12th IMEKO TC1 & TC7 Joint Symposium on
Man, Science & Measurement
September 3–5, 2008, Annecy, France

NEW METROLOGICAL HORIZONS: INVARIANT REFERENCE STANDARDS FOR INSTRUMENTS MEASURING HUMAN, SOCIAL, AND NATURAL CAPITAL

William P. Fisher, Jr., Ph.D.
Chief Science Officer, Avatar International, LLC, Sanford, FL 32771 USA, wfisher@avatar-intl.com

Abstract: Invariant, additive, and separable parameters for measures of human, social, and natural capital have repeatedly proven their value and utility globally over the last 50 years. Given growing demand for comparable living capital metrics, metrological organizations should position themselves to provide the needed calibration and traceability services.

Keywords: measurement, capital, intangibles

1. INTRODUCTION

Developments in measurement theory and practice are leading inexorably toward a transformation of metrology in the coming years. Human, social, and natural capital measurement and instrument calibration have advanced in recent decades to previously unimagined degrees of mathematical rigor and practical convenience. Measurement models commonly employed in achievement testing, performance assessment, and rating scale surveys globally are ideally suited to meet the growing demand for precision measurement emerging from the contemporary focus on sustainable human, social, and environmental economic policies.

Many among us are increasingly aware of these needs and are striving to meet them. Few decision-makers, however, are aware of the tools at our disposal, tools that will enable us to achieve goals set to new standards. It is often said that we manage what we measure; accordingly, we must wonder what we are managing when any given construct (literacy, health, innovation, etc.) is measured in local units of unknown quality and meaning. After describing developments in theory, research, and practice, the paper concludes with recommendations for human, social, and natural capital metrology standards.

2. FUNDAMENTAL MEASUREMENT THEORY AND PRACTICE

Invariant, additive, and separable parameters for non-physical measures of abilities, attitudes, health, etc. have repeatedly proven their value and utility in education and health care globally over the last 50 years [1-3]. Different tests or surveys measuring the same thing are routinely calibrated in meaningful, linear, and comparable quantitative units [4-6]. International assessments of educational achievement, such as PISA [7], strictly define the quantitative comparability of reading, math, and science ability measures, and establish metrics that remain invariant and linear across tests administered in different languages and over time. Adaptively administered, customized tests, which tailor item selection based on the response characteristics of the individual examinee, similarly require careful attention to the maintenance of a common unit [8].

Quantitative mathematical approaches are valued in economics and in the sciences at large to the extent that measurability translates into manageability. Fully mathematical measurement makes it possible to represent meaningful and invariant amounts of anything measured in an additive, divisible, and portable numeric form. When applied to various kinds of property and other capital resources, metrological standards make it possible to unify local economies at regional scales, and to unify regional economies at the global scale. They do so by reducing friction in the economy; that is, by greasing the process of exchange with the lubrication of common standards, which function as common languages for ascertaining value [9].

The property of transparency is remarkable for the practical convenience it provides. Though we do not usually think of them in such terms, standards for time, weight, length, temperature, etc. serve as currencies facilitating the exchange of each different kind of value. Just as time is money, so, too, are square feet of property, mass volumes of commodities, and thermal units for heating and cooling.

Despite the ongoing success mathematical modeling enjoys in the natural sciences and engineering, “it has become commonplace to observe that modern mainstream economics is not too successful at providing insight” [10]. The mathematical deductivist reasoning characteristic of mainstream economics is increasingly challenged by other approaches of diverse origins referred to as heterodox.

Interestingly, these challenges emerge in a context in which capitalism itself is no longer thought inherently misconceived so much as not fully living up to its own accounting principles [11]. Perhaps, economics and econometrics also are incomplete, with their mathematical values in need of further extension, not curtailing.

The main problem, in this case, would then be how to arrive at transparent, uniform standards for human, social, and natural capital that are meaningfully and not reductionistically calibrated to the same mathematically rigorous degrees of precision and accuracy as standards for manufactured capital and commodities are. Given the roots of economic capital in scientific capital, it should come as no surprise that such standards can be created and maintained via the theory and practice of fundamental measurement. This is firmly established by at least five classes of results.

First, a wide variety of ways of formulating requirements for objectivity in measurement have been shown to reduce to Rasch's models for fundamental measurement [12-13], as is expected given their basis in minimally sufficient statistics (i.e., those that are both necessary and sufficient) [14-16]. In presenting the necessary and sufficient conditions for quantification, it then follows that

> unweighted scores are appropriate for person measurement if and only if what happens when a person responds to an item can be usefully approximated by a Rasch model.... Ironically, for anyone who claims skepticism about 'the assumptions' of the Rasch model, those who use unweighted scores are, however unwittingly, counting on the Rasch model [of fundamental measurement] to see them through [15].

