A general case study of complexity science: analytical and logical interconnection between soft and hard sciences

Jack Jia-Sheng Huang[1,2] and Yu-Heng Jan[2,1]

[1]Source Photonics, 8521 Fallbrook Avenue, Suite 200, West Hills, CA 91304, USA

[2] Source Photonics, No.46, Park Avenue 2nd Rd., Science-Based Industrial Park, Hsinchu, Taiwan, R.O.C.

ABSTRACT

Complexity science is gaining popularity due to its unique approach to address convoluted and multi-dimentional problems. In this work, we present a general case study of complexity science by means of analytical and logical interconnection between soft and hard sciences. Hard sciences such as semiconductor technology and biology may branch out and offer useful analogous thinking for the study of soft sciences such as health care and social science.

Keywords: Complexity science, hard science, soft science, interconnection, logical thinking, analytical thinking

1. INTRODUCTION

Complex science is an emerging scientific field that studies the common properties of systems considered complex in nature, society and science [1]. It is a broad and multi-disciplinary subject dealing with complex systems and problems that are dynamic, unpredictable and multi-dimensional, consisting of a collection of interconnected relationships and parts [2,3]. The interest in complexity science is being driven predominantly by new challenges and demands in technology [4]. Various industries are becoming increasingly aware that traditional approaches to design and engineering are increasingly difficult to keep up with the increasing scale of today's systems. Complexity science touches on almost all aspects of modern science and technology.

One important mission of complexity science is to find linkage between different research fields such as health care [5], semiconductor technology [6-8], biology [9], and social sciences [10-12] as illustrated in Fig.1. In this study, we present a general case study of complexity science by means of analytical and logical interconnection between the soft and hard sciences [13,14]. We discuss the linkage between different fields in soft and hard sciences and demonstrate how to apply the analytical thinking to folster interdisciplinary communication.

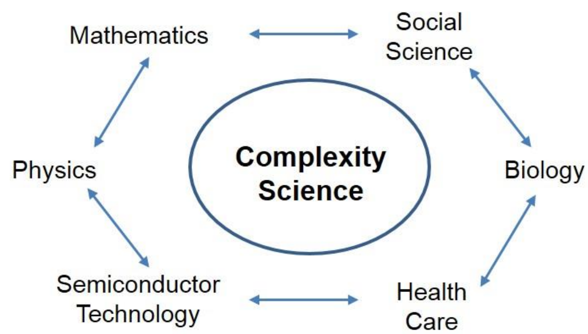

Fig. 1: Schematic of complexity science and its applications in different fields.

2. RESULTS and DISCUSSIONS

The different fields shown in Fig.1 can be further categorized in two branches. The first branch is called hard science that includes semiconductor technology and biology. We attempt to utilize the experimental data collected from hard science to

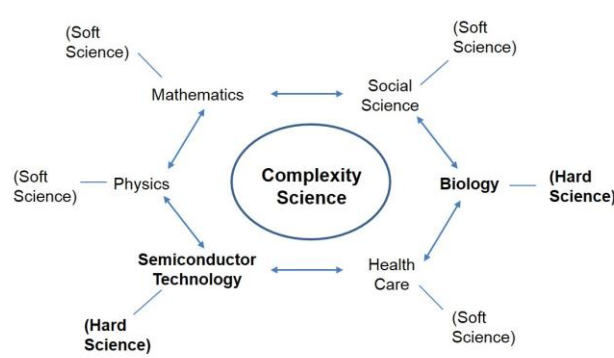

Fig. 2: Schematic of complexity science branched in terms of hard and soft sciences.

analytically and logically internnect with the other branch called soft science. The soft science in our study includes health care, social science, mathematics, and physics.

In the area of hard science, scientists and engineers use the scientific method to analyze the phenomenon observed in nature [15]. The experimental evidence observed in hard science provides very useful information for the study of complexity science. In the following, we discuss the interconnection between the soft and hard sciences using interdisciplinary method. We explain the detailed analogy and similarity in each case.

