THE SCIENCE OF INNOVATION:
Towards Developing a Theory of Innovation

IJIMSR, Vol.1, No.1, (2023) 23.1.1.001

Ritu Aggarwal*
University School of Automation and Robotics
East Delhi Campus, GGS Indraprastha University,
New Delhi – 110092, India
Clean and concise description of the reported work : Methodology and Formal Analysis, Writing

Avinash C Sharma
Indian Council of Social Science Research,
New Delhi – 110067, India
Clean and concise description of the reported work : Conceptualization, Supervision, Writing -review and editing

*Corresponding author

Received August 1, 2023; Accepted August 16, 2023

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Ritu Aggarwal
University School of Automation and Robotics
East Delhi Campus, GGS Indraprastha University,
New Delhi – 110092, India

Avinash C Sharma
Indian Council of Social Science Research,
New Delhi – 110067, India

ABSTRACT

The present paper attempts to improve our understanding of the phenomenon called ***innovation*** *and establish the science of it; from a perspective of a social physics modeling and theories in the spirit of conventional domains of physical sciences. Thus, aims to have a deeper insight into the concept, the properties & the dynamics of innovation, fostering the mindset of an innovative mind, developing a culture of innovation; and thereafter move towards developing a universal theory of innovation. The theory is expected to have significant impact on a wide range of domains of human activities, including mutual interactions and with nature and beyond. This would also go a long way in ensuring solutions for a sustainable quality of life on this planet as envisioned in SDGs enunciated by UNO.*

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I. INTRODUCTION

Today innovation is everyone's business. Everyone is expected to go lean and perform better with less, whether they work as a management for a large firm, an entrepreneur just starting out, a government official, or a teacher at an elementary school. Leading industrial economies are increasingly dependent on technological advancements for their expansion. Governments are now concentrating on research & innovation policy rather than science & technology policy [1] in order to play-around and drive-forward along the factors that influence the capacity & capabilities to innovate. The prime necessity of innovation is to bring the desired growth in both social and economic sectors by value addition through appropriate modifications in the performance behaviors of different socioeconomic parameters of growth. In fact, the history of human civilization is full of ‘inventions’ and ‘innovations’. Large-scale innovations that have powered our continuing growth and expansion include the discovery of fire, iron, coal, etc., along with machinery, tools, calculation, and most recently, digital information technology. Instead, the history of these discoveries is evidence of the tremendous inventiveness of our species. Many of these resulted into the paradigm shift in the growth process [2]. Unfortunately, there is no established quantitative ‘science of innovation’, and therefore, no universally agreed upon criteria or data relating directly to major innovations and paradigm shifts. Situation may well change as innovations becomes an increasingly active area of investigation, with researchers beginning to grapple with questions such as what innovation is, how do we measure it, how does it happen and how can it be facilitated.

Innovations are intermediate stages in the bigger process from birth of a technology or society or any economy to it's ultimate stagnation (and hence dissemination), and we should understand that it results from ideas that are acknowledged to be worthwhile for improving research practices or systems non-incrementally. An innovation is made to improve some aspects of the earlier versions deliberately. Truly said that an innovation presupposes rationality, at least minimally [3].

We urgently need a science of complex adaptive systems to address to the most of extraordinary challenging societal problems we face. After certain time, we stop to grow inspite of the fact that we eat continuously. This is a curious paradoxical phenomenon explained by the growth theory. Interestingly, the same (or at least similar) growth theory seem to be applicable to a vast variety of systems, e.g. companies, cities and it's economy. Understanding the mechanics of an open-ended growth, where the limited time singularity came from, and creating methods to regulate or avoid it can help the system expand sustainably.

Our quest for a universal growth theory leads us to a highly multidisciplinary approach involving the conventional STEM (science) areas, bio- & living systems and even the social sciences. It is interesting to address such questions apparently under the domain of social sciences from a more quantitative analytic viewpoint typically associated with the paradigmatic framework of traditional physics [4]. 'Social physics' [5] is a new way of understanding human social universe [6], based on analysis of big data. Few physicists would recognize/ accept it as 'physics', primarily because it doesn't appear to focus explicitly on the underline principles, general laws, mathematical analysis and mechanistic explanations. Nevertheless, the field has survived and is gaining attention of researchers, mainly because a number of concepts and terminology from physics is applicable in letter & spirit and fits-in very well and serves the purpose [7,8]. Today's social physicists are most likely those people who have worked in the technically difficult, frequently data-driven approaches located at the intersection of applied mathematics, computational modelling, and statistics [9]. It's more of a passionate group than a discipline, made up primarily of retired physicists and computer scientists who use a quantitative approach to understand people, the forces that shape their behaviour, how they interact with one another and their environment, how cultures develop into civilizations, etc.

In this paper we present a quantitative model for innovation and discuss its origin from the basics of mathematical physics. We attempt to argue-out the fact that an ideal model for innovation leading to a sustainable growth is super-exponential and is considered super-linear on a logarithmic axis. Different socio-economic and biological systems are discussed in the light of super-exponential growth. The need of paradigm shifts in the system to push away the singularity created from the model which could otherwise, collapse the growth of the system that is under investigation is discussed. It is further argued that the paradigm shifts are needed to happen at a regularly increasing pace for a continuous and a sustainable growth of the system. The other type of growth, sublinear, and its consequences is also discussed.

II. THE QUANTITATIVE MODELING METHODS (Re-Emergence of Social Physics)

The time evolution of any system, broadly speaking involves: Birth, Growth (maintenance + new elements) followed by death or collapse. Also almost always the process of evolution is exponential and is irreversible. From the point of view of physics, timely *innovations* (loosely speaking intraventions) are a necessity for its further growth or even for sustainability. The branch of physics of it involves studying equation of motion along the time axis.

The time evolution of any dynamical system is represented by a set of multivariate (variables x_i, $1 \leq i \leq N$), say n mathematical functions, f_i $(x_1, x_2, x_3, \ldots, x_n, t)$. In simplest form, a growth equation can then be written as

$$\frac{\partial f_i(x_1,x_2,x_3,\ldots,x_N,t)}{\partial t} = \sum_{1\leq j\leq N} \alpha_{ij} \frac{\partial f_i\ (x_1,x_2,x_3,\ldots,x_N t)}{\partial x_j} \tag{1}$$

where i & j varies from 1 to n & N respectively. Equation (1) represents a set of n equations in N variables. The α_{ij} are n x N parameter.

