Research Article

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Irreversibility as thermodynamic time

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Abstract: In Newtonian mechanics, time and space are perceived as absolute entities. In Einstein's relativity theory, time is frame dependent. Time is also affected by gravitational field and as the field varies in space, time also varies throughout space. In the present article, the thermodynamic-based time is investigated. In macroscopic view of thermodynamics, energy is conserved in every system or process. On the other hand, exergy (availability) is not conserved and can be destroyed, and "irreversibility" is generated. Since each thermodynamic system may generate different amounts of irreversibility, this quantity is system dependent. The present article investigates the characteristics of entity irreversibility. (1) It is found that the entity behaves in the similar manner as the clock time in the standard configuration of inertial frames under Lorentz transformation. (2) It is also found that the entity is affected by gravity fields in the similar manner as the clock time. We have demonstrated that, like clock time, irreversibility is frame dependent, and affected by gravity in the similar manner as the clock time. For these reasons, we propose to call the *irreversibility* of the system as the thermodynamic time. The time's arrow is automatically satisfied, since irreversibility generation always proceeds in one direction (toward future). Based on the strength of the findings (1) and (2), a possible application of the irreversibility is an interpretation and management of the aging of biological systems. It is shown by other authors that entropy generation (equivalent to irreversibility) is a parameter for the human life span. Our sensation of time flow may be attributed to the flow of availability and destruction of it through the living system.

1 Introduction

1.1 Time in classical mechanics

In Newtonian mechanics, the time in the universe is fixed regardless of location or epoch [1–4]. This means that all events can be regarded as having a distinct and definite position in space and occur at a particular moment of time. Time as one perceives is absolute and seems to flow steadily and uniformly regardless of anything external. This moment of time is taken to be the same for observers everywhere in the universe. Time is an un-stretchable quantity, in terms of which, changes in the whole universe could be uniquely described. The theory constructs a deterministic set of mathematical relations that allow prediction of the *future* and *past* behaviors of moving objects. All that one needs in order to do this are data in the *present* regarding these moving objects. Equations of motion in Newtonian mechanics are invariant under T.

1.2 Time in relativity theory

In the special and general theories of relativity, time is stretchable and varied from place to place. Einstein's mechanics indicates that the time passage for two individuals moving relative to one another, or experiencing a gravitational field, is different [1,2,5–7]. These theories finally break Newtonian mechanics' rigid conception, though the flexibility of time passage becomes apparent only at high speeds or in strong gravitational fields.

In the following subsections, the rates of clocks differ (1) on moving frames with a constant relative velocity and (2) on uniform gravity fields with different strength. In later sections, it will be shown that a thermodynamic quantity *irreversibility*, $\mathcal{I}$, behaves like time.

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1.2.1 Standard configuration [8]

The following frame arrangement is defined for use in future discussions.

Imagine that two rigid reference frames F and F' are in uniform relative motion with velocity v . For both frames, identical units of length and time are used. Their time t, t' and their Cartesian coordinates x, y, z and x', y', z' form the coordinate systems $F: \{x, y, z, t\}$ and $F': \{x', y', z', t'\}$. The systems are said to be in *standard configuration*, if they are arranged in the following way. The origin of F' -frame moves with velocity v along the x -axis of F , the x' -axis coincides with x -axis, while the y - and y' -axes remain parallel, so do the z - and z' -axes; and all clocks are set to zero when the two origins meet.

1.2.2 Rates of clocks in standard configuration

In special relativity, the Lorentz transformation equations for the primed and unprimed variables in *standard configuration* are as follows:

$$x' = \frac{x - vt}{\sqrt{1 - \beta^2}}, \quad (1.1)$$

$$y' = y, \quad z' = z, \quad (1.2)$$

$$t' = \frac{t - vx/c^2}{\sqrt{1 - \beta^2}}, \quad (1.3)$$

where $\beta = v/c$. The inverse of the last equation can be written as

$$t = \frac{t' + vx'/c^2}{\sqrt{1 - \beta^2}}. \quad (1.4)$$

Einstein has calculated the *time dilation* under the standard configuration. This proves that time is frame-dependent [6]. Consider two inertial frames F and in standard configuration. The frame F' moves at velocity v relative to the frame F along the x -axis. Consider a clock at rest in F' . Let two events be, 1 and 2, which occur at the same point $x'_2 = x'_1$ in F' , indicated by the interval as $\Delta t' = t'_2 - t'_1$. Substituting these values in equation (1.4) yields