2.1 Semiconductor Technology and Health Care

Here, we list three examples of experimental findings in semiconductor technology that show striking similarity to the phenomena of health care as shown in Table 1.

The first phenomenon is gradual degradation in semiconductor lasers due to defect formation [16,17]. Such gradual degradation usually occurs in a slow fashion and does not lead to immediate dead failure. In analogy, human beings and animals also experience similar type of degradation in their bodily functions as a result of aging.

Table 1: Interconnection between semiconductor technology (hard science) and health care (soft science).

	Semiconductor technology	Health care
Similarity-1	Gradual degradation over long aging time	Degradation of bodily function due to aging
Similarity-2	Soft degradation or latent damage after ESD stress	Diseases of civilization (anxiety, high blood pressure, high cholesterol, etc.)
Similarity-3	Non-critical visual defects (coating overspray, laser line particles, etc.)	Benign soft tissues (skin cysts, polys, lipomas, etc.)

The second similarity is between soft degradation in semiconductor devices and diseases of civilization in humans. For semiconductor, the devices that are subject to external stress such as electrostatic discharge (ESD) transient often exhibit latent degradation or exhibit no damage but with increased sensivity to further stress [18,19]. This type of device degradation is typically not fatal, but may degrade its tolerance to future stress to some extent. Today, diseases of civilization such as anxiety, high blood pressure, and high cholesterol are affecting millions of people. The adverse effects of such diseases include the loss of sleep, appetite, and happiness. Although it is deviating from perfect condition, such adversity is unlikely to result in any serious disease or death for most patients. Humans infected with such diseases typically can continue to live well with proper medication and treatment.

The third similarity is between visual defects of semiconductor devices and benign soft tissues of humans. Many of the visual defects in semiconductor devices are harmless [20]. For example, the laser diodes that show imperfect visual appearance often continue to function properly. In most cases, the visual defects such as coating overspray, terracing, facet contamination, particles on laser lines, and bondpad scratches are benign and only represent cosmetic issues that would not affect device performance and functionality. Interestingly, similar visual imperfections also appear in humans, who may develop growth of benign soft tissues such as skin cysts, polys, and lipomas. In most cases, those tissues are not life threatening.

2.2 Health Care and Biology

Health care is also tightly linked to medical branches of biology such as immunology, medicine, and physiology [21,22]. The knowledge of medical biology in hard science lays the foundation of health care in soft science. Table 2 shows two examples of inter-relationship between health care and medical biology.

Table 2: Examples of inter-relationship between health care and biology.

	Health care	Medical biology
Relation-1	Psychology (emotional and mental rehabilitation)	Psychiatry (medication treatment and management)
Relation-2	Physical therapy	Physiology and Surgery

The first example is psychology for soft science and psychiatry for hard science [23,24]. The two fields can achieve their synergy when they work together additively. Psychiatrists and psychologists often work together in the treatment of mental health patients. Psychiatrists prescribe medications to help patients adjust their chemical imbalance for the treatment of mental disorders, while psychologist focus on patient's thoughts, feelings, and general mental health. Psychiatrists often refer patients to fellow psychologists to receive counseling and/or mental therapy.

The second example is between physical therapy in health care and medical physiology in biology [25]. The latter is a branch of biology that deals with the functions and activities of life or living matter such as organs, tissues or cells. Due to the interplay between these two fields, physiology has gradually evolved to include a subset called exercise physiology. Exercise physiology studies the biological effect of exercise on the body's cells and organs, seeking to relieve symptoms through the cellular effect of exercise on the body. The practice of exercise physiology also seeks to prevent chronic diseases or to provide health benefits to those suffering from disease. Exercise physiology treats diseases such as diabetes, cardiovascular disease, and obesity. On the other hand, physical therapy focuses on restoring movement to the restricted parts of the body due to injuries or aging. The goal of physical therapy is to improve the quality of life through improved functional abilities and fitness.

