

## What is a clock?

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**Abstract.** Without differences between what we experience in different instants, we could never have a notion of time and its passage. The hands of a clock must move if it is to tell time and measure duration. As regards the direction of time, evidence from the Newtonian theory of gravitating point particles suggests that time's arrow is not, on the scale of the Universe, determined by the statistical growth of entropy and a very special initial condition but has a direct dynamical origin manifested as the growth of structure. This paper also draws attention to the fact, first revealed by geologists, that a single static structure contains information about both its own age and even the age of the whole Universe.

The only evidence for time is difference. If one closes one's eyes and opens them, one sees something; if one does it again, one sees something slightly different. If there were no difference, we could never have formed a notion of time. If what we experience is always the same, there is no becoming, only being and that is it. It is the difference between possible states of being that enables us to talk about time. It has been said that that is God's way of stopping everything happening at once. So difference is essential. Equally as the prerequisite for difference there must be structure in each of the different experiences we have. If what we see is blank uniformity, again we could not say anything. There has to be variety.



**Figure 1.** The hands of a clock must move.

Thus the measurement of time requires motion or change; something has to move. A clock is only useful if the hands move; if they get stuck, one cannot measure time. That was already recognised by Aristotle if not earlier. That time has something to do with motion is clear. But what is the criterion of a good clock? It is here where something important has been missed, moreover, by no less a person than Albert Einstein. He thought brilliantly about so much and deserved six or seven Nobel Prizes, but he does not seem to have asked himself seriously one critical question: What is a clock? Or at least when he did in his one actual attempt in 1910, his answer had several deficiencies. This is what he said: “*By a clock we understand anything characterized by a phenomenon passing periodically through identical phases so that we must assume, by the principle of sufficient reason, that all which happens in a given period is identical with all that happens in an arbitrary period.*”

The first problem with this definition is that identical phases are never exactly realised. For whatever it is that one takes to be a clock the identical phases through which it is supposed to pass are contained within the ever-changing Universe. Where is the boundary of the clock? Because it can never be completely shielded, to say it passes through identical phases is a dubious idealisation. More important is that Einstein’s criterion does not take account of why we need clocks and watches. We need them so that we can keep appointments. If I have an assignation with a girlfriend and her clock runs differently from mine, we will not meet. This simple fact does not appear to have been picked up in the literature. Clocks must run at rates that stay relatively constant. They must *march in step*, be that in seconds, minutes or hours. Einstein’s mistake was to define a solitary clock; he should have defined mutually consistent clocks.

The extraordinary thing about the Universe, even when one takes into account that clocks run differently at different altitudes or if they are moving differently, is that clocks can be found which do march in step. Thus, if different clocks are in states of different uniform motion or at different heights in a gravitational field, their rates will be different but the ratios of the rates of the clocks will not change. That is what makes clocks useful, it is that stability of the periods. Everywhere one looks, one can find clocks that march in step. This is an all-embracing phenomenon in the Universe. Somehow the law of the Universe brings it about. It does not matter what material a clock is made of – it can be made out of anything provided that care is taken in the construction. So the real criterion is that good clocks must march in step.

Nature has been kind to us; good clocks are everywhere although that fact took a long time to be recognised and to be exploited. First to be recognised were naturally occurring clocks, above all the rotating Earth, which gives us sidereal time that is determined when a particular star is due south on the meridian. Then an astronomer can say one day has passed. But the common day is when the Sun is due south and (after on average four minutes per day is taken into account to allow for the motion of the Sun around the ecliptic) defines mean solar time. These two times, sidereal and mean solar time, do not march in step, which was known to Aristotle; there is a discrepancy of up to 20 minutes or so at some times of the year. It was Ptolemy who insisted that one of those two clocks is clearly distinguished in comparison to the other. He could say that because he had set up geometrical theories of the motions of the planets, the Sun and the Moon. These were of course geocentric but a lot better than Ptolemy is given credit for; they were surprisingly accurate, simple and worked well. However, for the Moon, which moves across the sky much faster than the Sun and planets, the theory only worked if sidereal and not solar time was used. Ptolemy made it clear in his *Almagest*, written about 150 CE, that sidereal time must be used. After the Copernican revolution, the Earth, through its rotation relative to the stars, was recognised as the clock. What Ptolemy prescribed in fact survived until about 1960 as the standard of time. That is not a bad record, but initially it all hinged on a single clock. No other motion maintained the long-term accuracy needed to determine the laws of planetary motion.