The simplest form of the one-dimensional equation of growth shall look like a power law equation.

$$\frac{df(x,t)}{dt} = c + c_1 x + c_2 x^2 + \ldots + c_n x^n, \tag{2}$$

where, $f(x,t)$ would represent a given socio-economic or a bio-population in the given system with c_i's as system's initial parameters or constants. The quantity d $f(x,t)$/dt gives growth in the population with time t,

If,

$$\frac{df(x,t)}{dt} = c_1 x \tag{3}$$

the system is said to be undergoing exponential growth. The higher order terms bring-in further non-linearity in the system.

Invariably, almost always such set of equations are multivariate (x_i's), involves quite a large number of parameters (α_{ij}) and are, generally, badly coupled and highly non-linear (Eqn. 1). Many a times, the evolution is highly sensitive to the initial values of certain parameters and as how the different variables & parameters interact amongst themselves. Very often the systems tend to collapse systematically into chaotic state. Such studies involve the physics of uncertainty rather than the physics of stability'. That is what is required in real-life problems, wherein, exploring new opportunities and new solutions always involves making decisions in an environment of uncertainty.

Growth, i.e., the time evolution, can be also viewed as a special case of scaling phenomenon. A mature organism is essentially a non-linearly scaled-up version of the infant. Like organisms, cities are also approximately scaled versions of one another, despite their different histories and cultures, at least as far as their physical infrastructures is concerned. Growth as manifested by an open-ended increase in size cannot be sustained forever unless, of course, an intravention occurs. A crucial assumption is the derivation of these scaling laws has been that system maintains the same physical characteristics such as shape, density and chemical composition, as it changes size. Consequently, in order to build larger structures or to evolve larger organisms beyond the limits set by scaling law, innovations must occur, that either changes the material composition of the system or the structural design or both. Technically speaking, this is reparameterization of the same set of equations of growth for a given system under investigation.

Functionally, there are two types of scaling laws governing any '*growth*': one is relating to the scaling of physical size of objects. The other is related to the scaling of phenomenological behavior of the object/ machine. Mathematically, the power law is non-linear relationship between two quantities x and y that can be modelled generically by rather simple equation: y = a x^k, where a and k are constants; the exponent of the power law and the width of the scaling relationship, respectively. Numerous examples of power law driven growths occurs in nature. Some of the typical examples can be:

- Kleiber's Law [10]: for vast majority of animals, animal's metabolism rate scales to the ¾ power of the animal's mass.
- At cellular level, it means as increase in size and an increase in numbers of cells [11].
- In medicine science, growth may be associated with pathology (diseases) [12].
- Income distribution [13]
- Structural similarities of fractals [14]
- Biological systems [14,15]
- Bacterial growth [16]
- Growth of a corporations [3]
- Growth of cities [3]
- Human population growth [17]
- Virus spread [18], etc.

Even though the growth of organisms, cities; economies appears to be governed by very similar mathematical equations, their resulting solutions has subtle but crucial differences arising from being driven by two types of scaling: (i) sublinear scaling (the economies of scale of organisms) where $k < 1$, and other (ii) by super-linear scaling (the increased return of scale of cities and economies) wherein $k > 1$. (Fig.1).

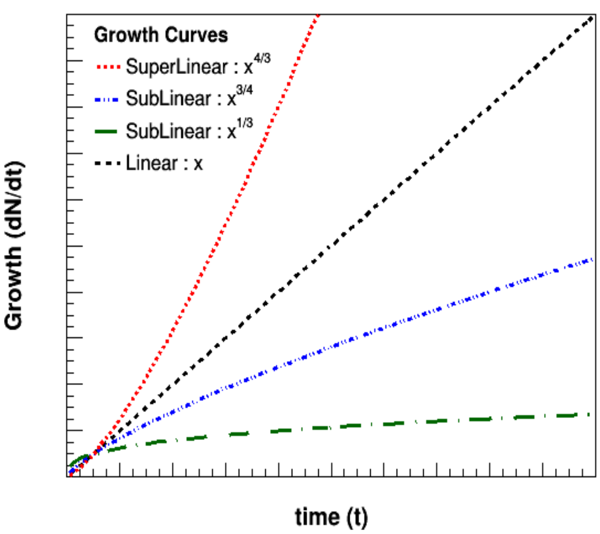

Figure 1: *SuperLinear (red) and SubLinear (blue and green) growth compared to the Linear growth (black).*

Interestingly, broadly speaking very often, nature appears to prefer 3/4, 4/3 & exponential scaling for growth. In fact, physicists have been quite familiar with such power laws. Some of the phenomenon well known & well-researched in the discipline of physics are:

- 4/3 scaling of entropy occurs in intermediate steps of Stefan's law of radiation [19];
- Entropy of circulatory systems scales by 4/3 exponent of volume [20]
- Lengths in 3 dimensions appears stretched by a factor 4/3 when projected from 4 dimensions.
- Fractals envelope of Brownian motion, etc.

The super linear case growth can be written as

$$dN/dt=x^{4/3}, \tag{4}$$

where, dN/dt represents the change dN in any studied quantity N with small dt increments in time t. On the other hand, the sub linear growth can be modelled using the function

$$dN/dt=x^{a}, \tag{5}$$

where, $a=1/3$ for the cases related to the social affairs and $a=3/4$ for the cases related to economic growth.

In super linear case, the general solution exhibits a curious property technically termed as '*finite-time singularity*'[21], which is a signal of inevitable change, and is indicative of a potential trouble ahead. The 'finite time singularity' occurs when one input variable is time, and an output variable increases towards infinity at a finite time. These are important in kinematics and partial differential equations – infinities do not occur in real physical world, but the behavior near the singularity is often of interest. A *finite time singularity* simply means that the mathematical solution to the growth equation governing whatever is being considered – the population, the GDP, the number of patents, etc, etc., - becomes infinitely large at *some finite* *time* (Figure 1). This is obviously impossible, and that's why something must be changed. Before addressing some consequences of the phenomenon, it is important to first discuss some salient features: Simple power law or sub linear exponentials are continuously increasing functions that also eventually becomes infinitely large, but they take infinite time to do so. In other words, in these cases the 'singularity' has been pushed off to an infinite time into future, thereby rendering it 'harmless' relative to the potential impact of *finite* time singularity. In case of growth driven by superlinear scaling, the approach to the finite time singularity, is faster than exponential. This is often referred to as super-exponential. This kind of growth behavior is clearly unsustainable because it requires an unlimited, ever increasing, and eventually infinite supply of energy and resources at some finite time in future in order to maintain it. Left unchecked, theory predicts that it triggers & transits to a phase that leads to stagnation and an eventual collapse (Fig.2).