What are referred to as assumptions in statistics are requirements in measurement. The inferential processes and interpretations typically employed in many statistical treatments of ability test and rating scale data inherently assume additive units and separable parameters. The transformation of these unexamined assumptions into explicit requirements for measurement creates the basis for a new metrological culture of human, social, and natural capital.

The reduction of different approaches to articulating the requirements of objective inference is a variation on the theme raised by Luce and Tukey [17], that when a concrete physical concatenation operation (Figure 1) is not possible, then "one should try to discover a way to measure factors and responses such that the 'effects' of different factors are additive." In practice, this means 1) devising observational

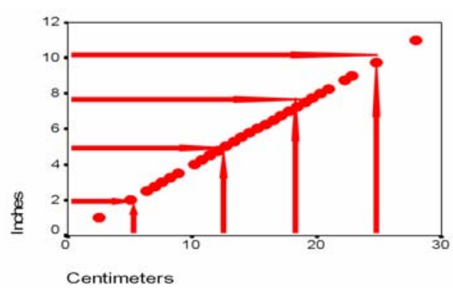

Figure 1. Concatenated measuring units indicative of invariant amount

frameworks that support internally consistent, monotonic data structures, and 2) transforming ordinal data from their instrument- and sample-dependent nonlinear raw score units and restricted ranges (Figure 2) to invariant measuring units and infinite ranges (Figures 3 and 4).

The simple log-odds approximation method [18] used to transform the scores in Figure 2 into the measures in Figure 3 gives less than perfect results. Most computer programs [19-

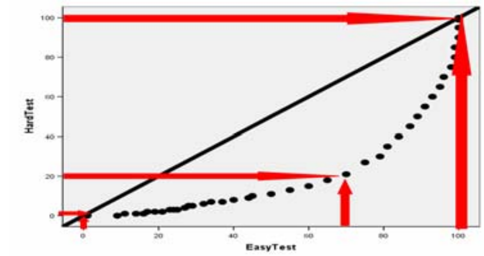

Figure 2. Ordinal measuring units indicative of order, not amount

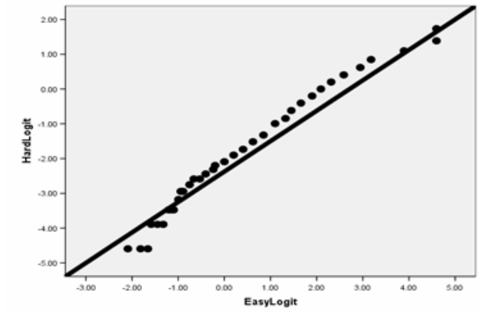

Figure 3. A log-odds transformation of the Figure 2 data

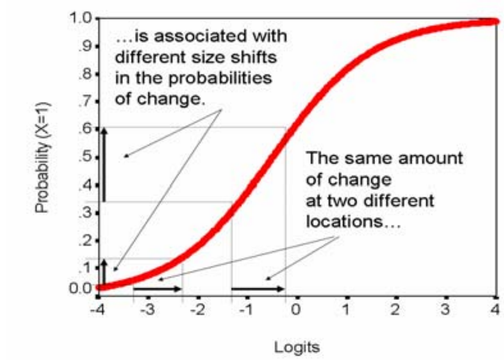

Figure 4. Finite score/percentage range vs. infinite measurement continuum

20] use joint maximum likelihood, fully conditional estimation, or Monte Carlo methods to remove the estimation process as a consideration in the definition of the unit.

A second plank in the platform for uniform standards for human, social, and natural capital involve a series of experiments that focused on reproducing physical measures using the kind of ordinal data produced by ability tests,

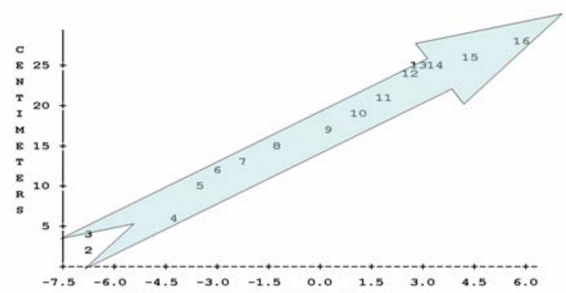

Figure 5. Ordinal-based length measures plotted against centimeters [21]

