is the case. All we have to do is to look at the system at an atomic rather than a molecular level. Given all the positions and velocities of all the *atoms* in the molecules, after the collision we could still, in principle, calculate the velocities of the molecules before the event.

There is, however, another possibility.

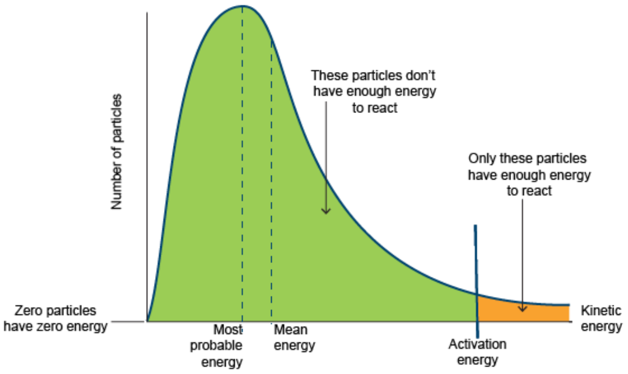
The collision might result in the *ionization* of one of the atoms involved.

The mean kinetic energy of a molecule at a temperature T degrees Kelvin is given by the formula

$$\mathrm{KE} = \frac{3}{2}kT \tag{1}$$

where k is Boltzmann's constant equal to 1.4×10^{-23} J K^{-1}. Putting $T = 300\mathrm{K}$ we find that the mean kinetic energy of a nitrogen molecule is 6.2×10^{-21} J or 0.04 eV. (1 eV or electron-volt is equal to 1.6×10^{-19} J)

Now the energy needed to knock an electron off a nitrogen atom is of the order of 10 eV so it is very unlikely that a collision between two nitrogen molecules at room temperature will result in ionisation. But it is not impossible. The figure of 0.04 eV is the mean value but roughly half the molecules in the gas will have greater energies than this and half less. The distribution of energies follows what is known as the Maxwell-Boltzmann distribution and it looks something like this:



The important thing to note is that, at any temperature, there are always a few molecules which have much greater energies than the mean. In fact it is easy to calculate the proportion of molecules which have energies greater than a given value because at high energies, the distribution is basically an exponential one. In fact since 10 eV is 250 times larger than the mean kinetic energy, we will not go far wrong if we assume that the proportion of nitrogen molecules with energies greater than 10 eV is of the order of e^{-250}. This is an incredibly small number and is effectively zero for all intents and purposes.

The upshot of all this is that, as far as collisions between nitrogen molecules at room temperature is concerned, all collisions may, indeed, be regarded as perfectly elastic and information is never actually lost.

So does this mean that the determinists are actually right and that there is no such thing as an irreversible event?

Not at all. Firstly we have only done the calculation at room temperature. If we were to raise the temperature of the gas to the point where the mean kinetic energy of the molecules was 10 eV (this turns out to be 77,000 K) then the nitrogen atoms would be almost continually being ionized. (Such a gas is called a *plasma*.) If information is *never* lost, we must show that the process of ionization is reversible at whatever temperature it occurs.

After a collision between two atoms (by now the nitrogen molecules will have been ripped apart anyway) which involves ionization, we now have three particles where before we had only two. If we are going to be able to calculate not only the velocities of the two atoms but also the velocity of the ejected electron after the collision, we need to know exactly where the electron was inside the atom before it was ejected. It is here that we encounter a serious difficulty. Quantum Theory insists that, while the electron is inside the atom, it *doesn't have a definite position or velocity* so it is impossible to calculate how it will be ejected. Quantum Theory will enable us to calculate the *probability* that it will be ejected with this speed in that direction – but it will never be able to predict the exact values. What you deduce from this will depend on your interpretation of Quantum Theory. The most popular interpretations of QT (the Copenhagen interpretation and the Many-Worlds interpretation) both accept in different ways that the actual outcome is, in an important sense, chosen *at random* from all the possibilities. Only the Pilot Wave interpretation is explicitly deterministic.

Assuming that we subscribe to either of the two most popular interpretations of QT, if we look at the situation from the point of view of information loss or gain, we see that, in fact, random information is *added* to the system because, given the velocities of the three particles *after* the event, it would be possible to calculate the velocities of the two atoms *before* it. It turns out that ionization is the opposite of an irreversible process because information is *gained*. I call this kind of process *irrepeatable*.