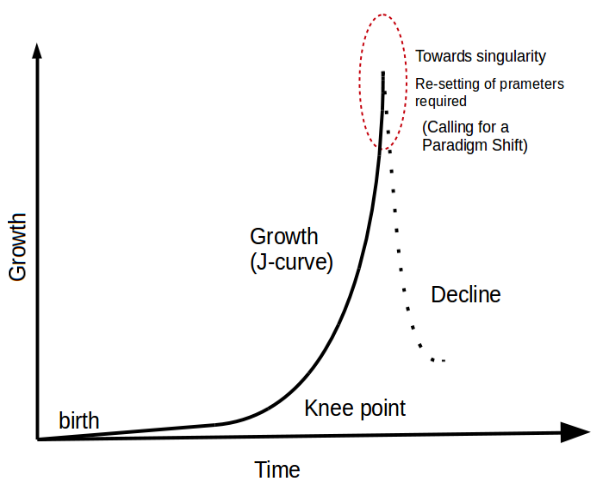

Figure 2 :*SuperLinear growth andpotential decline if the singularity (paradigm shift) is overlooked.*

If growth were purely exponential, then the production of energy, resources, and food could, at least in principle, keep up with exponential expansion because all of the relevant characteristics of economy or cities remain finite, even if they continue to increase in size and become very large. If it is expanding super-exponentially and getting close to a finite temporal singularity, this cannot be accomplished. In this case, demand grows continuously and inexorably over a limited time, eventually becoming limitless. It is clearly not feasible to provide a limitless supply of food, resources, or energy in a limited length of time. So, if nothing else changes, this extricably leads to stagnation [22] and collapse, (Fig. 2).

Unlike a normal exponential growth, where the curve looks the same at every point, super exponential growth has one or more "knees" in the curve, which are parts in the curve where growth which was initially slower, becomes suddenly faster. This kind of growth is often called as "Hockey Stick" or J-curve growth, being closer to capital J in shape. In the beginning occurs a period of slow growth, followed by a knee in the curve, and then a period of super-exponential growth which goes almost vertical. We present a review of some of cases where the growth is observed to be super-exponential. The J-curve type of growth is well studied and is commonly occurring curve in the discipline of physics. One of most fascinating example is the increase in the time interval when observed by a moving observer, a phenomenon termed as 'time dilation'[19]. This is a result of the fact, that a clock which is moving with a velocity, v ticks slower than the same branded clock which is kept stationary.

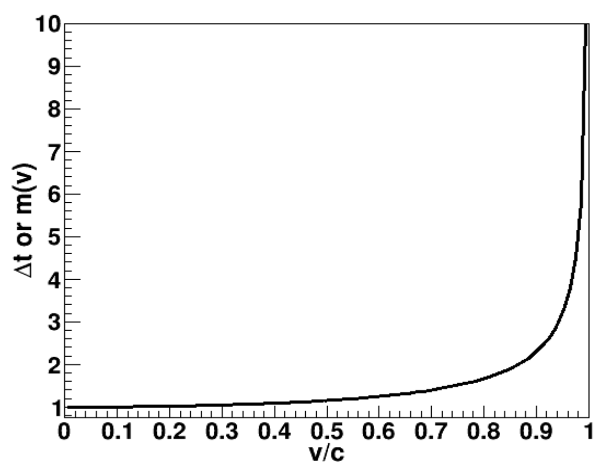

Figure 3: *Growth in mass or time dilation as the speed of the moving clock increases.*

The dilation in time approaches a knee point when the velocity of the moving clock becomes comparable to that of the light (c). However, it is another physics law which stops any material object from attaining velocity greater than that of light. The time interval Δt, measured by a moving clock change from the stationary clock's time t_0 using the following relation.

$$\Delta t = \frac{\Delta t_o}{\sqrt{\left(1-\frac{v^2}{c^2}\right)}} \tag{6}$$

The dilation curve of time as a function of the parameter speed of the observer (v) is as shown below in the Figure 3. Similarly, a change in mass is another phenomenon in the relativistic physics which follows a J-curve when studied with respect to the velocity of the observer. The mass of the moving particle (m) increases as the time dilates and follows the equation:

$$m(v) = \frac{m_o}{\sqrt{\left(1-\frac{v^2}{c^2}\right)}} \tag{7}$$

where m_o is the mass of the same object when it is stationary. There is singularity around the point v/c = 1, physically meaning thereby when the speed of the particle approaches the speed of light. Long back, physicists have developed very powerful & well-behaved technique, i.e. 'renormalization' to handle these singularities. And all these finer (quantum)effects are measurable and stands confirmed experimentally. Similar effects also occur in non-linear complex systems, nanoscience of materials, fluid dynamics, chaotic dynamics, cosmology, etc. In fact, physicists are used to such curves and are very comfortable in handling singularities and very effectively. From a social physics point of view, it is important to identify the point where the system turns chaotic and goes out of control and it further must be avoided by resetting the corresponding critical parameters.

III. THE SUPER EXPONENTIAL GROWTH AND THE SIGNIFICANCE OF INNOVATIONS

Some of the super-exponentially growing phenomenon which are of special interest are discussed in this section and the subsequent occurrence of '*finite time singularity*' is also highlighted**.** Such type of growth applies to many human-created technologies such as computer memory, transistors, microprocessors, DNA sequencing, magnetic storage, the number of internet hosts, internet traffic, decrease in device size, nanotech citations & patents, etc. Data on human population growth on large time scale & the growth of financial and economy indicators strongly support the theoretical prediction that we have been growing super-exponentially and are indeed heading towards such a singularity.

A. Human Population 'Explosion'

Human population growth is one of the most relevant examples of super-exponential growth with a very sharp knee as shown in Fig. 4. Contrary to bacterial growth exhibiting a normal exponential curve, which means a constant bend and a constant doubling time, human population is found to rise super-exponentially until the 1960s.

This was the case starting with the introduction of agriculture ten thousand years ago. There are a few 'knees' for this type of development areas where the curve shifts to an even faster super-exponential growth mode in the curve to the right. Different knees in the curve embark periods of major technological, industrial or medical revolutions. Due to the immense efficiency released by the Industrial Revolution, the sharpest knee is observed between 1700 and 1900. Another knee appeared in the middle of the 20th century, when growth accelerated to the point that it seemed vertical and was trending towards infinity in a limited amount of time.