2.3 Biology and Social Science

Social science is considered a branch of biology. Both biological system and social society exhibit cycles. For example, the most important cycles in the biological systems include the carbon cycle, nitrogen cycle, oxygen cycle, phosphorus cycle, water cycle, and boom and bust cycle [26]. On the other hand, the cycles in social science include economic cycle, dynastic cycle, etc. Table 3 illustrates two examples of similarity between biological and social cycles.

The first analogy is between water cycle in biological system and economic cycle in human society. The water cycle describes the continuous movement of water on, above and below the surface of the Earth [27,28]. The mass of water on Earth remains fairly constant over time but the partitioning of the water into the major reservoirs of ice, fresh water, saline water, and atmospheric water is variable depending on a wide range of climatic variables. The water moves from one reservoir to another, such as from river to ocean, or from the ocean to the atmosphere, by the physical processes of evaporation, condensation, and precipitation. For human society, there are several cycles of creation and destruction including economic cycle and money flow in stock market [29].

Table 3: Examples of analogous similarities between biological and social science cycles: creation and destruction processes.

	Ecological biology	Social science
Analogy-1	Carbon, nitrogen, oxygen, phosphorus, and water cycles	Economic cycle; money flow in stock market
Analogy-2	Boom and bust cycle (predator-prey cycle, population growth cycle, etc.)	Dynastic cycle (Chinese dynasty, etc.); Political cycle

The economic cycle is the natural fluctuation of the economy between periods of expansion (growth) and contraction (recession). During times of expansion, increased production leads to a lower unemployment rate that further increases demand. Increased wages lead to higher demand as consumers spend more freely with positive consumer sentiment. During times of contraction, unemployment rate is higher that reduces consumer demand. The lower spending further lower corporate's profit that further reduces business spending and employment [30,31]. Similar to the water cycle, the stock market operates as a closed system with all investors playing a zero-sum game. It is a continuous capital movement where the stock price is rising when demand is over supply or dropping when supply is over demand.

The second analogy is between boom and bust cycle in biology and dynastic cycle in human society. One vivid example of boom and bust is the predator-prey cycle. For instance, if the bear population grows particularly large in one year, the increased population will require more fish to feed it. This will make the salmon population to shrink. When the supply of salmon becomes less, there will be fewer food for all of the bears to eat. Some bears will starve and fewer cubs will be able to prosper, leading to a smaller overall population the next year. As more time passes and the bear population gets smaller, and the salmon population will start to increase again due to fewer natural predators.

In human society, man-made cycles such as cyclical change of political party or ancient dynasty tend to repeat their historical patterns. At the beginning of a dynasty, the new ruler normally employed benevolent domestic policy to achieve prosperity and harmony [12]. The growth cycle leads to population increase. After a few generations, the relative social equity or fairness start to decrease. The corruption and overpopulation cause famine and rebellion. The dynasty declines and enters periods of instability. Eventually, the dynasty gets overthrown by a new ruler to start a new cycle.

2.4 Social Science and Mathematics

During the advancement of human civilization, algebra was invented before century (B.C.) to enable people to perform calculation [32]. As shown in Table 4-1, one important application of algebra from mathematics is the price-earnings (P/E) ratio and interest rate in social science. In financial markets, P/E is an important parameter of measure for corporate's stock price [33]. The P/E is basically the inverse of interest rate. The higher the P/E, the more expensive the stock is compared to the interest earned from the bank.

Table 4-1: Examples of inter-relationship between social science and mathematics.

	Social science	Mathematics
Relation-1	P/E is inverse of interest rate	Algebra $Y=1/X$
Relation-2	Compound effect	Binomial expansion $Y=P(1+a)^n$

