THE NATURE AND MEASUREMENT OF INFORMATION:
TWO “GRAND CHALLENGES” FOR THE FIELD

Richard D. Taylor

Richard D. Taylor
The Pennsylvania State University
307-B IST Building
University Park, PA 16803
USA
rdt4@psu.edu

Abstract

Considerable attention has been given to the measurement of “information” for the purposes of guiding investment and policy. The effort presumes that we: i) know what information is, and ii) know how to measure it. Of course, what is measured are various proxies or indicators for information, for which we aggregate statistics and then apply quantitative procedures to reach conclusions about relative “e-readiness,” “e-leadership,” or the “digital divide.” This work suffers from lack of underlying theory, and this paper proposes that it is time to reconsider and update some earlier work on the nature of “information” and the nature of “measurement” as they have evolved over time. Then we may begin to have a theoretical foundation to understand both the limits and the potential of what can be usefully said based on current models.

Initially, the paper argues that there is no single, universally applicable definition of “information.” The meaning of the word has changed over time, and it is used in so many different contexts, that no unique definition is possible – and if it were, it would be so broad as to be meaningless. It can, however, be usefully defined for a particular purpose in a particular context.

The paper then discusses the nature of “measurement” and notes how it has changed over time, from the pre-scientific era, through classical science, to quantum physics. An analogy is then developed as follows. Newton’s laws of gravity were deduced from a wide body of observations. Newton never “saw” gravity, but he was able to say some things about it based on measurements that were quite useful. Then in the 20th Century came quantum physics, which used different approaches to measurement and theory to provide new insights into the nature of matter and energy, but often dealt in intangibles that could only be expressed in mathematics, and were grounded in uncertainty rather than predictability. While recognizing that no analogy is perfect, it is suggested that “information” can be looked at as a continuum along which at one end is “Newtonian” information (we can’t see it but we can predict its effects) and at the other “quantum information”, where we can pursue “information as thing.”
The first model of information leads to statistical approaches which enable us to say useful things about “information” in the economy. The second leads us to theories about the fundamental nature of things, the nature of consciousness, the role of the mind in “creating” reality, and the way “information” is conveyed between minds. Using the first, we can create better and better approximations of impacts using more data with increasingly sophisticated analysis. Special note is made regarding the use of Structural Equation Modeling in this regard. The second approach leads to a deeper understanding of the applications of quantum information (quantum computing, quantum communications, quantum encryption, “laws” of quantum information) for the future.

These two approaches present “grand challenges” for the information field. It is suggested that the first is a “ten year challenge” and the second is a “hundred year challenge.”

Keywords

Information; Measurement; Metrics; E-Readiness; Newtonian; Quantum; Quantum Information; Structural Equation Modeling; Grand Challenges

1. THE SEARCH FOR MEANINGFUL INFORMATION INDICATORS

1.1 Introduction: Why This Paper Was Written

Since the beginning of the “Information Age,” there have been efforts to quantify the impact of information as it relates to an array of social and economic factors, and to seek statistically meaningful relationships. This paper grew out of a series of studies by the Information Metrics Working Group at the Penn State Institute for Information Policy in that tradition1. While potential information indicators are plentiful, and statistical methods of analysis continue to improve, there has been a lack of overarching theory around which to focus data collection and testable hypotheses. At the same time, there have continued to be significant advances in the field of “quantum information.” This paper suggests a link between traditional information studies and recent developments in physics regarding quantum information, representing a continuum along which one can develop both theory and testable hypotheses. The questions presented, however, are complex, and may take a long time to resolve; thus, they are phrased as “Grand Challenges.” Suggestions for attacking the Challenges are offered. It is hoped that these Challenges will provide stimulation to a new generation of information-interested scholars of all kinds to try to further enhance our understanding of this fundamental area. This paper is based on an unpublished, monograph-length manuscript by the author.

1.2 Early Measures of the Information Society

In the scholarly literature, just prior to the Information Society, there was the “Post-Industrial Society,” which was born among a flurry of measures. The idea of a society moving away from heavy industries into knowledge-intensive ones was in circulation in the U.S. and Japan

---

in the 1960s and 1970s. In Japan, Umesao (1963), Hayashi (1967) and Masuda (1981) were early popularizers of the idea of the joho (or johonka) shakai or “informationalized society”. They paralleled in significant ways the work of Machlup (1962) and Bell (1973) in the U.S., who attempted to quantify the size of the “knowledge industry” and its workforce, and relate them to GNP. All highlighted the importance of knowledge to an economy, although taking somewhat different theoretical stances.

In the U.S., this approach was extended by Porat and Rubin (1977), using a typology of information work divided between primary and secondary information sectors. This foundational work initiated a lively discourse across economics, sociology, development studies and politics. This rich vein of literature is already well recorded. This history is introduced by way of background to demonstrate how measurement, and in particular measurement that relates information to economic development, has been part of the discourse of the “Information Society” from the beginning.

Noteworthy in that regard is the “Johoka Index,” probably the first serious effort, which was composed of a simple, summed index of indicators in four categories:

- Amount of information
- Distribution of communication media
- Quality of information activities
- The information ratio of each country

The Johoka Index used the approach of counting transmitted vs. “consumed” words and their equivalents in other media (e.g., one minute of color TV equaled 1,320 words). On this basis, countries were compared, both in the (then) present, and over time.

One of the conclusions drawn from this was, that at that point in time, development communications (mass media) was being supplanted in importance by development informatization (telecommunications). The related key insight was that the relative importance of the meaning (content) of communications was being overtaken by its volume (transmission). It was at about this time that telecommunications came to be recognized as a key development tool, as opposed to a mere playing tool for the privileged and the powerful.

In 1984, a more refined version of the Johoka Index was used by Ithiel de Sola Pool and his colleagues in a comparative study of communication flows in the U.S. and Japan (Pool, I. de S., 1984). He compared the quantity of print, electronic and face-to-face communication as

---


3 Some names often invoked in this period include, among others, Gilpin, Porat, Gans-Boulding, Lerner, Rostow, Schramm, Marschak, Nora and Mine, Drucker, Menou and Dizard; critical scholars including H. Schiller, MacBride, Matellart, Masmoudi, Hamelink, Chomsky, Smythe, Mosco, Sussman and Lent; Roszak; and economists including Coase, Knight, Stigler, Arrow, Stiglitz, Schackler, Ackerlof, Hirshleifer, Riley, Jonscher, Pauly, Lamberton, and Jussawalla.