An irrepeatable event is one in which information is gained.

Conversely, the process in which an electron is captured by an ionized atom is, like the collision between a snooker ball and a lump of putty, an *irreversible* process.

What I am saying is this. Quantum Theory dictates that, at a microscopic level, **irreversible and irrepeatable events are happening all the time; the total quantity of information in a closed system is not a conserved quantity; information can be gained or lost.** In short: **determinism is dead.**

Once we accept that random events actually occur and that information is not conserved, a number of paradoxes which have plagued physicists over the last few decades and centuries evaporate like morning mist. The principal ones are the **Black Hole Information Paradox**, **the paradox of the Second Law of Thermodynamics** and **the Measurement Problem**.

The Black Hole Information Paradox

This is the idea that, since the Schrödinger Wave Equation is entirely deterministic, information is never actually lost and that, even when a Black Hole evaporates by means of Hawking Radiation, the radiation must somehow preserve information about all the washing machines and supermarket trolleys that went into the Black Hole during the course of its history.

What this argument fails to take into account is that the action of crossing the event horizon of a Black Hole is an *irreversible event*.

Suppose you are in safe orbit around a large Black Hole; you throw a supermarket trolley out of your spaceship and watch it descend. After a time you can calculate that it will have passed the event horizon (according to clocks on board, that is) and you can even calculate the speed of the trolley inside the Black Hole (or rather, you can calculate the speed that an astronaut travelling on board might think he is travelling at). But once the trolley is inside the hole, it can never get back out again. If the velocity of the trolley were suddenly to be reversed, it would not re-emerge from the hole, it would enter some kind of internal orbit. This proves that the process of entering a Black Hole is *irreversible* and information is irretrievably lost.

The Paradox of the Second Law of Thermodynamics.

In a nutshell, the paradox is this: the Second Law of Thermodynamics claims that there is a well-defined quantity called entropy which in any isolated system either stays constant or increases. The problem with this is that all the laws of classical physics on which it depends are symmetrical with respect to time and it is difficult if not impossible to see how an asymmetric law can be deduced from a bunch of symmetric ones.

The canonical example of the Second Law in action is this. Suppose you break a phial of gas inside a completely empty evacuated chamber. Obviously the gas molecules will spread out and fill the chamber. Once the gas molecules, which have been bouncing around inside the phial, are let free, they will travel in straight lines until they hit the walls of the chamber after which they will move around apparently at random, filling the chamber.

But are their subsequent motions actually random? If, as the die-hard determinists believe, all the collisions between the molecules and the walls of the chamber are perfectly elastic and reversible, information is never lost. In particular, if you were able instantly to reverse the directions of all the molecules the whole system would wind itself back until all the gas molecules were back inside the phial again. Do you believe that this would actually happen? I don't. What the determinists fail to realize is that a gas confined inside a chamber whose walls are at a temperature T is bathed in thermal radiation and that, while the interaction between *molecules* may be perfectly elastic, the interaction between a molecule and a *photon* has an entirely different character.

There are several ways in which a photon can interact with a molecule or atom. The first is *ionization*. In this process the energy of the photon is used to knock an electron out of the atom. As I have said, typically this needs about 10 eV of energy and at room temperature the typical energy of a thermal photon is equal to kT or 0.025 eV and the number of photons with energies of 10 eV or more is vanishingly small.

Photons can also be *absorbed* by an atom causing one of its electrons to be raised to a higher energy level – but this typically need 2 or 3 electron-volts of energy and almost never happens at room temperature.

A third method of interaction is known as *Raman scattering*. This is when the energy of a photon is used to change the vibrational or rotational energy of a multi-atomic molecule. Typically the energy involved is less than 1 eV and there are sufficient photons in thermal radiation with this energy to cause several such events in a litre of gas at STP every second. But Raman scattering does not occur in monatomic gases like helium and I want my theory to apply to all gases.

Which brings me to the last and simplest interaction between a photon and a molecule – **Rayleigh scattering**. This is a simple elastic exchange of momentum between a photon and a molecule[1]. It is Rayleigh scattering which causes the clear sky to look blue.