The other important economic phenomenon of social science is compounding effect [34]. Albert Einstein once called compound interest "the eighth wonder of the world" [35]. One of the key reasons that Warren Buffett is regarded as the greatest investor in the world is his persistent finanical return from his investment [36]. Over 70 years of investment, his constant return has earned him the top five richest man in the world due to the power of compound effect. In mathematics, the compound effect originates from the binomial expansion. When the exponent (n) is small, the binomial may yield similar results compared to the linear multiplication $Y=P(1+na)$. Nevertheless, the binomial would become very significant when n is large. To illustrate the power of compound effect, we look at the annual return for 10, 20, and 30 years with and without the compound effect based on the 8% annual return, as shown in Table 4-2. Without the compound, the total returns based on pure multiplication are 80%, 160% and 240%, respectively. In comparison, the total returns after the compound become 116% for 10 years, 366% for 20 years and a staggering 906% for 30 years. Such compound growth has often manifested itself in the financial reward of 401k retirement account when a proper investiment portfolio is elected.

Table 4-2: Illustration of compound effect: total return with and without the compound.

Total return	10 years	20 years	30 years
8% annual return - No compound	80%	160%	240%
8% annual return - Compound	116%	366%	906%

2.5 Mathematics and Physics

Mathematics and physics are closely tied together. The knowledgement advancement of physics would have been slower without the great help from mathematics. There have been numerous notable inter-relationship examples of mathematics and physics. Table 5 lists two of the renowned examples: harmonics equation for classical mechanics [37] and Maxwell's equation for electromagnetics [38].

Table 5: Examples of inter-relationship between mathematics and physics.

	Mathematics	Physics
Example-1	$-kx = m\frac{d^2x}{dt^2}$	Classical mechanics-Harmonics equation
Example-2	$\frac{1}{\mu}\nabla xB = J + \varepsilon\frac{\partial E}{\partial t}$ $\nabla xE = -\frac{\partial B}{\partial t}$ $\varepsilon\nabla \cdot E = \rho$ $\nabla \cdot B = 0$	Electromagnetics-Maxwell's equations

The first example of the mathematical application in physics is the second derivative operation. For the harmonics oscillator equation in classical mechanics, the equation of motion for the harmonic oscillator may be derived from Hooke's law and Newton's second law where k is the spring constant, x is the displacement, m is the mass and d^2x/dt^2 is the second derivative of displacement or acceleration.

The second example of the mathematical utilization in physics is the vector operation. The Maxwell's equations in electromagnetics provides good general description of the relationship between the electric and magnetic fields. In the four Maxwell's equaions, the electric and magnetic fields are related to each other by means of vector and multiplication operations, where E is the electric field, B is the magnetic field, and J is the current density. The constants μ is the permeability, ε is the permittivity, and ρ is the resistivity.

2.6 Physics and Semiconductor Technology

Semiconductor transistor was first demonstrated in 1947 by three Bell Labs researchers, John Bardeen, Walter Brattain and William Shockley [39,40]. The underlying physics of transistor operation is based on band diagram of p-n junction where conduction band and valence band are separated by a bandgap energy defined by a given crystal structure. When semiconductor materials are doped into n-type, there are excess of electrons for transport in the conduction band. For a p-type semiconductor, there are excess of holes that can transport in the valence band. Combing the two materials into p-n junction would permit the operation of transistor where minority carriers of electrons and holes can be engineering tailored to meet the performance specification. By using the doping engineering, bipolar transistors (made of emitter, base, and collector) and unipolar or field-effect transistors (consisting of source, drain, and gate) can be devised for practical applications [41].

Table 6: Examples of Interconnection between physics and semiconductor technology.

	Physics	Semiconductor technology
Connection-1	Electrons and holes in semiconductor band diagram	Semiconductor transistor
Connection-2	Population inversion and direct bandgap	Laser diode

Semiconductor laser diodes utilize the physics of population inversion and direct bandgap [42,43]. For the latter, laser diodes are fabricated by employing direct bandgap semiconductors based on P-doped/intrinsic/N-doped structures. The active region of the laser diode is in the intrinsic (I) region, and the carriers (electrons and holes) from the N and P regions are pumped into the active region. During laser operation, electron and hole carriers are recombined in the I region, and the recombination energy is translated to light output. For the former, the population inversion occurs above the lasing threshold. A nearby photon with energy equal to the recombination energy can cause recombination by stimulated emission. This generates another photon of the same frequency, polarization, and phase, travelling in the same direction as the first photon.