4 See, for example, Dordick and Wang (1993), Schement and Curtis (1995, 2004)
well as the ratio of “words supplied” to “words consumed.” In the early 1980s, the OECD began to collect data, following Porat’s list of categories, for comparison between members. The Johoka Index was followed by the JIPDEC (Japan Information Processing and Development Center) Index in 1986, which was “three dimensional,” incorporating factors for hardware, software and transmission. (Dordick and Wang, 1993)

These early measures received ample critical analysis. For example, the method of converting images and sounds to an estimated number of “words” was a frequent target. However, even though there were substantial methodological shortcomings, the efforts at quantification embodied the apprehension that something important was going on in the world, and there needed to be some way to measure and harness it. These were first steps. But the question remained, whether what was counted was words or bits, what did the measures measure?

1.3 The Ongoing Search for Information Age Indicators

If this is the “Information Age,” then information technology (IT), including telecommunications, the Internet, and computing, is its driver. Governments, businesses and individuals collectively are making huge investments in this area. It is central to issues of economic development, and impacts correspondingly on social, cultural and political arenas. Because of its centrality, multiple attempts are currently underway by significant global, regional, corporate and research organizations to understand it. However, the relevant factors are many, and their interactions are complex. This realization is rooted in the understanding that “[w]hile everything matters in the Information Society, not everything matters the same”, so there is an ongoing effort to identify appropriate “information indicators” which can stand as proxies for multiple factors and sectors.

The following are examples of some initiatives to address these questions:

- The ICT Indicators Project - OECD
- Statistical Indicators for the New Economy - EU
- The Technology Achievement Index - UNDP
- The ICT Development Index - UNCTAD
- The Digital Access Index - ITU
- Monitoring the Digital Divide Project - ORBICOM/UNESCO
- Networked Readiness Index - World Economic Forum
- E-Commerce Readiness Assessment - APEC
- Global E-Readiness Ranking - EIU

One thing these studies have in common is that they predominantly use statistical analytical tools to correlate multiple factors to identify relationships between information stocks, flows and technology with other economic and non-economic factors. All of them utilize data collected by various national and international organizations. “E-readiness assessments” have been conducted in nearly every country on the globe, although the indicators selected and the data collection and recording methods are not standardized. Some of them reduce their results to a single number or ranking, which is of limited utility for planning purposes.

---

The larger problem is that there is no generally accepted overarching theory for this field, and most of the methodologies that have been used so far tend to be more descriptive than explanatory and predictive. By and large, the approach has been to sum up a variety of statistics of selected indicators (e.g., number of Internet connections), weight the factors based on expert opinions, and apply one or more statistical analytical methodologies. As time has passed, these procedures have become more sophisticated, but still suffer from serious limitations. One approach, using Structural Equation Modeling (SEM), seems to address many of these problems, but requires extensive amounts of data on which to operate. SEM is based solely on letting the data “speak for itself” (without injecting subjective “expert opinions”), and is in principle both explanatory and predictive. However, it still needs development and extensive testing with real-world data.

The primary reason that there is no theory is that there is no agreement on the nature of that which is being counted and measured – “information”.

2.0 WHAT IS INFORMATION?

Where is the Life we have lost in living?
Where is the wisdom we have lost in knowledge?
Where is the knowledge we have lost in information?
The cycles of Heaven in twenty centuries
Bring us farther from GOD and nearer to the Dust.

T.S. Eliot, The Rock

2.1 Brief History of the Evolution of the Term “Information”

We look here briefly at the roots of the word “information” in Latin and Greek, and follow its evolution through some major transformations of meaning over time. Divergences in meaning during a word’s evolution can help make clear why there is such an inherent difficulty in finding a univocal shared understanding of “information”. It can also help us understand how a single word can come to have multiple meanings, and thus begin to appreciate the fact that there may be intrinsic impediments to finding a single, fixed definition of information.

The English word “information” has Latin roots; however, Capurro (2003) has also explored the Greek origins of the concepts underlying the Latin word informatio, and related them to its subsequent development over time in Latin. It refers to the act of giving a form to something, as in Virgil’s verses on Vulcan and the Cyclops hammering out (informatum) lightning bolts for Zeus or a huge shield for Aeneas.

Capurro’s examples of the original Latin (and Greek) roots of the word “information” show a number of uses along a continuum, starting with “in-form,” i.e., to give shape to, as with incorporeal a priori eternal forms, or, in the material world, by analogy to developmental biology (as the skeleton “informs” [i.e., gives shape to] the fetus). Over time, it also came to mean to “shape” as in, to use virtues to shape a moral life, and, by further extension, to educate. However, the modern meaning of “information” as ideas, or knowledge in general, was still to come.

---

6 For examples of leading work of this kind, see Sciadas, 2002, 2003, 2005.
Later, Augustine conceived of information processes in a large pedagogical and moral context, where *informatio* means the forming of virtues (*informatio virtutum*) as well as of moral life as a whole (*informatio morum*).\(^8\)

With the crumbling of the Roman Empire came the evolution of the Romance languages. In the case of the Gauls, the path to French lay in the variety of dialects which developed when cut off from the Latin mother tongue. It was through these paths that the word “information” ultimately reached English. In Old French, *informare* emerged as *enforcer* with its original meaning largely intact, and added *enformacion*, a learned borrowing from Medieval Latin *informationem*, meaning outline, concept, or form of an idea.\(^9\) But unlike the gradual evolution of Latin into French, the entrance of French into English occurred more abruptly, with the Norman conquest of England.

The Normans brought their language with them. Evidently the predecessors of “information” were among them, although not appearing immediately in writing. Around 1386, the word “informacions” surfaced in Chaucer’s “Tale of Melibius”. By the time of Gulliver’s Travels (1727), Jonathan Swift applied a meaning to the word information which sounds modern.