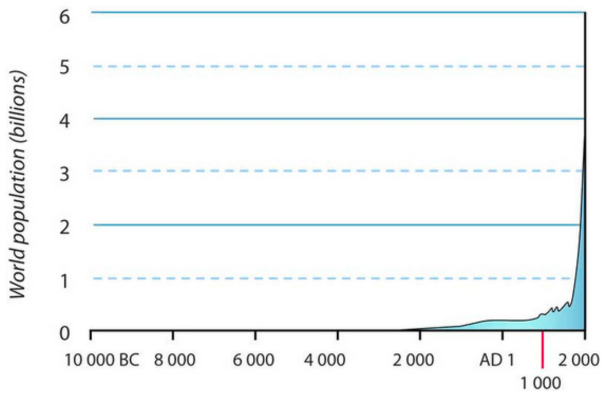

Figure 4: *Global Human Population, 10,000 BCE to 2000 CE [16]*

As our civilizations advanced, surviving family sizes continued to increase as death rates declined as a result of improved hygiene and as food became more freely accessible. The major cause of the super-exponential expansion of the standard exponential growth curve was the increasing number of surviving family members. Heinz von Foerster, an eminent theorist, published an essay on the population explosion in Science (1960) [17], and was titled '*Doomsday: Friday, 13, November, A.D. 2026*'. He pointed towards the super-exponential type of growth in human population and predicted a singularity in the growth which will occur by the end of 2026 when the human population will become infinite. There are different social factors which change over time and pushes this singularity to an infinite future. Some of the societal factors are: social pressures to start limiting family size and to have children a little later in life started to be felt in practically every country by the mid- 20th century, greater female independence, easier access to birth control, increased education accessibility, and increased competitiveness for well-paying employment are all other contributing factors.

B. Speed Curve Trends

Technology has also been observed to have undergone J-curve growth cycles. One of the best examples is related to the advances in human transportation. The *US Air Force Office of Scientific Research* commissioned a study in 1953 to plot successive maximum speed curves for transport technologies. Each technology starting from pony express to trains and autos had their own growth curve and many such curves gave rise to an envelope curve as shown fig.5. This curve was used to predict where transport speeds would be going next [23,24].

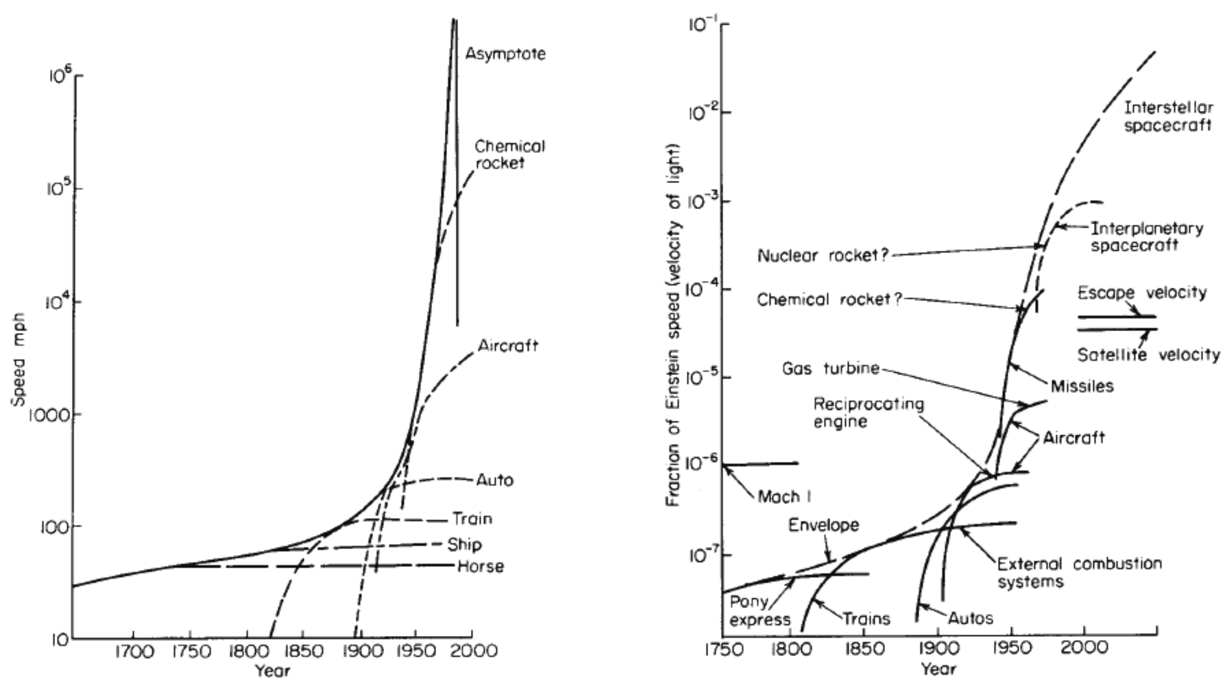

Figure 5 : *Speed Trend Curve (Source : [23,24])*

This was the case starting with the introduction of agriculture ten thousand years ago. There are a few ‘knees’ for this type of development areas. This study done by Martinox [23] had few interesting observations. The attainable speed curve has an envelope shape till 1953 with a super-exponential like growth structure appearing with the advent of chemical rocket missiles as compared to the previous gas turbine technology. From 1750 through the 1940s, the envelope curve had been super-exponential and curved up logarithmically. There is a knee point in the speed curve which shows prominent advancements in the technology with the advent of jet aircrafts. Another highlight of this study was the correct prediction from the extrapolation of graph that the satellite and escape velocity could be achieved in the years 1957 and 1959 respectively. It may also be noticed that the curve incorrectly predicts that spacecraft would achieve speeds of one thousandth the speed of light by the year 2000 and even faster speeds beyond that. Beyond missiles, Commercializable technology failed to emerge, and super-exponential expansion has temporarily come to a halt. With the present generation of technology, it appears that we have reached our financial and physical boundaries. This indicates towards a possible paradigm shift in the technology that should happen to go beyond the current limits.