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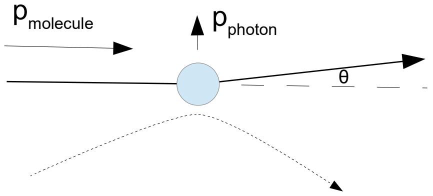
[1] It is often said that during Rayleigh scattering, the energy (and hence frequency and wavelength) of the photon is unchanged. This is not strictly true. The process will (almost always) change the speed of the molecule and any loss or gain in the energy of the molecule must be reflected in a gain or loss of energy of the photon. It turns out,

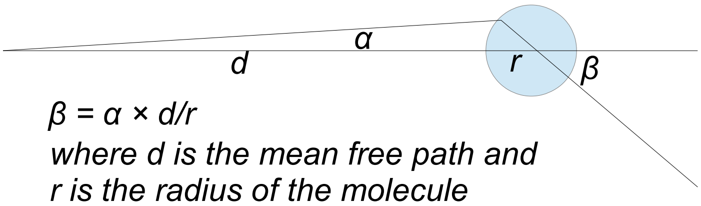


The diagram above shows a photon bouncing off a molecule causing it to recoil. The maximum amount of momentum which the photon can transfer is equal to $2p_{photon}$ but typically it will impart around $1p_{photon}$ at right angles to the direction of motion of the molecule. This will cause the molecule to alter its direction of travel by an angle θ typically equal to $p_{photon}/p_{molecule}$. The question is – how big is this angle?

Typical values of p_{photon} and $p_{molecule}$ for nitrogen at 300K are:

$$p_{phopton} = kT/c = 1.4 \times 10^{-29} \text{ kg m/s}$$
$$p_{molecule} = \sqrt{3kTm} = 2.7 \times 10^{-23} \text{ kg m/s}$$

and the ratio of these quantities is about 5×10^{-7}. In other words, Rayleigh scattering of a photon off a nitrogen molecule will cause it to deviate by something like half a millionth of a radian. Is this sufficient to destroy the correlation between the motions of all the molecules in a reasonable length of time? It most certainly is. Look at the diagram below. If instead of hitting a second molecule head on, the first molecule is deviated by a small angle α, the second molecule will move off in a direction with a much larger angle of deviation β.



β = α × d/r
where d is the mean free path and
r is the radius of the molecule

The radius of a nitrogen molecule is around 2×10^{-10} m. The mean free path of a nitrogen molecule at STP is about 7×10^{-8} m – i.e. 350 times the radius. If a nitrogen molecule suffers a deviation of half a millionth of a radian, then when it next hits a molecule, the error will be magnified 350 times; after 2 collisions the error will be magnified 350 × 350 = 122,000 times and in all probability the molecule will completely miss the third molecule which it would have hit had it not been deviated. In fact, the system of a collection of gas molecules at room temperature is so sensitive to its initial conditions that the slightest disturbance of a single molecule caused by photon scattering would be sufficient to eradicate all correlation between the motions of all the molecules in a litre of gas in a fraction of a microsecond. My conclusion is that:

Rayleigh scattering is the origin of molecular randomness and the fundamental reason why Boltzmann's H-theorem is valid.

But there is something missing here.

Rayleigh scattering is an *elastic* process. Energy is not lost. So how does it differ from the reversible scattering of molecules off each other? Why does the latter not result in molecular randomness while the former does?

The crucial difference between the two processes is that Rayleigh scattering is both *irreversible* and *irrepeatable*. Information is both *lost* and *gained*. Why is this?

From a classical point of view, what happens is that the varying electric field in the electromagnetic wave causes an electron in the atom to vibrate in sympathy; but since there is insufficient energy to excite the electron, the electron re-radiates the energy as a spherical wave in

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however, that at moderate temperatures the change in energy is negligible. In any case, what I am interested in is the change in *momentum*.

all directions. Translating this into the language of quantum theory, we say that the photon gives its energy to the electron which then immediately emits an (almost) identical photon is a random direction. Exactly how you describe how the system chooses in which direction the photon is re-emitted depends on your interpretation of QT: but, unless you subscribe to a fully deterministic interpretation such as the Pilot Wave Interpretation, you must agree that re-emission of the photon contains a random element which results in a change in information content. If you are told the positions and momenta of the photon and the molecule after the scattering event, you would be no more able to calculate the initial conditions than you could predict the final outcome given those initial conditions Rayleigh scattering is both irreversible and irrepeatable.