$$\Delta t' = \Delta t \sqrt{1 - \beta^2}, \quad (1.5)$$

where $\Delta t = t_2 - t_1$. Observers in F observe that the moving clock is running slow. This effect, *time dilation*, is reciprocal. That is, if a clock is at rest in F , observers in F' find that it runs slow as compared with clocks at rest in

their frame. The difference in the rates of two clocks is calculated next.

$$\Delta t' = \Delta t \sqrt{1 - \beta^2} = \Delta t - (1 - \sqrt{1 - \beta^2}) \Delta t,$$

$$\Delta t - \Delta t' = (1 - \sqrt{1 - \beta^2}) \Delta t \approx \frac{1}{2} \frac{v^2}{c^2} \Delta t, \quad (1.6)$$

neglecting magnitude of fourth and higher order [6]. If $v = 10 \text{ m/s}$, $1/2(v^2/c^2) = 5.563 \times 10^{-16}$, showing that the time dilation is very small with low velocity v .

1.2.3 Rates of clocks in gravitational field

In a uniform gravity field, a clock h sitting on a high shelf will run faster than a clock ℓ on the floor. If clock h is the emitter of light with frequency ω_h and clock ℓ is the receiver, Feynman [5]¹ finds the frequency at the receiver as follows. A photon of frequency ω_h has energy $\varepsilon_h = \hbar\omega_h$. Since emitted energy ε_h has the gravitational mass ε_h/c^2 the photon has a mass $\hbar\omega_h/c^2$ and is attracted by the earth. In falling the distance $H = H_h - H_\ell$ it gains an additional energy $(\hbar\omega_h/c^2)gH$, so it arrives at the receiver with the energy

$$\varepsilon_\ell = \hbar\omega_\ell = \hbar\omega_h \left(1 + \frac{gH}{c^2}\right).$$

We rewrite the equation as

$$\begin{aligned} & \text{(Rate at the receiver } \omega_\ell) \\ &= \text{(Rate of emission } \omega_h) \left(1 + \frac{gH}{c^2}\right). \end{aligned} \quad (1.7)$$

If we write the equation in terms of the time rate

$$\frac{1}{\Delta t_\ell} = \frac{1}{\Delta t_h} \left(1 + \frac{gH}{c^2}\right)$$

or

$$\frac{\Delta t_h}{\Delta t_\ell} = 1 + \frac{gH}{c^2}. \quad (1.8)$$

For $H = 20 \text{ m}$, $gH/c^2 = 2.182 \times 10^{-15}$, that is, for an altitude difference of 20 m at the earth's surface, the time difference, $\Delta t_h - \Delta t_\ell$, is only about two parts in 10^{15} . This result proves that time depends on the strength of a gravity field. Note that the quantity gH/c^2 is non-dimensional.

¹ Feynman derived the result with the help of the principle of equivalence. g is assumed constant in this thought experiment.

2 Availability and irreversibility

The conservation of energy for a control mass can be expressed as [9,10]

$$dE = \delta Q - \delta W. \quad (2.1)$$

The entropy equation can be written as

$$dS = \frac{\delta Q}{T} + \delta\sigma, \quad (2.2)$$

where σ is the *entropy production* which can be stated as:

$\delta\sigma > 0$ internally irreversible process,

$\delta\sigma = 0$ internally reversible process,

$\delta\sigma < 0$ impossible process.

A quantity *availability* (also called exergy, work potential, Arbeitsfähigkeit) has been used by engineers to assess the maximum work that can be obtained for a combined system, closed or open, in a given environmental condition [9,11,12]. It is known that all macro-processes are irreversible, and the availability is destroyed. The *destruction* of availability is called *irreversibility*.

Wall [13] stated that energy is motion or ability to produce motion and exergy is work or ability to produce work. He also stated that time is experienced when exergy is destroyed, i.e., an irreversible process, which creates a motion in a specific direction, i.e., the direction of time. The idea that availability can be destroyed is useful [9]. This concept essentially brings together the first and second laws.