3. CONCLUSIONS

We have presented a general case study of complexity science where the fields of semiconductor technology, health care, biology, social science, mathematics, and physics can be linked together. In our case study, we have shown explicit interconnection and analogy between the six different fields from hard and soft sciences.

By generating analogical thinking of input via inter-disciplinary communication, logical thinking of output can be enhanced to solve ever-increasing complexity in the future. We have demonstrated the feasibility of conducting multi-disciplinary approach by employing the creative aspects of analogical thinking to address the complex problems in scientific research and engineering design.

4. ACKNOWLEDGMENTS

The authors would like to acknowledge Prof. Nagib Callaos (President IIIS, Winter Park, FL) for the helpful discussions, Ashley Huang (UC, Davis) for review of the manuscript, and Emin Chou (Source Photonics, Taiwan) for support of this work.

6. REFERENCES

[1] https://en.wikipedia.org/wiki/Complex_systems
[2] A. Miles, "Complexity in medicine and healthcare: people and systems, theroy and practice", **J. Evaluation Clinical Practice**, vol.15 (2009), p.409-410.
[3] J. Ross and A.P. Arkin, "Complex systems: from chemistry to systems biology", **Proceed. National Academy Sciences**, vol.106, no.16 (2009), p.6433-6434.
[4] http://www.complexity.ecs.soton.ac.uk/
[5] J. Paley and E. Gail, "Complexity theory as an approach to explanation in healthcare: a critical