This explains neatly why reversing the velocities of the photons and molecules in a chamber of gas is never going to recreate the past.

Suppose you took a video of a child playing snakes and ladders. At each roll of the die, information is created. If you played the video backwards, you would see the counter moving in the wrong direction, climbing snakes and falling down ladders until it returned to the start. This is like reversing Time. But if you *played the game backwards* i.e. roll the die, move back 3 spaces, slide up the snake etc. you would not retrace the original game because every time you rolled the die *new information would be created*. The same would happen with the gas molecules. For a minute faction of a second they would retrace their steps but as soon as a photon scattered off a molecule, the randomness inherent in any quantum process would ensure that the system would diverge along a new path. In short:

It is the randomness inherent in the interactions between photons and matter which is ultimately responsible for the Second Law of Thermodynamics.

One other small issue needs to be addressed. How often does Rayleigh scattering occur in a litre of gas at room temperature?

A simple heuristic formula for the cross section for Rayleigh scattering for a molecule of typical dimension d for a photon of wavelength λ is $10d^6/\lambda^4$. Now the wavelength of a typical thermal photon is equal to hc/kT which evaluates to 4.8×10^{-5} m. This is in the far infrared. Using the formula quoted with $d = 4 \times 10^{-10}$ the cross section for nitrogen molecules at room temperature is $7.7 \times 10^{-39}\,\mathrm{m}^2$. The density of molecules in air at STP is about $2.7 \times 10^{25}\,\mathrm{m}^{-3}$ so each molecule occupies a volume of $3.7 \times 10^{-26}\,\mathrm{m}^3$. If the scattering cross-section is $7.7 \times 10^{-39}\,\mathrm{m}^2$ a photon must travel on average a distance of 4.8×10^{12} m before interacting with a molecule. Or, to put it another way, a single photon will undergo Rayleigh scattering on average once every 16,000 s or 4 to 5 hours. The final question we must now ask is this: how many thermal photons are there in a sample of gas at STP?

The gas must be contained in a container and it is the black-body radiation from the walls of this container that we are talking about. If we assume that our gas is contained in a box of surface area A, the energy radiated every second will be equal to $\sigma A T^4$ where σ is Stefan's constant. Assuming a cubical box of volume 1 litre with a surface area of $6 \times 10^{-2}\,\mathrm{m}^2$, this works out to be about 30 W. Dividing this by the typical energy of a single photon we find that the walls are radiating 7×10^{21} photons every second. Assuming that these photons only exist for as long as it takes to cross the box, there will be something like 2×10^{12} photons in the box at any one time. This means that Rayleigh scattering events will occur on average once every $16{,}000 / 2 \times 10^{12} = 8\times 10^{-9}$ s or over 100 million times a second.

I have already noted that it would need only one scattering event to completely destroy all traces of correlation between the molecules of a gas. No wonder that it is totally impossible for the reversed motion molecules to return to their original place!

The Measurement Problem

Once you have accepted that random events are fundamental and that information is not a conserved quantity, you can reject all deterministic interpretations of quantum theory such as the Pilot Wave Interpretation. You can also reject the Many Worlds Interpretation on the grounds that it offers no explanation of the role of probability. Since everything which can happens actually does happen in one world or another, in what sense are some worlds 'more probable' than others?

That just leaves us with the Copenhagen Interpretation and a host of other interpretations which rely on a process which turns the probabilities associated with the wave function into measurable realities. Adherents of the Copenhagen Interpretation like to talk about the wave function 'collapsing when a measurement is made'. But what counts as a measurement? Is it when a conscious observer notes down a reading – or does the wave function collapse when the photon hits a photosensitive emulsion?

Three of the most popular theories go by the names of the Ghirardi–Rimini–Weber (GRW) model, the Continuous spontaneous localization (CSL) model and the Diósi–Penrose (DP) model. I wish to propose a fourth possibility which is that:

The collapse of the wave function occurs whenever an *irreversible* event (including Rayleigh scattering) occurs.