If the state of a thermodynamic system departs from that of the environment, an opportunity exists for developing work. For a combined system of a control mass (closed system) plus the environment, the work W_c for the combined system is given by [9]

$$W_c = (E - U_0) + p_0(V - V_0) - T_0(S - S_0) - T_0\sigma_c. \quad (2.3)$$

Since $T_0\sigma_c$ is positive when irreversibilities are present and vanishes in the limiting case where there are no irreversibilities, the maximum theoretical value for W_c is obtained by setting $T_0\sigma_c$ to zero in equation (2.3):

$$\mathcal{A} = W_{c,\max} = (E - U_0) + p_0(V - V_0) - T_0(S - S_0). \quad (2.4)$$

The function $\mathcal{A}$ is called availability for the control mass. To sum up, the availability is defined as the maximum theoretical useful work obtained if a system is brought into thermodynamic equilibrium with the environment by means of processes in which the system interacts with this environment [14]. In the general case, a control mass may experience both heat and work interactions with other systems, not necessarily including the environment, and there is some availability destruction within it during such interactions.

$$\Delta\mathcal{A} = \int_1^2 \left(1 - \frac{T_0}{T_b}\right) \delta Q - (W - p_0\Delta V) - \mathcal{I}, \quad (2.5)$$

heat transfer work interaction irreversibility

where $\Delta\mathcal{A} = \Delta E + p_0\Delta V - T_0\Delta S$. The term irreversibility $\mathcal{I}(=T_0\sigma)$ accounts for the destruction of availability due to irreversible processes within the control mass.

Equations for flow availability can be written for an open system, including heat transfer and matter flow at the boundary surface [9,14].

3 Special features of irreversibility

3.1 Irreversibility and frame dependence

We shall demonstrate that the irreversibility $\mathcal{I}$ is frame dependent, similar to clock time. Planck² and Einstein³ considered thermodynamic systems which are in the *standard configuration* [10,15]. First, we note that irreversibility can be expressed as $\mathcal{I} = T_0\sigma$ [9]. In the standard configuration of frame F and frame F' , the quantities T_0 and σ are related by the following equations when Lorentz transformations are applied separately (p. 159, Tolman) [10].

$$\frac{T_{0F'}}{\sqrt{1 - \beta^2}} = T_{0F}, \quad (3.1)$$

$$\sigma_{F'} = \sigma_F, \quad (3.2)$$

which implies that σ is invariant under Lorentz transformation in the standard configuration. Then

$$\frac{\mathcal{I}_{F'}}{\sigma_F} = \frac{T_{0F'}\sigma_{F'}}{T_{0F}\sigma_F} = \frac{T_{0F}\sigma_{F'}}{T_{0F}\sigma_F} \sqrt{1 - \beta^2} = \sqrt{1 - \frac{v^2}{c^2}} \quad (3.3)$$

$$\mathcal{I}_{F'} = \sqrt{1 - \frac{v^2}{c^2}} \mathcal{I}_F \text{ implies } \mathcal{I}_{F'} < \mathcal{I}_F.$$

The difference in value is

$$\begin{aligned} \mathcal{I}_F - \mathcal{I}_{F'} &= \mathcal{I}_F - \sqrt{1 - \frac{v^2}{c^2}} \mathcal{I}_{F'} \\ &= \mathcal{I}_F \left[1 - \sqrt{1 - \frac{v^2}{c^2}} \right] \\ &\approx \frac{1}{2} \frac{v^2}{c^2} \mathcal{I}_F, \end{aligned} \quad (3.4)$$

² Planck, *Berl. Ber.* 1907, p. 542; *Ann. der Physik*, **26**, 1 (1908).

³ Einstein, *Jahrb. der Radioaktivität und Elektronik*, **4**, 411 (1907).

neglecting magnitude of fourth and higher order. Comparing this result with equation (1.6), we see that “time” and irreversibility behave similarly, i.e.,

$$\frac{\Delta t'}{\Delta t} = 1 - \frac{1}{2} \frac{v^2}{c^2} = \frac{\mathcal{J}_{F'}}{\mathcal{J}_F}. \quad (3.5)$$

3.2 Irreversibility in a gravitational field

In this section, we analyze the effects of a gravitational field on the value of irreversibility $\mathcal{J}$. The objective is to compare the result of this thought experiment with the gravitational field on “time” as described in Section 1.2.3.