This leads on to Johannes Kepler, who from 1600 had at his disposal the marvellous treasury of observations made by Tycho Brahe over decades at the maximum accuracy achievable with naked-eye observations. The quality of Kepler’s work is amazing and his second law of planetary motion provides the second clear example of a clock-defining motion. According to the second law, the planets do not move at a uniform speed as they go in their orbits around the Sun. However, the radius vector from the

Sun to the moving planet sweeps out equal areas in equal time as measured by the sidereal time corresponding to the rotation of the Earth. Now the various Keplerian times corresponding to the different planets do not advance at the same rate, but the rates of their advance, together with the rate of advance of sidereal time associated with the rotation of the Earth, all stay relatively constant. They all march in step. Kepler's discovery revealed a tight connection between seemingly quite different motions.

The next significant development in accurate time keeping came about 50 years after Kepler had made his discovery. Christiaan Huygens invented the pendulum clock and precise measurements by John Flamsteed at the Greenwich Observatory showed that the pendulum clocks kept excellent mutual time with each other with sidereal time associated with the Earth's rotation and with the motions of the planets governed by Kepler's second law. These are more interconnections in nature that provide an ever sharper notion of time or duration (a word that can be usefully employed to distinguish that aspect of time from its many others, for example, the time of day).

In summary one cannot say that a single clock keeps good time. One needs a collection of clocks that march in step; then one can say that they all keep good time. That they exist reflects the remarkable order, discovered through the scientific revolution, that reigns in the Universe.

Another aspect of time is ephemeris time. In the 1890s astronomers began to realise that there was an anomalous acceleration in the motion of the Moon. Observations seemed to show it going too fast in its orbit. It was speeding up. One theory was that gravity might be absorbed by matter, so when there was a total eclipse of the Moon the Earth might absorb some of the Sun's gravity and this could cause the Moon to accelerate in its orbit. However, the more popular idea, subsequently proved to be correct when in 1937 it was shown that *all* the planets exhibited an anomalous acceleration that could not possibly be due to absorption of gravity, was that the rotation of the Earth was not uniform compared with the ideal absolute time conceived by Newton and employed in his equations. This led the astronomers to introduce something they called ephemeris time. The idea behind it was based on the assumption that the Solar System, the internal dynamics of which are barely affected by other gravitating bodies, is indeed described by Newton's laws and that there is something which can be called time in the motions of a collection of bodies, all the planets in the case of the Solar System, and not just of a single body. It is there. But how does one extract it? The answer is that one inverts the established procedure. Instead of using known initial positions and Newton's laws to say what the positions will be in the future, the positions are monitored, a table is made of their successive positions, an *ephemeris* as it is called, and then the time is chosen such that used with Newton's laws the positions are correctly predicted. What is simultaneously being done is ensuring that the motions of the celestial bodies that have been employed to determine this ephemeris time conserve the total energy of the system.