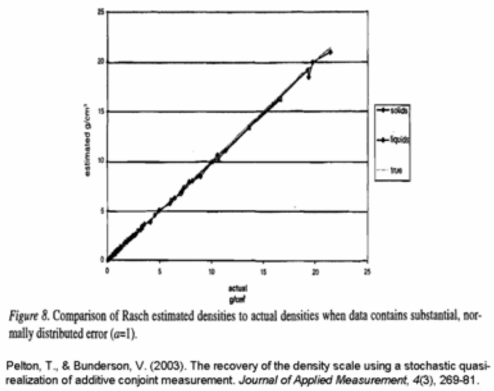

Figure 6. Rasch-estimated densities and actual densities compared [22]

performance assessments, and rating scales. The abstract axioms are illustrated concretely when 1) a length ruler with unevenly spaced ordinal units (Figure 5) [21], 2) intuitively judged paired comparisons of weight [22], 3) judged ratings of distance away [23], or 4) paired comparisons of material density [24] (Figure 6) are fit to a Rasch model, and the resulting measures plot linearly with the respective centimeters, grams, meters, and densities (grams per cubic centimeter).

Given, then, the capacity of the models to recover from ordinal data the same additive structures as those presented in accepted metrological standards, the third plank in the platform emerges. In their multiplicative form, Rasch's models have the same structure as the laws of natural science [3,25]. Measurement theoreticians and dimensional analysis methodologists have long noted that the laws of physics are typically expressed as multiplications or divisions of measurements [26]. Rasch [3] develops an extended analogy based in Maxwell's 1876 analysis of mass, force, and acceleration, expressed as

$$A_{vj} = F_j / M_v \qquad (1)$$

such that the acceleration A is equal to the ratio of the force F of instrument *j* to the mass M of object *v*. The structure of the Rasch Reading Law embodied in the Lexile Framework for Reading [25] and the National Reference Scale for Reading [27] can be read from the same equation, such that the comprehension rate A is equal to the ratio of the reading ability F of examinee *j* to the reading difficulty M of text *v*. The stability of this relationship has been observed many millions of times in the 55 years since Rasch scaled his first reading test.

Fourth in the line of supports for the role of fundamental measurement theory in the creation of capital metrology standards is the fact that multiple independent studies of the same variable show that constructs have markedly robust broadly mathematical properties across investigations using different instruments with different respondents [28], different instruments with the same respondents [29], or the same instrument with different respondents [30]. Research has repeatedly shown that variations on the same unit of measurement are produced and reproduced across samples of items and persons drawn from the same populations, across researchers, and across time and space (see Figures 7 and 8 for examples).

Figure 7. A typical plot of item calibrations estimated from two different samples (correlation r = 0.98) [unpublished data]

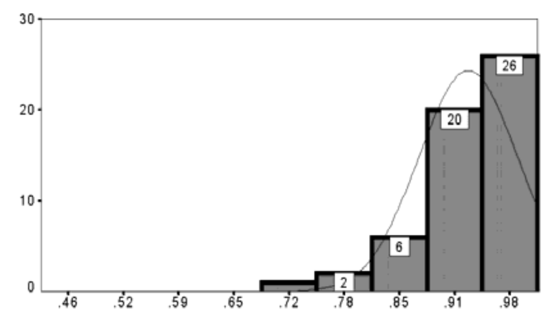

Figure 8. Fifty-five correlations of four instruments' item calibrations over ten samples [28]

Fifth, this applicability is emphasized in hundreds of published studies that populate the scientific literature in dozens of fields and demonstrate the versatility and applicability of Rasch's models relative to a wide variety of tests, surveys, and assessments. Examples of tests and surveys studied for their broad mathematical properties range from a test of the understanding of irony in poetry to measuring attitudes and behaviors related to studying and learning. The technical literature on measurement models, estimation methods, and the statistical study of failures of invariance is extensive.

These developments in theory and research have influenced and shaped practical applications in dozens of fields, in government, and in commercial enterprises. For instance, high-stakes educational measurement has employed fundamental measurement theory for graduation, admissions, certification, and professional licensure since the early 1970s [31]. The most notable example of a commercially available generalized metric is the Lexile Framework for Reading (www.Lexile.com).

3. THE ROLE OF METROLOGY

Capital is abstract meaning brought to life in two metrological phases characterizing the development of transferable representations, such as titles, deeds, and other legal, financial, and scientific instruments. In the first phase, something significant is conceived. That is, meaning is created experientially or experimentally by establishing the abstract existence of something capable of standing rigorously independent of the laboratory producing it [32] and the written, geometrical, metaphorical, historical, numerical, or dramatic figures carrying it. When a figure of any kind functions as a symbol, any instance of it is then potentially interpretable as significant in a specific respect.