We consider the irreversibility of a closed system with mass m as it is lowered from height $z = H_h$ to height $z = 0$ (datum). Equation (2.5) will be used. This process has no heat transfer δQ , no work W , no change in the volume ΔV , and no entropy change ΔS , so that

$$\Delta \mathcal{A} = -\mathcal{J} \quad \text{or} \quad \mathcal{J} = -\Delta \mathcal{A}.$$

This implies that during the process, availability is destroyed. The kinetic energy is not considered, so that E consists of internal energy U and potential energy mgz , assuming uniform field. Denoting $\mathcal{J}_h$ as the irreversibility generation for lowering the system from $z = H_h$ to $z = 0$, the above equation gives (g is assumed constant)

$$\begin{aligned} \mathcal{J}_h &= -\Delta E_h \\ &= -(E_0 - E_h) \\ &= -[(U_0 + 0) - (U_h + mgH_h)] \\ &= mgH_h, \end{aligned} \quad (3.6)$$

assuming $U_h = U_0$ (mainly a function of T). Next, we consider the irreversibility of the same system which is lowered from height $z = H_\ell$ to the height $z = 0$, where $H_\ell < H_h$. Denoting $\mathcal{J}_\ell$ as the irreversibility generation for lowering the system from $z = H_\ell$ to $z = 0$, we have

$$\begin{aligned} \mathcal{J}_\ell &= -\Delta E_\ell \\ &= -(E_0 - E_\ell) \\ &= -[(U_0 + 0) - (U_\ell + mgH_\ell)] \\ &= mgH_\ell, \end{aligned} \quad (3.7)$$

assuming again $U_\ell = U_0$. The irreversibility generation of lowering the system from H_h to H_ℓ is

$$\mathcal{J}_h - \mathcal{J}_\ell = mgH_h - mgH_\ell = mg(H_h - H_\ell) = mgH.$$

Next, dividing both sides by $\mathcal{J}_\ell$ yields

$$\frac{\mathcal{J}_h - \mathcal{J}_\ell}{\mathcal{J}_\ell} = \frac{\mathcal{J}_h}{\mathcal{J}_\ell} - 1 = \frac{mgH}{\mathcal{J}_\ell} = \frac{mgH}{E_\ell - E_0} \approx \frac{gH}{c^2}, \quad (3.8)$$

where we make approximation $E_\ell - E_0 \approx E_\ell \approx mc^2$, and finally obtain

$$\frac{\mathcal{J}_h}{\mathcal{J}_\ell} \approx 1 + \frac{gH}{c^2}. \quad (3.9)$$

Comparing equation (3.9) with equation (1.8), we observe the similarity between time and irreversibility in the presence of gravity field, i.e.,

$$\frac{\Delta t_h}{\Delta t_\ell} = 1 + \frac{gH}{c^2} \approx \frac{\mathcal{J}_h}{\mathcal{J}_\ell}. \quad (3.10)$$

3.3 Clock time versus thermodynamic time

After collecting the results from Sections 3.1 and 3.2, we shall examine the characteristics and implication of the entities irreversibility $\mathcal{J}$ and clock time Δt . Now we have two entities Δt and $\mathcal{J}$, both of which behave similarly under Lorenz transformation in one case (equation (3.5)) and under gravity influence in separate case (equation (3.10)). It is proposed that Δt be called “clock time” and $\mathcal{J}$ be called “thermodynamic time.” It appears that Δt is more abstract and theoretical and that $\mathcal{J}$ is more tangible and operational [16–18]. The research on clock time is being continued: Barbour has described timeless quantum cosmology, and Smolin has argued evolutionary time. Currently, Δt can be measured with utmost precision and $\mathcal{J}$ can be measured with as high degree of precision as energy measurement. It can be expected that $\mathcal{J}$ will find application in which energy flow is involved.