> It was necessary to give the Reader this Information, without which he would be at the same Loss with me . . .\(^{10}\)

That other writers of the era, such as Defoe, Jefferson, and Tennyson expressed themselves by using “information” in ways which would be familiar to us points to the current meaning of information as part of the emergence of the modern era. The perspective which treated information like a material thing had gained acceptance in literary circles by the middle of the 18\(^{th}\) century. As part of this process, “information” also became a central subject for philosophers, “rationalists” and early scientific thinkers.

In connection with the decline of Scholastic philosophy caused by the rise of empirical science, Peters states:

> In the feverish demolition of medieval institutions in the seventeenth and eighteenth centuries, the notion that information consisted in the activity or process of endowing some material entity with form remained largely unchanged. But the notion that the universe was ordered by forms fell into disrepute, and the context of this in-forming shifted from matter to mind. Both changes inaugurated a massive inversion in the meaning of information.\(^{11}\)

The transition from Middle Ages to Modernity in the use of the concept of information -- from “giving a (substantial) form to matter” to “communicating something to someone” -- today’s meaning of information -- arrived at a time when European culture was forming the world view which we now share. The 18\(^{th}\) and 19\(^{th}\) centuries were a time when literate individuals, at least, were becoming aware of information as a distinct phenomenon.

---


\(^{9}\) Barnhart, 1988, p. 527.


Information came less and less to refer to internal ordering or formation, since the emerging empiricism allowed for no preexisting intellectual forms outside of sensation itself. Instead, information came to refer to the fragmentary, fluctuating, haphazard stuff of sense. Under the tutelage of empiricism, information gradually moved from structure to stuff, from form to substance, from intellectual order to sensory impulses.

Most recently, constructions of information within the philosophy of science and analytic philosophy, particularly during the last half of the 20th century, have been related to specific sciences, particularly physics, biology, and linguistics. As a result of this development the tendency has been to re-humanize the concept of information; that is, to place it within a cultural context.

2.2 Information and Economics

Economists in particular have struggled both with the role of information in neo-classical economics and with treating information as a “thing” or commodity. This has resulted in inconvenient outcomes, as the characteristics of information are different from other commodities. This is not to say that information cannot be commoditized – it can be and widely is, based on its embodiment in material packages. However, it is not a traditional type of commodity, and so we need to look a little more closely at its special characteristics.

- Information is heterogeneous.
- Information is non-consumable
- Information is cognitive
- Information is contextual
- Information is indivisible
- Information is cumulative
- Information is “leaky
- Information is “bundled”
- Information is about more than money/economic value
- Information wants (or at least tries) to be free
- Information is an “experience good”
- Information is a “public good”
- Information is multifaceted – economists have described it as a factor of production, a resource, an asset, an input, an output, a sector, a good, a multiplier, a service, and an activity, as well as a commodity

Economist Robert Babe has observed that information does not fulfill the definitional or conceptual requirements of a commodity, raising questions about neo-classical economics’ internal validity, while also asserting that economists’ insistence that information is a commodity obscures many essential properties of information, as well as the consequences of informational exchange, thus creating a crisis of external validity (Babe, 1994)

The pioneer of the field of information economics, Donald Lamberton, after studying the issue for decades, expressed his frustration with the challenges of information and economics by calling for a “new taxonomy” of economics and information.

2.3 Problems of Definition
Common sense tells us that “information” is a single word; therefore, it should refer to a single thing. Why can’t we just look up the definition and be done with it? This may be an example of a situation where language can be misleading: there doesn’t have to be a real thing for every noun. And, unfortunately, the very notion of a “definition” is a complex and contested one. A survey of the literature suggests that there are many kinds of definitions, including:

- Descriptive definitions
- Stipulative definitions
- Lexical definitions
- Analytical definitions
- Extensional definitions
- Operational definitions
- Contextual definitions
- Theoretical definitions
- Précising definitions
- Notational definitions
-Enumerative definitions
- Ostensive definitions
- Recursive definitions
- Intensional definitions
- Nominal definitions
- Persuasive definitions

So there could be many different types of answers to the seemingly simple question, “What is the definition of information?” In this light, we must at least raise the question of whether it is meaningful (or useful) to speak of “information” as if it were a single thing, which could be simply defined. Perhaps there are other, more useful, ways to think about “defining” information. We could, for example, look at the ways the word “information” is used.

Knowing how different people apply the terms they use is helpful. Studies of how a term has been used cannot, however, help us to decide how we should define it. When we use language and terms, we perform some kind of act, with the intention of accomplishing something. The different meanings of the terms we use are more or less efficient tools to help us accomplish what we want to accomplish. Different conceptions of fundamental terms like information are thus more or less fruitful, depending on the theories (and in the end, the practical actions) they are expected to support.

---

13 For the incorrigible lexicographers, the Oxford English Dictionary (1989) provides eight primary definitions of “information”.
14 Capurro, 2003
A good example of this approach is Braman (1989) writing in the context of defining “information” for policy makers. Noting the range of alternative approaches, she cites Cohen, writing for lawyers:

Among the difficulties that stand in the way of a comprehensive view of the legal order is the naïve view of definitions as propositions which are either true or false. . . Once we recognize that a definition is, strictly speaking, neither true nor false but rather a resolution to use language in a certain way, we are able to pass the only judgment that ever needs to be passed on a definition, a judgment of utility or inutility.

She concludes it should be possible for policymakers to use more than one definition of information in resolving a particular problem. She cites the benefits of acceptance of a pluralistic and hierarchical approach to defining information.

2.4 “Information” in the Sciences

“Information” emerged as a key word in the sciences in the mid-20th century. In this context, it appears that “information” is either used ambiguously, as a collection place for multiple significations that are generated in the application of the term to a wide range of different practices; or very narrowly, so that its meaning becomes attached to narrowly specific technological functions, such as those generated in the fields of information science or engineering.