Once so conceived, the new form of life must be nurtured by progressively determining the limits of the environment required to sustain it. A sense of these limits is typically obtained via metrological ruggedness tests [33], wherein the conditions under which the invariant additivity, divisibility, and mobility of the numeric or other symbolic figures instrumental to capital representations come to be understood. In the human sciences, such ruggedness tests have taken the form of multiple independent experimental investigations of the fit of data to mathematical models of fundamental measurement [28,34]. In this initial phase of capital formation, the form of life acts consistently as an agent compelling agreement among investigators as to its independent real existence [35].

For this potential to be made actual, for what has been conceived and gestated to be born as an independent form of life, the second, maturational, phase of development must take place. In this phase, the symbol is mobilized via a standardized inscription device within a network or ecological niche prepared to recognize and accept it as a common currency mediating the exchange of its particular value. This kind of cross-laboratory coordination of instruments, samples, operators, number systems, etc. is typically obtained by metrological round-robin trials [36]. In this second phase are determined the various conventions through which a particular form of capital will be recognized for what is. Where the consistent display of invariant properties characterizes the first phase of capital formation, in the second phase the former agent of agreement is transformed into a product of agreement [35].

A law of living capital [38] can be stated formally because, as Rasch [3] observed,

> Where this law [relating reading ability and reading difficulty via comprehension rate] can be applied it provides a principle of measurement on a ratio scale of both stimulus parameters and object parameters, the conceptual status of which is comparable to that of measuring mass and force. Thus, ... the reading accuracy of a child ... can be measured with the same kind of objectivity as we may tell its weight.

To satisfy the requirements of this separability theorem, hash marks on a ruler that appear evenly spaced must consistently correspond with apparently evenly-spaced differences observed in some relevant range of objects extended in space, and vice versa. The convergence effected between any one instrument and any one set of things measured must then be generalizable in the sense that the same qualitative relations must be found to hold 1) when the instrument is applied to a new sample, and 2) between any other instruments of the given type and any other samples from the same population of objects. Studies of this kind of invariance are the object of metrological ruggedness tests in the natural sciences and engineering.

Similar requirements must be posed and met in the human, social, and environmental sciences for their respective forms of capital to be brought to life. Examination, survey, and assessment questions must also be required to take up consistent and invariant orders and spacings along measurement continua in association with appropriately varying observations of human, social, or natural capital phenomena. Though such a requirement may seem too rigid an obstacle for many instruments to overcome, it is met fairly routinely in the context of probabilistic models that allow for, and estimate, small amounts of error in the calibrations and measures [1-8,12-15].

4. TRENDS DEMANDING A NEW METROLOGICAL INFRASTRUCTURE

Despite developments in measurement theory and practice suggesting their viability, little or no effort has yet been invested in national or global metrological standards for the variables of human, social, and natural capital. This will soon change as global financial managers and investment analysts put 2 + 2 together. Four major factors are contributing to the emergence of metrological reference standards for the intangibles of human, social, and natural capital.

First, the need to harmonize sustainable human activity with the natural environment is prompting the emergence of ecologically-informed comprehensive economic models focusing on the conception, birth, and maturation of living capital [11,38]. These biomimicry models are based in the increasing recognition that transparent and transferable representations of living capital are fundamentally rooted in metrology, since they are necessarily additive, divisible, and mobile within the networks in which their value is recognized and accepted [32]. Many nations and international aid organizations are therefore focusing economic development efforts on building infrastructural capacities for the low-friction flow of capital [39].

Second, the vital importance of human, social, and environmental resources for the long-term sustainability of economic relationships is now so apparent that researchers and investment firms are developing metrics for measuring and managing these intangible forms of capital [40-42]. Similarly, local, regional, national, and international governments are actively exploring the creation of alternative productivity measures that more authentically gauge the positive and negative value of human, social, and environmental impacts [43].

These efforts have not yet fully articulated, much less addressed, the challenge. Dissatisfaction with the nonlinearity of the ratings used, the lack of effective quality assessment of the data, and the incommensurability of instrument-dependent ratings and scores will eventually create opportunities for metrological entrepreneurs in this area. These opportunities will be supported by the fact that, in many respects, Georg Rasch's probabilistic measurement models synthesize, reframe, and efficiently package key econometric assumptions and methods [44], as could be expected given his mentoring and collaborations with Nobel-winning econometricians, such as Ragnar Frisch and Tjalling Koopmans [45].