1. In describing time, what we are conscious of is a memory of the past tinged with an expectation of the future [19]. Once the occurrence of an event has passed, the event has become a memory and cannot be repeated or corrected. In the words of Bohm [20]: “Although the present is, it cannot be specified in words or thought without slipping into the past.” Penrose [21] stated that central to our feeling of awareness is the sensation of the progression of time. Based on these dialogs which come from human (biological systems), time appears to be the energy (in this case, irreversibility generation) flowing through the biological system. The future is an untrailed territory that is hidden behind a mist.
2. The entity $\mathcal{J}$ is always positive and zero in the limit. The notion of irreversibility presupposes “time’s arrow,” because the direction of the process is always in the direction toward future. Time is asymmetrical with

respect to the event axis (world line). This is commonly called the arrow of time.

Our experience shows that time is asymmetric to the past and the future, and analogous to the flight of an arrow. This means that if we arrange events in the chronological order along an axis, the time appears to be asymmetric with respect to the axis. This also means that the events are irreversible; the events cannot be played back as a movie playing backward.

The physical basis of the direction of time has been discussed by many authors [2,16,18,22–27]. There appears to have arrow of time of different origins: the thermodynamic arrow of time, biological arrow of time, the arrow of time of retarded electromagnetic radiation, cosmological time asymmetry, and others. For the thermodynamic arrow of time, Smolin [16] stated that small bits of the universe, left to themselves, tend to become more disordered in time (the spilt milk, the air equilibrating, and so on). It is noted that our direct contacts with the nature follow macroscopic thermodynamic laws, and the thermodynamic arrow of time prevails.

Good examples showing the asymmetry of time are biological systems. All biological systems are subject to continuous irreversible changes through their entire lives. There is a type of people called *progerin* who grows much faster than ordinary people. This indicates that time passage depends on individual systems.

3. According to the Copenhagen interpretation of quantum mechanics, quantum evolution is governed by the Schrödinger equation, which is time symmetric, and by wave function collapse, which is time irreversible. Despite the post-measurement state being entirely stochastic in formulation of quantum mechanics, a link to the thermodynamic arrow has been proposed. Thus, the modern physical view of wave function collapse, the quantum de-coherence, the quantum arrow of time is a consequence of the thermodynamic arrow of time [27].

4 Irreversibility of various systems

Once the similarity of irreversibility $\mathcal{J}$ and clock time is discovered, we may want to find its applications. A thermodynamic system may be closed or open, biological or inanimate. The system interacts with its environment and in the process destroys availability and generates

irreversibility (or entropy because $\mathcal{J} = T_0 \sigma$). This signifies as degradation of the useful energy of the system, and we have interpreted this as the passage of time for the system, i.e., the system possesses its own time.

For inanimate systems, irreversibility can also be generated. This includes oxidation, erosion, or heat transfer. Some inanimate systems, such as diamond or gold, may produce irreversibility at slow rates. This implies that the change of the state (time) proceeds slowly for these systems.

The irreversibility comes from heat transfer, diffusion, fluid viscous dissipation, and chemical reactions, which may operate at the cellular level. Some examples of irreversibility production are as follows:

1. Heat transfer – The irreversibility production comes among bodies with finite temperature differences [9].
2. The irreversibility production in pipe flow in which the temperature of fluid is different from that of the pipe [28].
3. Diffusion of fluids of different types produces irreversibility.
4. Combustion of various types produces irreversibility [9].
5. The irreversibility production of flowing viscous fluid in a pipe [28].

The system in these examples may be either biological or inanimate.

4.1 Application of thermodynamic time in human aging

Silva and Annamalai [29,30] correlated life-span entropy generation and the aging of human. The organs considered are brain, heart, kidney, liver, adipose tissue, skeletal muscles, and the rest of the organs. To estimate entropy generation during a human life span, an availability analysis is applied to the metabolic oxidation of the three main nutrient groups: carbohydrates, fats, and proteins, in order to obtain the entropy generated for each of them under isothermal conditions.

Entropy generated over the life span of average individuals (natural death) was found to be 11,404 kJ/K per kg of body mass. The entropy generated predicts a life span of 73.78 and 81.61 years for the average US male and female individuals, respectively, which are values that closely match the average life span from statistics (74.63 and 80.36 years). These articles assume that entropy generation is the mechanism for biological aging, and that life comes to an end when entropy generation reaches its maximum.