From another viewpoint, the general terms of the debate about the nature of information have focused on two broad ideas. First, there are those who see information as a tangible entity which can be processed, moved, changed and so on (Buckland, 1991). Second, others, generally speaking, see information as existing only in the human brain, the result of absorption of symbols and signs. (Browne, 1993)

The abundance and diversity of definitions of information can bewilder. Machlup and Mansfield voiced a common frustration over this confusion: “Evidently, there should be something that all the things called information have in common [but] it surely is not easy to find out whether it is much more than the name.”

Almost every scientific discipline today uses the concept of information within its own context and with regard to specific phenomena. Under these circumstances, can a common meaning for this term be derived, or do we have to accept the pessimistic view expressed by Bogdan:

My skepticism about a definitive analysis of information acknowledges the infamous versatility of information. The notion of information has been taken to characterize a measure of physical organization (or decrease in entropy), a pattern of communication between source and receiver, a form of control and feedback, the probability of a message being transmitted over a communication channel, the content of a cognitive state, the meaning of a linguistic form, or the reduction of an uncertainty. These concepts of information are defined in various theories such as physics, thermodynamics, communication theory, cybernetics, statistical information theory, psychology, induc-

tive logic, and so on. There seems to be no unique idea of information upon which these various concepts converge and hence no proprietary theory of information.\textsuperscript{16}

Reductionism has been responsible for much of the success of the scientific method, but with information, reductionist strategies are unlikely to succeed. Claude Shannon (1993), for one, was very cautious:

The word “information” has been given different meanings by various writers in the general field of information theory. It is likely that at least a number of these will prove sufficiently useful in certain applications to deserve further study and permanent recognition. It is hardly to be expected that a single concept of information would satisfactorily account for the numerous possible applications of this general field.\textsuperscript{17}

Or perhaps, faced with the variety of uses of “information”, we can at least take a pragmatic approach. It has been suggested that one can survey the landscape seeking to identify groupings of uses of the term “information”. The definitions may not be fully satisfactory, the boundaries between these uses may be indistinct, and such an approach could not satisfy anyone determined to establish the one correct meaning of “information”; but it has been argued that if the principal uses can be identified, sorted, and characterized, then some progress might be made. Using this approach, Buckland (1991) identified three principal uses of the word “information”:

1. Information-as-process
2. Information-as-knowledge
3. Information-as-thing

From another perspective, the physicist, Peter Paul Kirschenmann (1970) asserted that information receives different meanings according to whether it results from ordinary language, linguistic processes, information theory, or signal theory. He then placed the question of information squarely athwart the whole tradition of Western logic. “The assumption of only two components of reality—materiality and spirituality—is based on a simplification since there is always a remnant which cannot be assigned to either and which cybernetics designates with the word ‘information’. The very foundations of our thought — classical, two-valued logic as corresponding to a metaphysical dualism — are shaken. We must turn to a logic with at least three values”\textsuperscript{18}. In other words, like energy, information challenges the two ontic elements of Aristotle’s forms. This may explain why some scientists equate information with energy, he said. This, as it turns out, may have been somewhat prescient.

2.5 “Naturalizing” Information

The term “naturalization of information” refers to the integration of the concept of “information” into the framework of contemporary natural sciences, especially physics.

\textsuperscript{17} Shannon, 1993.
Sometime in the period immediately following the Second World War, information became the key term that united a diverse number of technical and scientific disciplines: biology, cognitive science, information science, computer science, psychology, physics, economics, etc. In order to serve as the basis of the sciences, information had to be conceived of as discrete bundles, physically decontextualized and fluidly moving. This content-blind conception of information is clearly evident. As Webster describes it, “searching for quantitative evidence of the growth of information, a wide range of thinkers have conceived it in the classic terms of Claude Shannon and Warren Weaver’s information theory. In this theory information is a quantity which is measured in bits and defined in terms of the probabilities of occurrence of symbols. This approach allows the otherwise vexatious concept of information to be mathematically tractable”.

Shannon’s mathematical theory of communication (“MTC”) is not a theory of information in the ordinary sense of the word. The “mathematical theory of data communication” is a far more appropriate description than information theory. As Weaver (1949) remarked “the word information relates not so much to what you do say, as to what you could say. MTC deals with the carriers of information, symbols and signals, not with information itself. That is, information is the measure of your freedom of choice when you select a message”.

In physics, according to Mahler (1996), information is a “contextual concept”; in other words, the question: “What is information?” cannot be stated without reference to a situation. According to Mahler, “information can only be defined within the scenario, it is not just out there”. In other words, information is not a pure observable, but a theoretical construct. It is “interpreted data.” In his view, it has no independent existence, physical or otherwise.

To the contrary, according to Stonier (1990) “information exists”; that is, information exists independently of human thinking. Stonier follows Norbert Wiener’s famous dictum:

The mechanical brain does not secrete thought “as the liver does bile,” as the earlier materialists claimed, nor does it put it out in the form of energy, as the muscle puts out its activity. Information is information, not matter or energy. No materialism which does not admit this can survive at the present day.

As Stonier puts it, “information exists. It does not need to be perceived to exist. It does not need to be understood to exist. It requires no intelligence to interpret it. It does not have to have meaning to exist. It exists.” The old debate between Plato over whether perfect forms actually exist, or, as Aristotle would have it, they exist only as embodied in things, lives on.

Lyre (1998) developed “a quantum theory of information” with “basic alternatives” representing the information content of a yes/no decision or one bit of quantum-theoretic potential information. According to this, structural and kinetic information is an intrinsic component of the universe. It is independent of whether any form of intelligence can perceive it or not. Information may exist in a particular form, comparable to photons, as “infons”. The

---

term “infon” was coined by Keith Devlin and refers to parameters corresponding to individuals and locations. (Capurro, 2003)

As Bennett and DiVincenzo (2000) show, an information theory based on quantum principles extends and completes classical information theory. A quantum bit or “qubit” is a microscopic system, such as an atom, or nuclear spin, or photon. Every particle, every field of force, even the space-time continuum itself derives its function, its meaning, its very existence entirely, even if in some contexts indirectly, from the apparatus-elicited answers to yes-or-no questions, binary choices, bits. For Wheeler, “It from bit” symbolizes the idea that every item of the physical world has at bottom a very deep bottom, in most instances an immaterial source and explanation; that which we call reality arises in the last analysis from the posing of yes-no questions and the registering of equipment-evoked responses; in short, that all things physical are information-theoretic in origin and that this is a participatory universe. (Wheeler, 1990)

As is apparent, no consensual definition of information exists as yet, even in the sciences. The importance of concepts related to information across the physical, biological, and social sciences indicates the value of the enterprise. That so many have gone before, with so little concluded, testifies both to the promise and the challenge.