My justification for this assertion is simply one of symmetry and elegance. When a system passes from being in a classical state to a quantum state it is always because the system has a choice of possible outcomes. When a photon encounters a half-silvered mirror it can either be transmitted or reflected with equal probability. In the usual language of quantum mechanics it enters a *super-position* of states in which it is *both* transmitted *and* reflected. An alpha particle inside the nucleus of a radioactive atom is in a continuous state of being both inside the nucleus and outside it. When a photon undergoes Rayleigh scattering off a molecule, the direction in which it is travelling is undecided. It is in a superposition of states in which it is travelling in all possible directions. It should be clear from these examples that classical states turn into quantum states when *new information is needed* to allow the system to develop – in other words, whenever an *irrepeatable* event occurs. It seems to me, therefore, perfectly logical to propose that wave function collapse (or Objective Reduction or whatever you like to call it) occurs whenever *information is lost – i.e. whenever an irreversible event occurs*.

A formula for the frequency of Rayleigh scattering

In the previous section we worked through an example calculating the frequency of Rayleigh scattering events in a litre of gas in a container at STP. It would be useful to generalised this calculation to a cubical sample of solid matter of volume V (surface area A, edge x) containing N molecules at a temperature T. (For the purposes of this calculation we shall assume that molecules touch each other and that the the diameter of the molecules is therefore approximately equal to the cube root of V/N.) The calculations go like this. The cross section will be:

$$\sigma_s = 10\frac{d^6}{\lambda^4} \approx 10\frac{V^2}{N^2\lambda^4} = 10\frac{V^2}{N^2}\left(\frac{kT}{hc}\right)^4$$

The time between events for a single photon will be:

$$t = \frac{V}{\sigma_s c\, N}$$

The number of photons in the sample will be:

$$N_p = \frac{\sigma A T^4}{kT}\frac{x}{c} \approx \frac{6\sigma V T^3}{kc}$$ [2]

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[2] The surface area of a cube multiplied by its edge is 6 times the volume.

and the frequency with which Rayleigh scattering occurs will be:

$$f \;=\; \frac{N_p}{t} \;=\; \frac{6\sigma V T^3}{kc} \times \frac{\sigma_s c N}{V} \;=\; \frac{6\sigma T^3 N}{k} \times \sigma_s$$
$$\;=\; 86\frac{\sigma T^3 N}{k} \times 10\frac{V^2}{N^2}\left(\frac{kT}{hc}\right)^4 \;=\; 60\frac{V^2 \sigma T^7 k^3}{N h^4 c^4}$$

For a small speck of sapphire containing 10^{17} molecules[3] at room temperature, this works out to be about 300 events per second. But the equation contains a factor in T to the power of 7 so at a temperature of 30K the frequency drops to 1 every few hours. If, as I claim, Rayleigh scattering is the principle reason why macroscopic objects cannot be held in a superposition of states, then there should be no problem, eventually, in holding quite large systems in a superposition of states for considerable periods of time even at temperatures as high as that of liquid nitrogen.

If we consider the case of a cat of mass 5 kg, volume 0.005 m^3 containing about 10^{26} molecules, then the frequency works out to be $4.5 \times 10^{11}\ \mathrm{s}^{-1}$, so a cat is not going to stay in a state of being both alive and dead for very long. You would have to cool him down to below 8 K in order to preserve his dual state for more than a second.

But then, he would be dead anyway...

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Appendix

The mathematics of the frequency of Rayleigh scattering events in a gas is as follows (d is the diameter of a molecule):

$$\sigma_s \;=\; 10\frac{d^6}{\lambda^4} \;\approx\; 10 d^6\left(\frac{kT}{hc}\right)^4$$

The time between events for a single photon will be:

$$t \;=\; \frac{V}{\sigma_s c N}$$

The number of photons in the sample will be:

$$N_p \;=\; \frac{\sigma A T^4}{kT}\frac{x}{c} \;\approx\; \frac{6\sigma V T^3}{kc}$$

and the frequency with which Rayleigh scattering occurs will be:

$$f \;=\; \frac{N_p}{t} \;=\; \frac{6\sigma V T^3}{kc} \times \frac{\sigma_s c N}{V} \;=\; \frac{6\sigma T^3 N}{k} \times \sigma_s$$
$$\;=\; 6\frac{\sigma T^3 N}{k} \times 10 d^6\left(\frac{kT}{hc}\right)^4 \;=\; 60\frac{d^6 N \sigma T^7 k^3}{h^4 c^4}$$

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[3] In 2023 a speck of sapphire containing 10^{17} molecules was placed in a state of superposition – but this was at a temperature of 0.01K.