In practice because the other planets have relatively little effect on the motion of the Earth and Moon in the gravitational field of the Sun, it was sufficient to use the three-body system of the Earth, Sun and Moon to determine ephemeris time. The background of the fixed stars provided the clock face for the astronomers and the moving Moon was the hand that enabled them to read the time. In terms of the displacements  $\delta \mathbf{r}_a$  of the bodies, the increment of ephemeris time in the case of an arbitrary number of particles, which could even be all the particles in the Universe, takes (with  $E$  the total energy and  $V$  the potential energy, which depends on the instantaneous separations of the particles) the form

$$\delta t = \sqrt{\frac{\sum_a m_a \delta \mathbf{r}_a \cdot \delta \mathbf{r}_a}{2(E - V)}}. \quad (1)$$

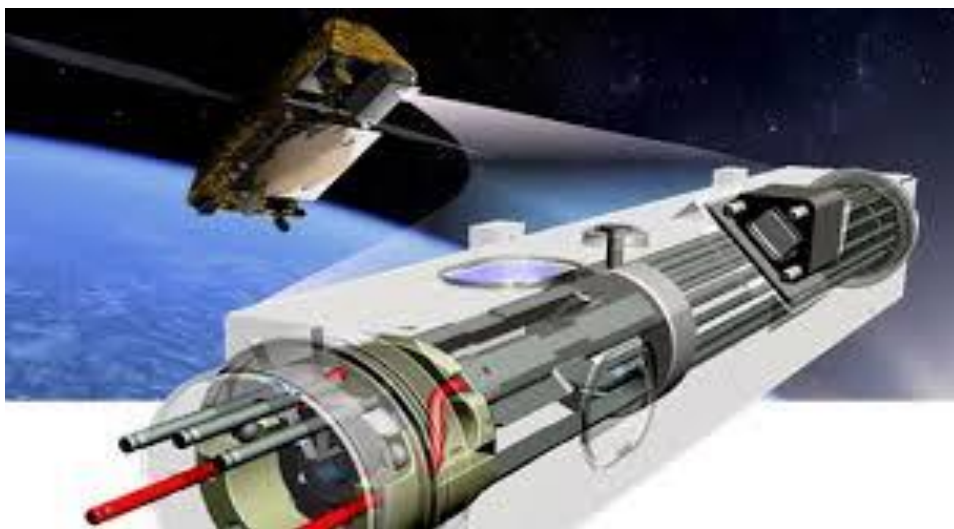
It can be said that time is the distillation of all change. This paper presupposes a notion of simultaneity, which may well be present in general relativity, even though it certainly is not in special relativity, which is a theory with far less explicit structure.

As the astronomers developed ephemeris time, it was just for our Solar System or it was at least in principle even if only the Earth, Sun and Moon were considered. However, the principle also works if

there are different solar systems well apart from each other. Although they have essentially no interaction with each other, the ephemeris times that they tell will still march in step. This is because if one system is descending into its gravitational potential well, making its particles move faster and the displacements  $\delta r_a$  greater in the numerator of (1), which would make it seem that the clock runs faster, the effect is cancelled out because at the same time the denominator has become larger. Thus different solar systems well apart from each other, which therefore have no effective interaction with each other, will still march in step because of the balancing between the numerator and denominator of each ‘solar-system clock’ just described. It is a wonderful self-compensating mechanism, a remarkable feature of Nature and one of the manifestations of the law of energy conservation, which many physicists regard as one of the, if not the, most fundamental laws of nature. Hence that is why time is the distillation of all change.

Below is a summary of the now known naturally occurring clocks in the order in which they were discovered and thus successively made chronology and indeed, the very notion of time – or, more specifically, duration – amenable to true scientific description:

- Ptolemy in *The Almagest* (circa 150 CE) said that sidereal rather than mean solar time was most used in his models of celestial motions because of the Moon’s rapid motions.
- Kepler’s Second Law (1605) showed that the planets sweep out equal areas in equal sidereal times as measured by the Earth’s rotation relative to the fixed stars.
- Flamsteed’s experiments (1660s) at the Greenwich Observatory showed that pendulum clocks march in time with sidereal time.
- Ephemeris time from the 1890s until its replacement by atomic clocks in the 1960s.



**Figure 2.** An atomic clock in space. It works because the state of atoms is changed as they stream through it, creating a feedback mechanism that controls the accuracy.