discussion", **Int. J. Nurs. Study**, vol.48, no.2 (2011), p.269-279.
[6] S.A. Kozlov, "Fundamentals of femtosecond optics", (**Woodhead Publishing**, Cambridge, UK, 2013).
[7] S.A. Kozlov, "Photonics and optical informatics", **National Research University of ITMO website**, St. Petersburg, Russia.
[8] J.S. Huang and Y.H. Jan, "Interconnected analogy and resemblence: from classical music to modern semiconductor technology", **Int. J. Electrical Electronics Engineering**, vol.5, issue 2 (2016), p.1-8.
[9] Fulvio Mazzocchi, "Complexity in biology. Exceeding the limits of reductionism and determinism using complexity theory", **EMBO Report**, vol.9, no.1, (2008), p.10–14.
[10] M. Benham-Hutchins and T.D. Clancy, "Social networks as embedded complex adaptive systems", **J. Nurs. Admin.**, no.40, issue 9 (2010), p.352-356.
[11] Z. Zhang, "The origin of intelligence, past, present and future of man", (**Apollo Science Publishers**, San Diego, CA, USA, 2008).
[12] R. Zahn, "Engineering perspectives of human society: application of control theory, game theory, and information theory to social phenomena", (**Nova Science** Publishing, New York, NY, USA, 2004).
[13] N. Callaos and J. Horne, "Interdiciplinary communication", **J. Systems Cybernetics Informatics**, vol.11, no.9 (2013), p.23-31.
[14] L.V. Hedges, "How hard is hard science, how soft is soft science?", **American Psychologist**, vol.42, no.5 (1987), p.443-455.
[15] Y.T. Lee, "Sustainability and science for all", **International Council for Science, International Innovation** (2013), p.38-40.
[16] J.S. Huang, "Design-in reliability for modern wavelength-division multiplex (WDM) distributed feedback (DFB) InP lasers", **Appl. Phys. Res.**, vol.4, no.2 (2012), p.15-28.
[17] J.S. Huang, Y.H. Jan, D. Ren, Y. Hsu, P. Sung and E. Chou, "Defect diffusion model of InGaAs/InP semiconductor laser degradation", **Appl. Phys. Res.**, vol.8, no.1 (2016), p.149-157.
[18] J.S. Huang, R.S. Miao, H. Lu, C. Helms, C. Wang and H. Demerci, "Theoretical and experimental thermal analysis of InP ridge lasers on submounts and TO packages", **IEEE Tran. Device and Mater. Reliab.**, vol. 7, no.2 (2007), p.363-368.
[19] J.S. Huang and H. Lu, "Size effect on ESD threshold and breakdown behavior of InP buried heterostructure semiconductor lasers", **The Open Appl. Phys.**, vol. 2 (2009), p. 5-10.
[20] J.S. Huang, T. Nguyen, W. Hsin, I. Aeby, R. Ceballo and J. Krogen, "Reliability of etched-mesa buried heterostructure semiconductor lasers", **IEEE Tran. Device Mater. Reliab**., vol. 5, no. 4, p.665-674 (2005).
[21] N.A. Campbell, L.G. Mitchell and J.B. Reece, "Biology: concepts and connnections", 3rd Ed. (**Addison Wesley Longman**, San Francisco, CA, 2000).
[22] R.J. Hedaya, "Understanding biological psychiatry", (**W.W. Norton & Company**, New York, NY, USA, 1996).
[23] D.G. Myers & N. Dewall, "Psychology", 11th Ed. (**Worth Publishers**, Duffield, UK, 2015).
[24] B.J. Sadock, V. A. Sadock and P. Ruiz, "Kaplan and Sadock's synopsis of psychiatry: behavioral sciences/clinical psychiatry", 11th Ed. (**Wolters Kluwer**, Philadelphia, PA, 2015).
[25] J.E. Hall, "Guyton and Hall textbook of medical physiology", 13th Ed. (**Elsevier**, Philadelphia, PA, 2016).
[26] https://en.wikibooks.org/wiki/Ecology/Biogeochemical_cycles
[27] S.R. Emerson and J.I. Hedges, "Chemical oceanography and the marine carbon cycle" (**Cambridge Unviversity Press**, New York, NY, 2008).
[28] R. Olien, "The water cycle at work (water in our world)" (**Capstone Press**, Mankato, MN, 2016).
[29] "Measuring the economy a primer on GDP and the national income and product accounts", **U.S. department of Commerce** (2015).
[30] R.A. Arnold, "Economics", 5th Ed. (**South-Western College Publishing**, Cincinnati, OH, 2001).
[31] R.J. Barro, "Inflation and economic growth", Working Paper 5326, National Bureau of Economic Research, (Cambridge, MA, USA, 1995).
[32] E.W. Swokowski and J.A. Cole, "Algebra and trigonometry with analytic geometry", 8th ed. (**Brooks/Cole Publishing**, New York, NY, 1993).
[33] B.E. Needles, Jr., "Financial accounting", Third Edition, (**Houghton Mifflin**, Boston, MA, USA, 1989), Chapter 15.
[34] "Investing 101: the concept of compounding", by Investopedia Staff.
[35] http://www.quotesonfinance.com/quote/79/Albert-Einstein-Compound-interest.
[36] www.**forbes**.com/billionaires/
[37] J.B. Marion, "Classical dynamics of particles and systems", 2nd edition (**Cengage Learning**, Boston, MA, USA, 1970).
[38] John R. Reitz, Frederick J. Milford and Robert W. Christy, "Foundations of electromagnetic theory", (**Addison-Wesley Publishing**, Reading, MA, USA, 1979).
[39] W.B. Shockley, M. Sparks & G.K. Teal, "p-n junction transistors", **Phys, Rev**., vol.83 (1951), p.151-162.
[40] J. Bardeen & W.H. Brattain, "The transistor, a semi-conductor triode", **Phys. Rev**., vol.74 (1948), p.230-231.
[41] S.M. Sze, "Physics of semiconductor devices", 2nd Ed. (**John Wiley & Son**s, New York, NY, USA, 1981).
[42] O. Svelto, "Principles of Lasers", 4th edition (**Springer**, New York, NY, 1998).
[43] L.A. Coldren, S.W. Corzine & M.L. Masanovic, "Diode Lasers and Photonic Integrated Circuits", 2nd Ed. (**John Wiley and Sons**, New York, NY, USA, 2012).