3. WHAT DOES IT MEAN TO “MEASURE” INFORMATION?

Objective measurement is the repetition of a unit amount that maintains its size, within an allowable range of error, no matter which instrument, intended to measure the variable of interest, is used and no matter who or what relevant person or thing is measured.24

3.1 How the Concept of “Measurement” Has Evolved

The history of measurement is the history of humanity’s attempt to understand the world. Throughout history, the tools of measurement have been critical to the development of human civilization. It is easy to assume that the concept of “measurement,” has always been understood in the same way. In reality, the understanding of “measurement” has greatly evolved, from pre-historic times to the present, passing from primitive to classical to quantum measurement. Each era needed appropriate measures to fit its dominant social and economic forms – agrarian, feudal, industrial and now, “information.” If all or parts of human society are becoming an “Information Society” -- in which information work, assets and tools predominate -- what are the appropriate metrics for its evaluation, guidance, and growth? This section analyzes the concept of measurement and how it applies to the “Information Society,” and suggests a basis for understanding what is -- and is not -- possible in shaping goals for the future.

At the heart of the problem is finding meaningful ways to speak about the “measurement” of information. Information in the abstract is intangible, which makes it unlike any material resource or commodity. It can be embodied in various tangible forms that serve as “containers” for the information, and the characteristics of these containers can be measured. On the other hand, are we then to say that information is completely immeasurable and has no connection

24 See: http://www.rasch.org/define.htm
at all to the physical world? This does not seem to be the case either. Of course, we cannot actually see information, but we can observe its effects, which can be measured.

3.2 In the Beginning: Mathematics without Measurement

Measurement is one of the most fundamental characteristics of human behavior. There are artifacts which show the use of measurement which pre-date even the beginning of the written word. Early hunters were, for the most part, migratory peoples. They needed measures of number, of distance, and of the passage of time. When humans settled into semi-permanent or permanent communities their needs became more sophisticated. They became engaged in agriculture and in trading. Markets developed locally and along popular travel routes. New kinds of measurements were called for. In agriculture, measurements of land, predictions of when to plant and when to reap, consistent measurements of the weight of agricultural products, and of the value of those products were called for. In trade, merchants needed to develop measures of weight, volume, size, value and other indicators. These were all very concrete specific elements applied to tangible goods.

It is not surprising that the earliest mathematics we know of is concerned with problems about weights and measures. Going as far back in time as Noah’s Ark, the lack of a yardstick was not a serious drawback. Most measuring was done by one craftsman completing one job at a time. It didn’t make much difference how accurate the measuring sticks were or even how long they were.

European systems of measurement were originally based on Roman measures, which in turn were based on those of Greece. Plato and Aristotle did not believe our five senses were capable of the accurate measurement of nature. Plato noted that when the soul depends on the senses for information, “it is drawn away by the body into the realm of the variable, and loses its way and becomes confused and dizzy.” Why did Plato and Aristotle, with their penetrating intellects, shy away from the category of the usefully quantifiable? There two points to be made here.

First, the ancients defined quantificational measurement much more narrowly than we do, and often rejected it for some more broadly applicable technique. Plato recommended turning away from the material world because, “it’s always becoming and never is” and turning toward “that which always is and has no becoming.” He directed our attention to absolute beauty, goodness, and righteousness, and to the ideal triangle, square, and circle, two abstractions that, he was sure, existed independently of the material world. He was certain that attaining knowledge of such entities could be accomplished only by “the unaided intellect.” (Crosby, 1997)

Knowledge, Plato thought, was to be found not by starting from “facts” observed by the senses, framing generalizations, and then returning to the facts for confirmation, but by turning away and escaping as fast as possible from all sensible appearances. In other words, the universe can be understood by pure logic, without recourse to experimentation, a notion exactly contrary to the whole concept of modern science.

Aristotle said that the mathematician measures dimensions only after he “strips off all the sensible qualities, e.g., weight and lightness, hardness and its contrary, and also heat and cold and other sensible contrarities to use.” Like Plato, Aristotle found description and analysis
more useful in qualitative terms than in quantitative ones. The delimiting influence of this outlook lasted over 1500 years, exemplified in the generally unquestioning acceptance of the assertion – readily refuted by observation – that the planets move in circular orbits around the earth. Observation and measurement were subordinate to ideas and theory. (Crosby, 1997)

During the Roman Empire and the centuries that followed its demise, the development of quantification was constrained by the limited capabilities of Roman numerals. In addition, the idea of measure was divorced from the idea of "experimentation" or testing in the modern sense, which only developed in the 17th Century. Measures of reality were grounded in what "ought" to be, based on philosophical thinking or religious beliefs. In the Age of Exploration, approximations were considered "close enough" -- the idea of precision in measurement had not yet emerged. But in the Renaissance came a new tool -- the introduction of Indo-Arabic numbers -- which allowed for significant advances both in mathematics and quantification. In the Age of Enlightenment, math and measurement finally began to come together. This did not happen as easily as it might appear from a modern perspective.