C. Computing Technology

The advancement in computing technology in the past few decades has successfully been explained by the Moore’s law which states that the number of transistors on a integrated chip double after every two years. The exponentiality implicated by Moore’s law is a result of a series of innovations leading to shrinking sizes of the transistors. In 2009, Christopher Magee from MIT demonstrated that two-third of the growth in the computational technology is due to innovations in Materials [25]. Last few decades have seen a number of predictions reflecting the end of Moore’s law in terms of shrinking sizes of the devices & its electronic components, which haven’t been correct. The question remains that whether there will be an exception to Moore’s law? This arises from the fact that increasing the number of transistors on a chip is bound to saturate due to various factors. The manufacturers are increasing number of processors on a chip making then multicore and have temporarily shifted their focus from increasing the speed of a single processor. Also decreasing the size of the transistors will at some point bring down the size of ‘information carriers’ to atomic level or even to a single particle level. The optimism lies in the development of new technology which would take atoms or even electrons to represent one bit. This could further increase the density of transistors on a chip. Experiments are underway for using a single electron / particle or any other particle or even a quantum of light, the photon as the carrier of digital information. Such technologies are at different stages of laboratory-level research and are still far from public use at the moment. An alternate technology which is far from use at this point is the brain-like chip which would be immensely parallel. There are very few pioneers works on the behavior of neurons and are trying to implement the learnings to build a massively parallel bio-inspired-chips. One such interesting example is the SyNAPSE research project of Dharmendra Modha et al. [26,27] at IBM Research. Building and development of such parallel computing technology will lead to an exponential socioeconomic growth. As the shrinking of transistor has hit a saturation point, there is a need to further innovate to keep up the exponential and super-exponential growth in computing performance. It is anticipated that each technology will have its own Moore’s law with innovations in the field, leading to another round of the exponential & super- exponential growth.

D. Economic Growth

Another intriguing example of super-exponential development is economic growth. The economies appear to be seeing straightforward exponential development after a few decades. But when we examine economic growth over a sufficiently large of time-band, it looks to be super-exponential, as is seen with computing innovations.

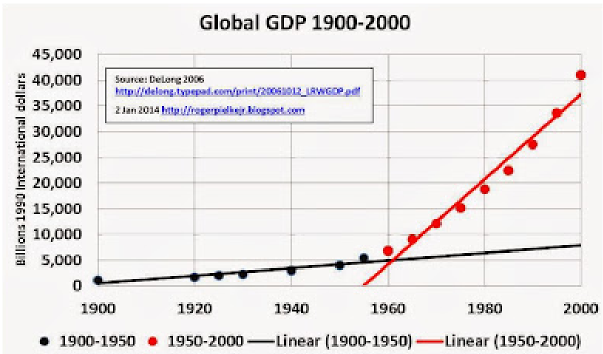

Figure 6: *Global GDP growth per capita (Sources: [28,29])*

Figure 6 shows the GDP per capita in Western Europe over a period of a thousand years as plotted by Angus Maddison in 1999 [28,29] - a famous economist working for Economist Intelligence Unit. The social parameters and outcomes are related. Similar to the human population, the J-curve of GDP growth shows its knee in the 1850s, at the height of the Industrial Revolution. From that time on, when plotted globally, GDP growth has seemed to be growing more vertical.In the 1960s, the population growth was saturating, however, whereas the global economic growth changed to an even steeper curve. Global economic growth is currently much faster than it was in 2000. In recent years, several Chinese cities have had yearly economic growth rates of over 20%, and many emerging nations' economies are expanding at rates far higher than the 2-3% annual worldwide pace we witnessed in the middle of the 20th century.

One of the interesting questions for the economists is that if the GDP growth will soon saturate, similar to the one we had seen in the computing technology or in the transport technologies. On first thought, it would seem logical to anticipate that it would. However, if this growth is primarily fueled by technical productivity and if technologies continue to experience fast exponential or super-exponential growth, GDP will continue to grow for some time to come. Nanotechnology and information technology automation & machine intelligence are becoming more capable of engaging in their own technical, economic, and intellectual discoveries, contests, and economic activities. These pursuits may progressively supplant human-driven technological, economic, and intellectual challenges.

IV. RE-SETTING THE CLOCK: QUEST FOR INNOVATIONS

In an interesting study [30], published as *Limits to Growth,* an eventual collapse of the environment and economy is predictable, if the patterns of the human behavior don't change (Fig. 7). A model is defined with five parameters, namely population, pollution, food production, industrialization, and consumption of nonrenewable natural resources. All of these factors were growing at the time of the research and were expected to continue to do so exponentially, while technology's capacity to expand resources grew only linearly [30]. These researchers [30], in fact, wanted to investigate if it was possible to construct a durable feedback loop by changing the growth patterns of the five variables. In four of the parameters an overshoot and collapse is projected. In the parameter *resources*, an exponential decline is shown.

The idea is that if the rate of resource use is growing, the number of reserves cannot be determined by simply taking the present known reserves and dividing them by the current yearly consumption, as is generally done to create a static index, was one of the main ideas of The Limits to Growth. These analyses have now been enhanced, and they now forecast a collapse that occurs far sooner than predicted by the "limits of growth" curve. Ever increasing rate of growth is indicative of the upcoming finite time singularity demanding appropriate remedial measures.

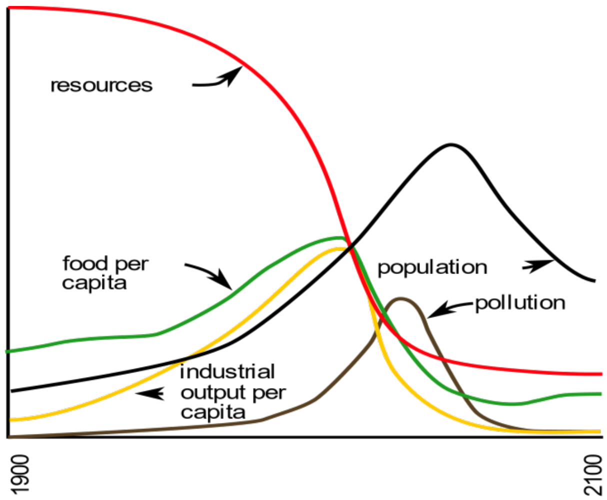

Figure 7 : *Limits of Growth*

The question of interest is how to avoid such a collapse while still manifesting the open-minded growth? One of the striking examples of appropriate & timely intraventions is the use of solar energy being aggressively promoted both at the community and industrial levels. This shall surely play an important role to flatten the energy curve and postponing the energy crisis. As a result, the use of renewable sources of energy is being emphasized over the fast-declining nonrenewable natural resources.

As in the discipline of physics, the existence of the singularity predicts transition of system from one phase to another phase with quite different properties (e.g. the transition steam↔water↔ice). Unfortunately, for cities & socioeconomic systems the phase transition (stimulated by finite time singularity) is from super exponential growth to stagnation & collapse, and this could lead to potentially devastating situations as shown in Figure 7. This graphics summarizes the fact that population, pollution, industrial growth and food per capita are all inter-related and may hit a stagnation and potential collapse in the coming years, and appears to be governed by similar quantitative models of growth.