The articles cited here provide additional and tangible evidence for our discovery that the irreversibility and clock time are intimately related. The entropy generation σ in these articles is similar to the irreversibility generation $\mathcal{J}(=T_0\sigma)$, but entropy is invariant under Lorentz transformation. As indicated by Denbigh [31], the concept of irreversibility has a much wider field of application than has the concept of entropy generation. In addition, irreversibility has the dimension of energy, which may be easier to visualize and control.

5 Concluding remarks

We have two stems of time, i.e., thermodynamic time and clock time, both behave similarly under Lorentz transformation and a gravity field. These times are local and system dependent. The overall picture is that as the availability (exergy) of the system is destroyed, the thermodynamic time progresses, like the progress of the clock time. As we know, the irreversibility of all systems increases. If the system is biological, we may call this aging.

5.1 Thermodynamic time and its application

In Section 3.2, we have seen the calculation of irreversibility for a closed system. If we desire not to have the size (mass) of the system as a parameter, we may use $\mathcal{J}/m$, so that the size of the system may not become a parameter and comparison between various systems can be performed, i.e.,

$$\Delta\tau = C \frac{\mathcal{J}}{m},$$

where τ is a thermodynamic time and C is a dimensional constant. The treatment of human aging by Silva and Annamalai [29,30] cited in Section 4.1 has used open systems. Since for an open system mass and energy are not fixed, analysis is more complicated. Here, we may use the instantaneous values of $\mathcal{J}/m$, $\mathcal{J}/E$, or $\mathcal{J}/\mathcal{A}$ within the control volume.

It is natural to ask how $\mathcal{J}$ and Δt are related. From the work of Silva and Annamalai [29], the following numbers can be listed.

1. Entropy generated, kJ/kg K: male, 11,508; female, 11,299
2. $T_0 = 37^\circ\text{C} = 310\text{ K}$

3. Irreversibility generated, MJ/kg: male, 3,567; female, 3,503
4. Equivalent human age, year: male, 74.63; female, 80.36
5. $\mathcal{J}/m$ J/kg s: male, 1.52; female, 1.38

These results may be interpreted as that a human male destroys about 1.5 Joule of useful energy per kg body weight every second in his life span.

5.2 Impacts and implications of thermodynamic time

The contribution of the present article is the derivation of equations showing that irreversibility $\mathcal{J}$ behaves like time (1) in the standard configuration of inertia frames under Lorentz transformation, and (2) $\mathcal{J}$ is affected by gravity fields in the similar manner as the clock time. As pointed out previously, thermodynamic time $\mathcal{J}$ has the dimension of energy. Many phenomena in biological systems where duration is involved, such as aging, biological clocks, and defects in biological clocks (Parkinson's disease), may be closely related to energy flow through irreversibility. Our sensation of time flow may be explained as the availability flow and destruction of it (irreversibility), in the body and brain. Our understanding of these problems is in the infant stage, and further research is required. Since irreversibility is based on a thermodynamic concept which is universal, further application to other fields, such as cosmology (the Big Bang, inflationary cosmology, and black holes), is possible.

Nomenclature

c	velocity of light
E	energy
F, F'	coordinate systems
g	acceleration of gravity
H	height separation
m	mass
p	pressure
Q	heat energy
q''	heat flux per unit area
S	entropy
T	temperature
t	time
U	internal energy

V	volume
v	velocity
W	work
x, y, z	Cartesian coordinates
y_i	mass fraction of i-species
z	elevation above some datum
$\mathcal{A}$	availability
β	v/c
$\varepsilon_h, \varepsilon_\ell$	energy states of a photon
γ	$1/\sqrt{1-\beta^2}$
$\hbar$	Planck's quantum mechanical constant
$\mathcal{I}$	irreversibility
σ	entropy production
ω	frequency of light
Δ	difference
η	efficiency
τ	thermodynamic time
Superscripts	
'	moving frame
Subscripts	
1, 2	location
b	boundary
c	combined
F, F'	frames
h	high
ℓ	low
s	surface
0	dead state; environment for pressure and temperature

Conflict of interest: The author states that he has no conflict of interest.

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