Money had a lot to do with it. The Roman Empire functioned on cash, while initially the West did not. There was little trade, and much of that was barter. Coins had little abstract value beyond of the value of their metal. Currency ceased to circulate for the lack of commerce, commerce was crippled for the lack currency. But in time feudal lords established law and order of a sort, and agricultural productivity edged upward. Supply grew, commerce and towns revived, and once again money was in demand. Cities and designations began to issue coins, and Western replaced non-Western coinage. (Crosby, 1997)

Westerners found themselves sliding into a cash economy, each item in their lives reduced to a single standard in the process. Price quantified everything. The seller set a price on what he or she had to sell because everything the seller needed or wanted had to be paid for in turn. Wheat, barley, oats, rye, apples, spices, woolens, silks, carvings, and paintings and developed prices. That was relatively easy to understand for the common people because they could be eaten, worn, touched, and observed. It was harder to understand when money substituted for obligations of service and labor set long ago by custom. When time proved to have a price -- that is to say, interest on debt calculated in accordance with the passage of months and years - that strained in the mind and the moral sense as well, because time was God’s exclusive property. If time had a price, if time were a thing that could have a numerical value, then what about other on unsegmented imponderables, like heat or velocity or love?

We would assume that weight, hardness, and temperature “and other sensible contrarieties to use” are quantifiable, but that is not implicit either in these qualities or in the nature of the human mind. Weight, hardness, and temperature do not come to us as quantities of discrete entities. They are conditions, not collections; and, even worse, they are often flowing changes. We cannot count them as they are; we have to see them with our mind’s eye, quantified them by fiat, and then count the quanta. That is easily done with measuring length -- for example, this lance is so many feet long, and we can count them by laying the lance on the ground and stepping off its length. But hardness, heat, speed, acceleration – it is far from self-evident how to quantify those. (Crosby, 1997)

However, once scholars in the 14th century began to think about the benefits of measuring not only size, but also qualities as slippery as motion, light, heat, and color, they forged right on, jumped the fence, and talked about quantifying certitude, virtue, and grace. The West’s dis-
tinctive intellectual contribution was to bring mathematics and measurement together and to hold them to the task of making sense of a sensorially perceivable reality. (Crosby, 1997)

The emerging new empirical model was distinctive in its growing emphasis on precision, quantification of physical phenomena, and mathematics. Even so, in the 14th century certain Schoolmen made great progress in mathematics-without-measurement. Impressive as the work of these people might be, one is struck by the absence of actual measurement. The Schoolmen considered things as more or less than each other, but not in terms of multiples of a definite quantity such as inches, degrees of arc, degrees of heat, and kilometers per hour. The Schoolmen, paradoxically, were mathematicians without being quantified. (Crosby, 1997; see also generally, Woolf, 1961)

3.3 The Arrival of Scientific Measurement

The fields of physical science studied during the 17th century can be divided into two groups. The first, the traditional sciences, consisted of astronomy, optics, and mechanics, all of which had received considerable qualitative and quantitative development in antiquity and during the Middle Ages. These fields can be contrasted with a new cluster of research areas that owed their status as sciences to the 17th century’s characteristic insistence upon experimentation and upon the compilation of natural histories. To this second group belonged particularly the study of heat, electricity, magnetism, and chemistry.

The idea that social topics could be subjected to quantitative analysis also acquired prominence in the first part of the 17th century. One can point to concrete concerns: the rising insurance systems which required a formal numerical foundation, and the prevailing belief of the Mercantilists that size of population was a crucial factor in the power and wealth of the state. Undoubtedly the progress made by physics, mechanics, and mathematics in the 17th century facilitated the introduction of quantitative methods into the study of social and economic phenomena.

During the first half of the 19th century, there was an important change in the character of research in many of the physical sciences, particularly in the cluster of research fields known as physics. The period also witnessed a vast increase in the scale of the scientific enterprise, major changes in patterns of scientific organization, and a total reconstruction of scientific education.

As society evolved, measurement units became more complex. The invention of numbering systems and of science and mathematics made it possible to create whole systems of measurement units suited to trade and commerce, land division, taxation, or scientific research. Most notably, this included the introduction of the metric system.

In 1790 the French national assembly obtained Louis XVI’s assent to commission the country’s leading scientists to recommend a consistent system for weights and measures. It has been estimated that France at that time had about 800 different names for measures, and taking into account their different values in different towns, around 250,000 differently sized units. The metric system was adopted in France in 1795. In the 1860s in Britain, the United States and the German states all made moves towards adopting the metric system. It has gradually been adopted nearly universally. (Macey, 1989)
The Scientific Revolution brought with it the “classical” (also called “Newtonian”) scientific view of the laws of the universe. The Industrial Revolution saw the extension of science and the rise of the “social sciences,” extending the idea of what could be measured. The early 20th century introduced radio waves and the “unseen world.” Physics visualized the “stuff” of reality as aggregates of uniform units. Then came a new paradigm -- the advent of quantum theory, in which quantum measures are inferences obtained by approximations, things are known by their effects, and the observer and the instrument all are part of a system that affects the outcome. Reality is stochastic (probabilistic) and time and distance are divorced from matter. New theories of entangled states, quantum information and quantum communication were developed, in which the carrier and the information were entangled. Classical information theory came to be seen as a subset of quantum information theory.

3.4 Quantum Measurement

*I know I have the best of time and space
And was never measured and never will be measured

Walt Whitman, Song of Myself

In 1900 Max Plank introduced the quantum of energy, “quantum” from the Latin for “how great” or “how many.” The idea that Plank was forced to accept much against his will was that in nature energy comes in discrete values, the smallest value being one quantum. Einstein took over the concept and in 1905 postulated that light comes in quanta; in doing so he explained the photoelectric effect. The small energy packets are light quanta, which since the 1920s have been called photons. Experimentation has revealed a number of very non-classical characteristics of particles at the quantum level. One of these has to do with the fundamental nature of quantum measurement.

In quantum physics, observational conditions and results are such that there is no categorical distinction between the observer and the observing apparatus, or between the mind of the physicist and the results of physical experiments. The measuring apparatus and the existence of an observer are essential aspects of the act of observation. We can no longer “see” the pre-existent truths of physical reality through the lenses of physical theory in the classical sense. In a certain sense, at the quantum level, reality only becomes concrete when a measurement or observation occurs. Experimental evidence strongly suggests there is a direct relationship between observation by a conscious mind and the fundamental behavior of quantum particles. The observer and the observed are not separate and distinct, but are joined in a system. When quantum physicists talk about “the measurement problem,” they are talking about something a lot more profound than not having a ruler. (Nadeau, 1999)

4. A “NEWTONIAN” AND “QUANTUM” INFORMATION CONTINUUM?

4.1 The Newtonian Universe: Predictability

In the “classical” universe of Isaac Newton:

- Material reality was composed of tangible, real “things” that followed known, universal, predictable rules
- Time was a constant, and space was three dimensional
- Time moved only forward, and effect came after cause
If you knew the “thing” and you knew the rules, then you could predict with certainty the future situation.