These forecasts or anticipations presuppose that the parameters of the growth equation remain same and many a times constant. This might not actually be the case. For example, at a stage when Moore's law shall go down to the atomic scale, newer parameters prevalent at nano & quantum scales, shall become predominant and therefore would require altogether different innovative modelling.

Therefore, '**resetting the parametric space**', before the singularity is reached, is a clear technique for preventing a possible disaster. Additionally, the driving term in the equation—'social metabolism'—must continue to be superlinear for the new dynamic to be driven by the positive feedback forces of social interaction that are responsible for innovation, as well as for the creation of wealth and knowledge. ***Such an 'intravention' is usually referred to as an 'innovation'.*** A major innovation effectively resets the clock by changing the condition under which the system has been operating and driving the growth. In order to stop the imminent singularity and prevent collapse, a newer innovation that resets the clock must be introduced. This will allow growth to continue. Major innovation may be viewed as a mechanism to circum-navigating the potentially devastating discontinuity seen in the limited temporal singularity, so as to ensure a smooth transition to a new phase. Once the change has been made and the "clock" has been "reset" in order to prevent stagnation and collapse, the process starts afresh with the continuance of super-exponential growth, eventually leading to a new finite time singularity that must also be avoided. Here it may be noted that the basic dynamics and therefore the growth-equation (now with the different set & values of the parameters) remains the same. The entire sequence is repeated, thus delaying any potential collapse as far into the future, as human resourcefulness, ingenuity, creativity & inventiveness allow.

This can be restated as a sort of **theorem*: 'to sustain open-ended growth in the light of resource***

limitation requires continuous cycle of paradigm shifting innovations'[Fig.8]. Breaks between consecutive phases are not sharp & discontinuous but are smeared out over related short period of time around each transition. Important point here is also to note is that the results of one stage are used to create the next stage. On grand scale the discoveries of iron, coal, computation, and most recently, digital information technology are among major innovation that have fueled our continued growth and expansion. But the time-intervals of successive approaches of singularity ('innovations') have continuously decreased (Fig.8: $\Delta t_1 > \Delta t_2 >> \Delta t_3$). Instead, the history of such discoveries is a testament to our extraordinary ingenuity [31].

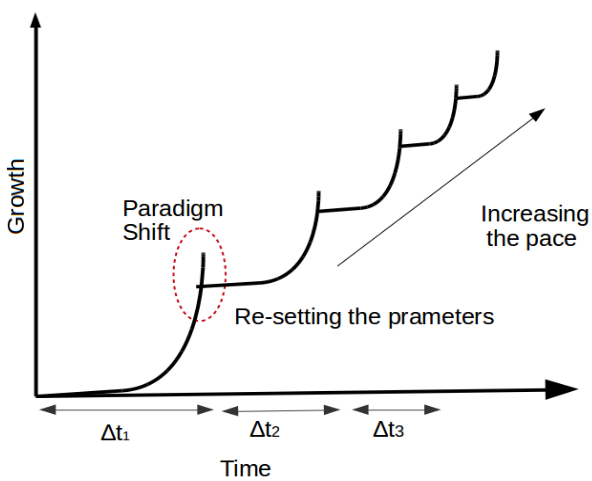

Figure 8 : *Paradigm shifting cycle of innovations relevant for a continuous growth.*

Thus, the underlying theory dictates that to sustain *continuous growth the time between the successive innovations has to get shorter and shorter.* Thus paradigm – shifting discoveries, adaptations and innovations must occur at an increasingly quicker & quicker accelerated pace. Not only does the general pace of life inevitably quickens, but we must innovate at a faster and faster rate!! This is an extraordinary scenario. Nevertheless, the scenario these successive accelerating cycles of faster than exponential growth predicted by the theory are consistent and well supported by the data for growing cities, technological changes, the human's world populations among several other such examples growth cities, wave of technological change, etc. as shown in Figs. 4-7. One of the issues here is, deciding which one out of the enormous numbers of possible innovations constitute major paradigm shifts. To some extent, this lies in the eye of the beholder. But, most of us would agree that certain discoveries and innovations such as printing, coal, the telephones, & computers constitute a major "paradigm shifts", whereas railways & cellphone may be more debatable.

It is the very nature of a super-exponential growth that future becomes the present at an increasing more pace, so much so that by the time a problem has arisen it's often too late to address it successfully. Given the general attitude towards this silent threat of exponential expansion it is important to realize its implications.

Almost all aspects of our lives have been speeding up during our lifetimes. Howsoever big hurdles & challenges of life one overcomes & leaves behind, one has to keep up ever-present treadmill that seems to be getting progressively faster and faster. The inbox is always full no matter how many messages we delete and how many we answer. Many a times one will find oneself dangerously behind with completing not just this year's but last year's taxes. There are continuous seminars, meetings, and events that one would love and are supposed to attend, but one would struggle to remember the semi-infinite number of passwords, that allows him to access himself through his various accounts and affiliations, and on and on. Each one of us surely has our own version of this, a similar litancy of time pressures that never seems to abate no matter how hard we try to defeat them. And this is even worse if one lives in a large city, have small children, or ran a business. This speeding up of the socioeconomic time is integral (rather hallmark of) to modern life is the Urbonocene.

V. CREATING THE ECOSYSTEM FOR INNOVATIVE MINDS

A collaborative approach between Academia and industry is required to make an environment suitable for innovating minds [32]. The fundamental research done by the Academia cannot be ignored, which has time and again removed the stagnancy and death in preceding innovations. Technology is made possible by science, which also in-turn serves as the foundation for technology-driven innovation. The development of microchips with billions of transistors was ultimately made possible by the science of precise atom control in semiconductor materials. Cell phone screens were made possible by the physics behind the growth of silicon carbide and gallium nitride single crystals. Flat panel displays were made possible by the technology of laser crystallization of amorphous silicon. Digital cameras were made possible by the technology of hot electron injection in thin layers of insulators.

A discovery resulting from fundamental research must travel a long and difficult path before becoming a commercially available good, method, or service. A deeper comprehension of fundamental physics usually leads to innovations in the industrial sector. Often referred to as spinoffs, engineering inventions resulting from scientific findings frequently serve purposes other than that of the initial investigations. Numerous examples may be found in many different domains, such as space physics, laser physics, plasma theory and their technologies. Initial purely scientific research has greatly benefited high voltage circuit breakers, ozone generators, high power CO_2 lasers, excimer bulbs, and plasma projection panels. The newer avenues, including the internet, www, data science, and data cleaning algorithms, a variety of novel materials, ultra-high vacuum methods, high precision measurement technologies, a number of medical technologies etc., have all developed from experimental high energy physics (HEP). Many of these sectors have developed into multi-billion-dollar industries over time [33].