An example of an atomic clock is shown above (see figure 2). They can be found to march in step with all other clocks. In fact just over 40 years ago there was still a possibility that the strength of gravity would not march in step with the strength of electromagnetism. Given the accuracy available at that time, a possible discrepancy was just about at the limit of what would be expected on the basis of the age of the Universe and its expansion. However, things are determined now by better than two orders of magnitude and there seems to be no evidence at all that gravitational clocks differ in any way from other ones.

There are two further comments that can be made. The first is that an atomic clock works because the state of the atoms that are used changes, so this is just another example of the fact that to measure

time the hand of a clock must move. The second is that the most accurate atomic clocks are incredibly sensitive – even a change of their height by a metre or so in a laboratory changes their rate – but they are not totally stable, which is why the atomic time that determines the standard for the world is an average of a dozen or so master clocks and around a hundred secondary clocks distributed around the world. This all goes to show that Einstein’s definition of a clock given at the start of this paper does not capture the real essence of time-keeping. On the subject of time-keeping in general and atomic clocks in particular, an excellent account is given in [1].

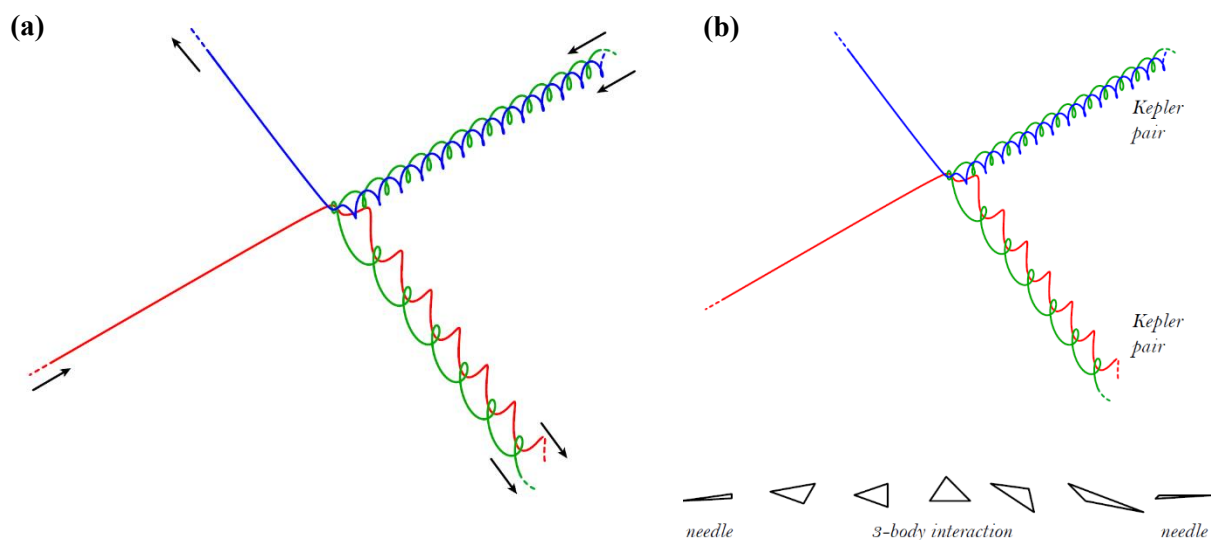
To return to conceptual issues, the first person who seriously started to make sense of Newton’s statement that absolute time, as he called it, flows uniformly without relation to anything external, and in his first law of motion said that any body left to itself will either remain at rest or move uniformly in a straight line, was the German mathematician Carl Neumann in 1870. He pointed out that to say a single motion is uniform is an empty statement because everything must be relative. There is a scene in *Hamlet* in which Hamlet wonders whether he can trust what the ghost had said to him. When the actors arrive, he is delighted, hatches a plot with them and in the couplet that ends the scene, says “*I’ll have grounds more relative than this. The play’s the thing wherein I’ll catch the conscience of the king.*” The Oxford English Dictionary cites this as the first use of ‘*relative*’ in the sense of more pertinent, more telling. Neumann said that if one is confident that a particle is not subject to frictional forces and can see that it is moving rectilinearly (which he granted is an assumption), the distance it traverses can be used as the measure of time and then with that as a clock one can see if a second particle is moving uniformly. That is meaningful, it is relative, as is everything that is meaningful in physics. It allows sense to be made of what would be the simplest law of a universe according to Newton: particles that all move inertially. If that were the dynamical law of the entire Universe, any particle in it could be used as a clock. Every other motion could be checked against it and any other particle could be used to do the same thing. Such a universe would be a single interlocking system with one thing compared to another. Although Neumann failed to say how rectilinearity of motion could be verified, he did identify the kind of thing that is behind the mutual consistency of clocks.