The analogy was that nature was “like a clock” or “like billiards.”

The physics which followed from this assumed that all things – including molecules and atoms – followed the same rules.

4.2 Einstein’s Universe: Relativity

In the “relative” universe of Albert Einstein:

- Time is relative, and is related to velocity.
- Matter and energy are interchangeable.
- The greatest possible velocity is the speed of light.
- “Space” was relative; it could be bent, for example, by gravity.
- Space could be multi-dimensional and/or have different shapes.
- Time was not forbidden from going backwards (tachyons).
- The rules of the ultra-micro world (quanta) showed surprising properties that were very non-Newtonian.

4.3 The Quantum Universe: Information, Matter and Mind

Even Einstein had some limits on what he would accept. When it came to the basic rules underlying physics he said:

- “God does not play dice with the universe” – rejection of fundamental randomness.
- “No spooky action at a distance” – locality of events.
- “I think that a particle must have a separate reality” – particles are real and independent.

Subsequent experimentation, however, suggests he was wrong on all three points. A widely held view of quantum mechanics suggests (based on extensive experimentation) that:

- There is a duality of waves and matter.
- At the smallest level, things do not exist in any particular state – they exist in a state of all possible states simultaneously.
- We cannot know both the position and the momentum of a particle (uncertainty).
- “Particles” only assume a particular state (decoherence or collapse) when they are observed. The act of observation participates in creating the reality (the problem of measurement).
- Particles can be “entangled” and act simultaneously irrespective of distance (non-locality).
- The collapsed state of the particles is inherently unpredictable. At the quantum level, nature is truly random. We know only probabilities.

Quantum physics is not only about “matter,” it is also about information. In fact, it is possible to usefully think of the universe as composed of quantum information (quantum bits or “qubits”). There are rules for quantum information, just as there are for matter and energy (e.g., a law of conservation of information). It is equally possible to describe the universe as being composed of information as it is of matter. (Lloyd, 2006)
In mainstream quantum theory, the role of the observer is key. Things happen in the event of an observation. The observer and the observed are joined in some way. The presence of a conscious mind appears to make a difference. Observation in some way creates reality. Quantum information may tie together theories of “reality” and theories of consciousness. It has already been used by some to explain the nature of consciousness. (Penrose, 1994)

4.4 The Information Continuum

Isaac Newton was a multi-faceted genius who made contributions to many fields of science and mathematics. However, he is best known in popular lore (the fabled falling apple) for his discovery and explication of the “Law of Gravity”. Of course, Newton never actually “saw” gravity – we’re still looking for it. What he did do (apples aside) as a student of heavenly bodies, was to build on the work of his predecessors (as he readily admitted, he “stood on the shoulders of giants”).

Starting with the theories of Copernicus (who believed the planets moved in circular orbits) and the observations of Galileo, he had the benefit of near-lifetimes of recorded observations by Tycho Brahe and Johannes Kepler (who demonstrated elliptical orbits), amassed in a vast collection in the form, among other things, of highly accurate charts. It was from this mass of data that Newton was able to deduce – brilliantly -- a set of rules which best fit the observations, and then tested them – successfully – with predictions.

Newton identified gravitation as the fundamental force controlling the motions of the celestial bodies. He never found its cause. To contemporaries who found the idea of attractions across empty space unintelligible, he conceded that they might prove to be caused by the impacts of unseen particles.

The proposition is put forward here that at the macro level, we are in a position with information analogous to the position Newton was in with gravity. We have not seen its invisible “particles,” but we have seen its effects. We do not, however, have the benefit of a modern Brahe or Kepler of information data collection. Nor do we have the benefit of the equivalent of an orderly and regular night sky. Indeed, the analogy has many rough edges -- we cannot assume there are such convenient and regular laws awaiting only our sufficiently brilliant insight (it’s probably all stochastic). However, at the macro level, we can free ourselves of the need to search for information as a single “thing” and focus our attention on specific questions (albeit complex ones) and relationships. We can refine the idea of “necessary but not sufficient” conditions to expressions of probabilities in unique and multi-dimensional contexts.

In the overall scale of the world of matter and particles, as size descends from macro to micro, there is a point of transition, where the rules change from classical to quantum. The everyday world of our perceptions does not operate (fortunately for us) on the rules that apply at the quantum level. But it is still all the same universe. The exact location of, and reason for, this transition is a matter of scientific debate. But even though we don’t yet know exactly where and how the line is drawn, we know that it is there. It is suggested that the same may be true for “information”.

18
It is on the micro level where we can pursue the idea of information as “thing,” (i.e., a phenomenon cognizable by the rules of physics) keeping in mind that at the quantum level the word “thing” is at best a rough analogy for what it is we mean to say, which is best expressed mathematically. For many these are new and foreign ideas. The test for non-physicists will be their ability to accept that this represents a compelling and powerful perspective of reality on a scale of the great transformative ideas of history. It is no coincidence that both the U.S. National Research Council and the Federation of American Scientists have put quantum science and technology at the top of their lists of grand challenges.

5.0 TWO GRAND CHALLENGES FOR THE INFORMATION FIELD

5.1 What is a “Grand Challenge”?

The idea of “Grand Challenges” is adopted from the physical sciences. Typically, they are questions the answers to which are extremely difficult but not impossible in principle to resolve. They are ambitious and visionary but not unrealistic. Their resolution should lead to solutions to a range of sub-problems. Success should be well defined and measurable. They should be compelling to the general public and motivating for the research community. They should be subject to experimentation such that “failure” should point the way to needed improvement.