In summary, the training of *physics offers a strong foundation both in terms of materials as well as the requisite imaginative & innovative mindset;* The discipline of physics has seen several phases in the last century. Prior to the 1970s, it was an era of nuclear physics mixed with cosmic-ray physics, followed by a few decades belonging to high-profile particle physicists. Since around year 2000 & thereafter, it has been nano-science& nano-technology, growing nano-structured new materials & crystals, all throughout. In last 50 years of so, there has hardly been any big breakthrough idea or a quantum leap experimentally, although there has been significant advancement in high-precision science experimentation & new technological spinoffs thereon. Simultaneously, the recent past has seen the emergence of new directions like environmental physics, physics of life & living systems, physics of medicine, physics of sustainable developmental studies, social physics. etc., which are expectedly highly multi-disciplinary & inter-disciplinary in nature. The physics of active matter is another interesting major subject of research in recent times. Examples abound amidst the flowing, orderly, and leaderless flocks of birds in the natural world, structure forming cytoskeletons of cells, etc. More recently, Social physics or sociophysics can be described as the study of human crowds by using mathematical tools inspired from physics. It is interesting to note that 'finite time singularity' occurs naturally in the growth equations in all these fields. And the challenge is to develop techniques to identify and pre-empt its occurrences. In modern commercial use, it can also refer to the analysis of social statistics and social dynamics using big data; and it also covers a quantitative study of human society & social statistics.

VI. DISCUSSION AND CONCLUSIONS

Innovations are must for a sustainable growth of any ecosystem, whether it is living, or non-living or a combination of the two. The aim is to develop a quantitative universal model and possibly a theory for the innovation. Toward this goal, we have attempted to model a scientific basis and a conceivable roadmap for quantitative analysis of innovations that characterizes paradigm shifts in a growing ecosystem found at different scales & sizes [1]. It has been observed that highly similar super- growth trends are being followed for most of the growing ecosystems around us covering wide range of scales, whether its living bio-systems or, corporations or even cities. This, indicate universal underlined mathematical structures for growth-oriented ecosystems covering a wide range of scales i.e. nano to astronomical scale. The time evolution of such systems is represented by a set of coupled nonlinear equations which are multivariate and involves a number of interdependent parameters. The solutions to these are characterized by occurrence of '*finite time singularities*' that signifies the onset of stagnation or a potential collapse. Ingenuity lies in developing techniques to avoid or push forward, in time coordinate, the singularity. This is achievable by identifying right set of parameters and undertake reparameterization in a way so as to ensure that the growth continues. History of humans is filled with instances supporting this hypothesis.

This paper highlights the fact that the large number of socioeconomic growing bio-systems follow a super exponential growth curve, steep-diving down into a finite time singularity. The super linear growth is very commonly studied in different physical phenomenon like, time dilation, Brownian motion, fractal analysis etc. The super exponential growth heads towards a potential stagnation and decline in the given socioeconomic biosystem. In the domain of physics also, such a situation is termed as a 'singularity' and is circumvented by the mathematical technique namely 'renormalization'. In the socioeconomic systems, such singularities can be pushed to the future by redesigning the parametric space that characterizes the paradigm shifts. Further, in order to sustain the smoothness of the growth curve, these paradigm shifts need to occur at an increasing pace.

This further indicate that the area of such research i.e. the ***social physics*** is indeed highly multi-disciplinary involving various branches of physical sciences, biology, and human sciences like psychology, various advanced technologies, computational techniques, data-science, etc.; wherein the basic laws of physics are likely to prove vital. That implies a newer perspective necessary for an effective, meaningful, and long-lasting social transformation, which is possible only through trans-disciplinary working methodologies. The progress in these directions is crucially dependent on establishing strong and intellectually-vibrant inter-disciplinary research communities that include physical scientists, mathematicians, & biologists and of course the social scientists who are open to insights from outside their respective domain. It is rightly emphasized by K.K. Aggarwal [34] that ".... *only the most enlightened ones can be an effective change agent. Otherwise, the change is made for the sake of change and (for all the wrong reasons) may end up with chaos*...". Generating a workforce with such a mindset, involves new type of well-structured training and appropriate intraventions; in fact, calls for an overhauling & redesigning of our entire formal education-imparting ecosystem. Developed nations have their education policy synchronized to creating a workforce with innovative mindsets. The developing nations should also work to align their education policy to inculcate a culture for multidisciplinary and interdisciplinary research coupled with design thinking. One recent example has been initiated in the form of recent *New Education Policy* (NEP 2020) of India [35,36].

The expected universal theory of innovation shall also prove to be a powerful tool in achieving *Sustainable Development Goals* (SDGs) enunciated by UNO for sustainable life for all on this planet. In the present work, we have attempted to develop a line of thought and provided a scientific basis for a possible universal theory of innovation for sustainable growth which would require paradigm shifts at an increasing pace. The basic principles in physical sciences are used to develop a solid foundation for understanding the human-centric growth centered phenomenon in the spirit of social physics. In near future, the authors plan to carry forward this work by applying it to the more exhaustive data and develop rigorous analysis in the spirit of the prescription laid down by Tunner [37] for developing theory in social science. Nevertheless, an interesting fundamental question remains, i.e. '*whether to innovate is basic characteristics of social universe*'; and needs serious investigation.

ANNEXURE- A

For completeness we give here the relevant equations that represents the time-evolution of any (complex) system represented by a set of n-functions: f_i (x_1, x_2, x_3, … x_N; t) of N variables (x_j); $1 \le j \le N$, where $1 \le i \le n$. The most general growth equation is

$$\frac{\partial f_i(x_1,x_2,x_3,\dots,x_N;t)}{\partial t} = \sum_{0\le m\le p}\sum_{1\le k\le n}\sum_{1\le j\le N} \alpha_{ijkm}\frac{\partial f_k^m\ (x_1,x_2,x_3,\dots,x_N;t)}{\partial x_j} \quad \text{(A1)}$$

wherein, the α_{ijkm} are set of n x N x n x p parameters. The eqn. (A1) is coupled and also nonlinear (m is exponent).