Moving onto something which is much more interesting is when gravitational or other forces come into play. The almost universal belief that only very special initial conditions at the birth of the Universe can explain the second law of thermodynamics is incorrect, as explained in [2]. Let us consider what happens in the simplest non-trivial dynamical problem, which is the Newtonian three-body problem of three particles interacting gravitationally. The example given is for three equal masses, but exactly the same behaviour is obtained whatever the masses. The simplest and most illuminating case is when the energy and angular momentum of the system are both zero. In that case the motion unfolds on a plane. It is striking what happens. The equations that govern the motion have perfect time symmetry, which is reflected in their solutions, but these however invariably exhibit arrows of time, as illustrated in figure 3.

Whichever way the direction of time is chosen, the state in the infinitely distant past, as shown in figure 3a, always consists of a single particle (a singleton, shown in red) coming in inertial motion (bottom left) towards (from top right) a Kepler pair: two particles orbiting each other in elliptical motion around their common centre of mass. When the distance from the singleton to the centre of mass of the particles that form the pair becomes comparable to the separation within the pair, simultaneous interaction of all three particles becomes strong. There is a period of chaotic three-body motion, as a result of which there may or may not be a swapping of particles with one particle (the green one) of the original pair linking up with the singleton.

Now the direction of Newtonian time, which itself is invisible, is purely nominal. However, it can be assumed that the particles are models of massive bodies like planets and visible. In every instant of the motion they form a triangle, the successive shapes of which are shown at the bottom of figure 3b. If one looks at the diagram, it can be seen that there is qualitative symmetry about a point in the middle. It is always there and may be called the *Janus point* because the Roman god could stand at that point and see the same kind of behaviour unfold in each time direction. Close to him there is chaotic motion, but further away in each time direction the motion becomes ordered. The two particles of the Kepler pair

move ever more regularly around each other, becoming in fact a clock that ticks as each period is completed. While this is happening, the singleton settles down into inertial motion that is uniform as timed by the Kepler pair. There are *bidirectional arrows of time* emanating from the Janus point. They are arrows that point from disorder to ever more perfect order. This is the exact opposite of what happens to molecules trapped in a box. Moreover, there is no need to impose any condition of initial low entropy. The behaviour described is a direct consequence of Newton’s laws and holds however many particles there are. Despite the time symmetry of the equations of motion, there is a very strong arrow of time in either direction from the Janus point. If one supposes that there is a timeline, which is of course invisible, Newton’s laws by themselves ensure that there will always be a Janus point on it provided the weak condition that the total energy is non-negative holds. The timeline is not a one-way street over its whole length but it is, from the Janus point, in two opposite directions. Each half is a history in which order and time emerge from disorder.



**Figure 3.** Paths of two particles of a Kepler pair meeting a single particle with shapes of the triangles they form at different instants.

This fact has nothing to do with a special initial condition of some mysterious unknown origin. Every single solution of the relevant system of equations has the property – it has a Janus point. Of course, to get one particular solution one has to specify some condition, but whenever that is done, there is bound to be a Janus point somewhere in the solution provided the mild condition that the energy is not negative is satisfied. To get in all cases the behaviour illustrated in figure 3 with a Kepler pair and singleton, one does need to impose the condition that both energy and angular momentum vanish but as argued in *The End of Time* [3], there are plausible arguments to believe that the Universe should satisfy conditions like that. The laws of nature may be far more powerful and give much more explanation of phenomena than people have yet realised. They explain why we are all getting older together, as are the stars and why we never meet anyone getting younger.