For example, the U.S. National Research Council has offered six grand challenges in the area of physics:

1. Developing quantum technologies
2. Understanding complex systems
3. Applying physics to biology
4. Creating new materials
5. Exploring the universe
6. Unifying the forces of nature

The Federation of American Scientists has suggested:

1. Quantum Science and Technologies
2. Nanosciences
3. Complex systems
4. Applying physics to biology and medicine
5. New materials
6. Exploring the universe
7. Unifying the forces of nature
8. Physics in support of Homeland and National security

Each of these is then subdivided into numerous subsidiary challenges.

This idea has already been adapted to the field of computing and information science. One list offers:

Another list proposes:

- A post-disaster safety net
- “Cognitive partners” for humans
- Personalized lifelong learning environments
- Unfailingly reliable systems
- Making information technology less complex

5.2 Grand Challenge One: The Macro-Dynamics of Information

Recent efforts, using advanced statistical tools, have begun to tease out the relationships between the many variables involving information. While these approaches steadily improve, they can approach, but not achieve, certainty, as they are all dependent on a vast number of critical initial conditions, so that as each analysis becomes more precise, it becomes a case unto itself. Information can be measured in its various aspects: commoditized; transported; processed; mediated; and integrated, as well as in information stocks and flows and information accounting. Collectively, these measures act as proxies for measuring information and let us predict likely outcomes. The causal mechanisms which produce these outcomes can, in principle, never be completely known, but for pragmatic social and economic applications, very useful rules and relationships can be, and are being, developed.

Grand Challenge One: Following a globally organized research protocol, identify the approaches most likely to yield meaningful data for developing an explanatory and predictive understanding of the interactions of key information proxies with other selected factors in the human environment.

This would involve, at a minimum:

- Development of some initial theories and models
- Identification of information indicators appropriate to the assigned goal(s)
- International standardization of data collection formats
- Establishment of uniform methods of data collection
- Creation of a public centralized and standardized data recording facility
- Making data conveniently and reasonably available to researchers
- Review and comparison of available statistical tools for data analysis to find those which can appropriately be used to test certain theories

---


29 At the IIP, we are currently using a model based on: connectivity; capability; content; and context.
- Generation of testable hypotheses regarding impacts and interactions of the information sector with economic, social, cultural and governmental factors
- Creation and testing of uniform instruments, research designs, and research data bases
- Development of multi-dimensional models which are empirically testable over time, in different places, and at different scales
- Continuous application and refinement of these models in real-world situations

5.3 A Meta-Challenge: Implementation

One might argue that the actual implementation of Challenge One is a meta-challenge (or mini-challenge) in itself. Given the importance and potential value of this project, one might envision a massive international initiative to address this Challenge. Since that outcome seems remote, a somewhat more modest proposal with some shelf-life might involve raising the profile of the issue and presenting it as a coherent research front, including:

- Basically, investing Information Metrology with all the modern trappings of a discipline
- Institutionally recognizing “Information Metrology” as an academic field. It is not computer science, nor economics, nor mathematics, nor telecommunications, but includes all of them and more – with an interdisciplinary core. Departments could be created, Chairs endowed, etc.
- Have an annual (or biennial) high-profile international conference on the topic
- Have a competition for the best papers; give awards and distinctions
- Give lifetime achievement awards to distinguished scholars
- Create an on-line journal
- Have an Information Metrology researchers website
- Lobby major funders to add the topic to their list of areas for support
- Etc.

If any reasonable facsimile of this agenda were adopted, Grand Challenge One could well be on its way to resolution as a ten-year challenge.

5.4 Grand Challenge Two: Quantum Information, Mind and Matter

Quantum science and technology have already been identified by major science organizations as a top Grand Challenge; evidently quantum physicists will not need to be persuaded of its importance. However, at present, much of the research time, money, thought and energy appears to be going into short-term applications. Challenge Two goes to the issues of basic, not applied, research in quantum information.

Grand Challenge Two: Develop an experimentally verifiable theoretical structure which explains and connects the apparent behavior of quantum-scale particles and integrate this with a theory of the fundamental nature of information.

This would address, among other things:

- Elaborating the basic rules of behavior of quantum information
- Understanding the interconnectedness of conscious perception and decoherence
- Explaining the underlying principles involved with non-locality (entanglement)
- Clarifying the role of information along with matter and energy as a fundamental constituent of reality (is “information” an under-recognized element of the universe, along with “mind,” so that the fundamental constituents of reality might consist of time, space, energy, matter, information and mind?)
- Identifying whether information and consciousness are connected to the “physical” universe through quantum phenomena
- Showing how, if at all, quantum behavior relates to consciousness
- Illuminating the relationship between consciousness and the brain
- Demonstrating how information is conveyed from one consciousness to another

Grand Challenge Two does not get a macro-mini-challenge. The scientific community is already aggressively pursuing this, and it is the responsibility of scholars in other disciplines to be aware of their work and its implications. The final piece would be to find linkages between the macro and micro scale, to suggest a “grand unified theory” of information. Challenge Two could be a one-hundred year challenge.

5.5 Final Comments

Here we come back to the debate between Plato and Aristotle. What is reality? This is where classical information theory meets quantum information theory. As with the physics of matter, there is the quantum/classical phase boundary problem. By analogy, there should be both a “classical” and “quantum” level of information laws, which would work quite differently. Aristotle may be more appropriate at the “classical” level, and Plato at the “quantum” level. Analogies are never perfect, but sometimes thinking by analogy opens up new areas for exploration and testing.

It is said that physics involves questions about the world that are testable, and metaphysics involves questions that are not testable. In this paper we have come close the boundary between the two. For a mind inclined to speculation, it is not a huge leap to the many imaginative suggestions about information have been put forward in fiction and popular science writing. More recently, there has been a series of books by academic experts in the field suggesting this is a potentially fruitful line of research and many important discoveries await us. These are well worth reading by the generalist, for an expanded perspective.

It is hoped that these reflections and Challenges help bring fresh life and passion to the ongoing study of an incredibly interesting and important topic, which deserves an even higher level of recognition and acceptance as a coherent and critical field of study.

---

REFERENCES