The simpler form of eqn.(A1) is

$$\frac{\partial f_i(x_1,x_2,x_3,\dots,x_N;t)}{\partial t} = \sum_{1\le k\le n}\sum_{1\le j\le N} \alpha_{ijk}\frac{\partial f_k(x_1,x_2,x_3,\dots,x_N;t)}{\partial x_j} \quad \text{(A2)}$$

Here α_{ijk} are set of n x N x n parameters. This eq. (A2) is coupled, but still linear.

A still simpler form of the equation can then be written as

$$\frac{\partial f_i(x_1,x_2,x_3,\dots,x_N;t)}{\partial t} = \sum_{1\le j\le N} \alpha_{ij}\frac{\partial f_i\ (x_1,x_2,x_3,\dots,x_N;t)}{\partial x_j} \quad \text{(A3)}$$

Here the α_{ij} are n x N parameter. This set of equation **is** neither coupled and nor nonlinear.

ACKNOWLEDGMENT

Interesting and useful discussions with Professors K.K. Aggarwal, R.C. Verma and Manjit Kaur are gratefully acknowledged. Authors are also thankful to them for critically going through the final manuscript.

REFERENCES AND FOOTNOTES

1. L.M. Branscomb, *Technological Innovation*, chapter in book '*International Encyclopedia of the Social & Behavioral Sciences*', Oxford, 15498-15502 (2001).
2. Geoffrey West, The Scale", Penguin Press (2017).
3. Thomas Sturm, Scientific innovation: 'A conceptual explication and a dilemma' *History and Foundations of Science*, 34(3), 321 (2019).
4. P. Ball, *Why Society is a Complex Matter*, Springer, Berlin (2012).
5. ***Social physics*** or ***sociophysics*** is a field of science that uses mathematical tools inspired by physics to understand the behavior of human crowds. In modern commercial use,

it can also refer to the analysis of social phenomenon with big data; and it covers social statics and social dynamics, an quantitative study of human society & social statistics. For a review see: Marko Jusup et.al, *'Social Physics'*, Phys. Rep. Vol. 948, 16 Feb. 2022, p. 1-148; V.I. Yukalov, Physics **5** (2023) p. 704-75 and references therein**.** (link : https://doi.org/10.3390/physics5030047

6. M. Jusup *et al*, Social physics, Physics Reports **948**, 1-148 (2021).
7. J. Q. Stewart*, 'The Development of Social Physics',* American Journal of Physics,**18** (5), 239 (1950).
8. M. Perc, '*The social physics collective*', Sci Rep**9**, 16549 (2019).
9. D. Lazer et al., *Computational social science*, Science **323**, 721 (2009).
10. K. J. Niklas, U. Kutschera, '*Kleiber's Law: How the Fire of Life ignited debate, fueled theory, and neglected plants as model organisms*', Plant Signal Behav**. 10,** 7 (2015).
11. M. Cerrolaza et al, *Numerical methods and advanced simulations in biomechanics and biological process*, Academic Press (2018).
12. J. Mendelsohn et al*, The Molecular Basis of Cancer*, Saunders, (2015).
13. F. P. Gustav et al*, The effect on income distribution of development, the growth rate and economic strategy*, Journal of Development Economics **23,** 55 (1986).
14. S.V. Buldyrev*, Fractals in Biology* chapter in: R. Meyers, (eds) *Encyclopedia of Complexity and Systems Science*. Springer, (2009).
15. G.A. Losa, T.F. Nonnenmacher, *Self-similarity and fractal irregularity in pathologic tissues*, Mod Pathol. **3**, 9 (1996).
16. M. Scott and T. Hwa, *Bacterial growth laws and their applications*, Current Opinion in Biotechnology 22, 559 (2011).
17. Heinz Von Foerster, Patricia M. Mora, Lawrence W. Amiot, '*Doomsday: Friday, 13 November, A.D. 2026*', American Association for the Advancement of Science, *Science* **132**, 1291 (1960).
18. D. Wodarz, On the laws of virus spread through cell, J. Virol**2**, 89 (2015).
19. Arthur Beiser, *Concepts of Modern Physics*, (Ed. 5). New York: McGraw – Hill (1995).
20. Yeh Jia- Rang et al, Scale-dependent intrinsic entropies of complex time series, Phil. Trans. R. Soc. A **374**, 20150204 (2016).
21. The term '***singularity***' comes from astrophysics and particle physics wherein it is used to refer to a point in space-time where the rules of ordinary physics do not apply. Mathematically it is a point for which a mathematical function is not defined.
22. Stagnation is prominent in the growth following S-curve. For more detailed discussion, refer to [2].
23. Joseph P Martino, '*An introduction to technological forecasting*', Gordon and Breach (1973).
24. R.U. Ayres, '*Technological Forecasting and Long Range Planning*' New York: McGraw-Hill (1969).
25. C.L. Magee, S. Basnet, J.L. Funk, C.L. Benson, *Quantitative empirical trends in technical performance,* Technological Forecasting and Social Change 104, 237-246 (2016).
26. A. Andreopoulos *et al*., "*Visual saliency on networks of neurosynaptic cores,* "IBM Journal of Research and Development**, 59** 9:1-9:16 (2015).
27. Dharmendra Modha, Video on 'The Synapse Project' *https://insidehpc.com/2013/07/video-cognitive-computing-with-the-synapse-project*
28. Angus Maddison*, The World Economy: A Millennial Perspective,* OECD Development Centre (2001).
29. Angus Maddison*, Monitoring the World Economy: 1820 -1992*, OECD Development Centre (1995).
30. D. H. *Meadows et al, The limits to Growth; A Report for the club of Rome's Project on the Predicament of Mankind, Universe Books, (1972).*

31. I. Sam Saguy, *Academia-Industry Interaction in Innovation: Paradigm Shifts and Avenues for the Future*, Article in Procedia Food Science (2011).
32. D. Skalkos, *Advanced Food Products Prepared Through Academic and Industry Collaboration*. International Journal of Innovation and Economic Development, ***6(5)***, 7 (2020).
33. Ulrich Kogelschatz, *Plasma Sources* Sci. Technol. **11**A (2002).
34. K.K. Aggarwal (*Private communication*), Inter-disciplinary research approach is already promoted and followed at many institutions including the IPU with which the authors have the honor to be associated with.
35. H. Verma and A. Kumar, *New Education Policy 2020 of India: A Theoretical Analysis.* Intl. Journal of Business and Management Research **9**, 302 (2021).
36. Weblink:*https://www.education.gov.in/sites/upload_files/mhrd/files/Draft_NEP_2019_EN_Revised.pdf*
37. J. Tunner, Humbolt J.of Social Relations, 17, 1 (1979/80). Weblink: *https://www.jstor.org/stable/2326175*