To end, let us consider a notion that was introduced in *The End of Time*, in which a *time capsule* was defined, not as a typical collection of objects contemporary with the construction of a house and placed in one of its walls for later discovery, but rather “*Any static configuration that appears to contain mutually consistent records of processes that took place in a past in accordance with certain laws.*”, p 31 [3]. The most significant empirical fact about our existence, on the largest and smallest scales, is that the current shape of the Universe is a vast time capsule. Although it takes prior knowledge to do so, the age of the Universe can be read off one ‘snapshot’ of a remarkably small part of it. In fact, *everything* we know about the Universe and its age is certainly contained on the surface of our Earth, which includes

of course photographs of the surface of the Moon. To give the simplest example of how *age* can be deduced from a single shape, a mathematician who knows the theory of Newtonian three-body motions described previously and shown one of the ‘needle’ shapes in figure 3b could immediately say that it belongs to the late history on one side of the Janus point.

Of course this is the simplest conceivable situation. About two and a half centuries ago, the scientists now called geologists began to ask themselves how structures on the surface of the Earth came to be the way they are. For example, they started to determine how much time it would take for mountains to be eroded by the effect of frost and rain. This led them to measure the rate at which the erosion products are carried away from mountains by streams and rivers. Bit by bit they came to the conclusion that the only way in which what they found could be understood was to assume that the surface of the Earth had over an immense stretch of time been subject to change brought about by processes governed by physical laws. The notion of deep time replaced the biblical account of creation in the relatively recent past. Jean-Baptiste Lamarck, the early proponent of biological evolution, commented on this development that “*the surface of the Earth is its own historian.*” In other words it is a time capsule in the sense defined above.

In truth, to grasp the full significance of time capsules one needs to look to the Universe and not just the Earth. It presents us with an extraordinary profusion of time capsules. Not only do cosmologists and astronomers say with confidence how old the whole Universe is, they can also say to very respectable accuracy how old each of the trillions of stars they observe within it are. They can give good estimates of when during the 13.7 billion years the Universe has existed each of those stars was born and when it will die. What is more, there are examples of very similar possibilities all around us, not in stars but in us. Look at other people in the street. A multitude of different faces, but in a single glance one can estimate pretty well how old each person is; there is no need for a birth certificate. And there is no need for the hands of any clock to move!

In his book *The Fourth Dimension, The Enigma of Time* [4], the biologist Dayalanand Roy argues that time is “a measurement of age”. In fact the specific proposal made in *The Janus Point*, chapter 18, [2] for the way time should be defined in quantum gravity is quite close to Roy's proposal.

Whatever it is, time is a slippery thing. Does it in any sense exist? No-one would argue that what we experience in an instant, this very one, for example, does not exist. It is steeped, even drenched, in time. What is the power which makes that possible? Hamlet said “*There’s a divinity that shapes our ends*”. Gottfried Leibniz wrote a paper with the title *The Ultimate Origination of Things*. A conjecture is that the things for which Leibniz sought the origin are possible shapes of the Universe. To conclude is a fitting remark from [3]: “The instant is not in time; time is in the instant.”

## References

- [1] Jespersen J and Fitz-Randolph J *From Sundials to Atomic Clocks*, free download from NIST, Boulder, Colorado
- [2] Barbour J 2020 *The Janus Point. A New Theory of Time* (New York: Basic Books)
- [3] Barbour J 1999 *The End of Time. The Next Revolution in Our Understanding of the Universe* (London: Weidenfeld and Nicolson)
- [4] Roy D 2021 *The Fourth Dimension: Enigma of Time* (Irvine: Brown Walker Press)