Third, the economic power of distributed cognition—the "wisdom of crowds" effect—stems from the way metrological infrastructure makes it possible for us to more fully realize the maxim of "acting local, thinking global" [46]. To reward improved quality, consumers need to be able to think and act in concert, on the basis of readily available, accurate, and universally uniform information. To improve quality, service providers also need to be able to think and act in concert without having to laboriously communicate facts expressed in locally-dependent incommensurable metrics.

Fourth, though the major barrier to the development of reference standards is the cost, that cost is an investment providing substantial returns in human, social, and economic value. It has been estimated that investments in metrological infrastructure in the U.S. amount to two to three times the value of investments in research as a whole [32]. Universal reference standards and metrological improvements benefit everyone, with economic returns on investment ranging from 40% to over 400% [47]. Because the cost of providing standards is so high, even with returns of this size it is not economically feasible for any one firm, or even group of firms, to underwrite the costs themselves. It is therefore essential to have public support for the development and maintenance of common metrics for human, social, and natural capital.

It is only a matter of time until these factors converge with the established value and utility of invariantly additive measures of human, social, and environmental capital. The latent demand among investors, consumers, and quality improvement specialists for comparability is such that international metrological organizations should already be positioning themselves to provide the needed calibration and traceability services. In the next few years, institutes for standards and technology will begin establishing new divisions focused on creating and maintaining universal uniform metrics for human, social, and natural capital.

5. RECOMMENDATIONS FOR A NEW METROLOGICAL CULTURE

Though they are rarely explicitly employed, it is easy to see that the axioms of fundamental measurement theory are routinely assumed to hold in econometrics generally and in the measurement of capital especially. Rasch developed his practical mathematical sensibility in a context saturated with concern for these issues, with his own parameter separability theorem and minimally sufficient estimators markedly similar to previous work performed by his mentor, Ragnar Frisch [48], and Frisch's colleague, Irving Fisher. The latter is celebrated as the foremost American economist in the history of the discipline [49,50].

The relationships between interest rates and inflation described in the Fisher equation, for instance, or between prices, the money supply, and quantities of available goods in the derivation of an economic index [51], are typically interpreted as satisfying Fisher's parameter separation theorem [52]. This is so even though data are rarely tested in explicit experimental tests of that hypothesis [53], and even though mainstream economics persists in using mathematical deductivist reasoning despite its general failure in providing insight [10].

Why might explicit experimental tests of key assumptions be so rare? Why might the mathematical models typically employed not succeed in illuminating economic conditions more clearly? Both of these questions could have the same answer, namely, that too many unexamined presuppositions about numbers and objectivity are simply not justified. This point is increasingly of interest in finance, the history of science, and economics, as is shown by the emergence of heterodox methods [54].

But the proper response to this situation certainly ought not to be a methodological free-for-all, in which everything is relative and anything goes. Instead, we ought to consider the significance of the fact that Fisher's equation of exchange [49], written as it is as a multiplication or division of measurements, and being explicitly presented in the form of a balance scale model [55], expresses the same logic of lawful relations as the laws of physics or a Rasch model. Indeed, several different approaches to economic modeling can be construed in this way, though they rarely have been so interpreted, and so have not yet "accomplished the close interaction between observation and theory that is characteristic of the natural sciences" [53]. But might efforts aimed at bringing fundamental measurement theory to bear in econometrics succeed in accomplish-ing this goal? Might the close interaction between observation and theory achieved in the Lexile Framework's modeling of literacy capital as a fungible common currency serve as a model for how to proceed with other forms of human, social, and natural capital?

The convergence of fundamental measurement theory with heightened demand for meaningful, precise, and convenient aids to the management of living capital makes it possible to formulate and propose the following recommendations.

- Because the difficulty experienced in measuring capital [42] is strongly related to the approaches used, those interested in addressing the problem must be informed about the relevant methods:
  - instead of forcing unanimous agreement on the content and format of indicators, focus on criteria for construct definition involving tests for additivity, unidimensionality, and parameter separation;

    - instead of setting the stage for confusion by basing metrics in the instrument-dependent ratings of particular collections of indicators, set the stage for transparency by basing metrics in universally available uniform metrics and equating instruments measuring the same thing to the reference standard;
    - instead of constraining the management of living capital to a microscopic focus on its local definitions and manifestations, liberate it by allowing its local forms to be expressed in global terms;
    - instead of defining living capital markets in the manner of medieval European village markets, each with their own distinct weights and measures, define them instead in the manner of the *Système International d'Unités*, so that they all refer to common metrics; and
    - instead of encumbering the exchange of living capital with numerous sources of friction, lubricate its flow with the common currencies of metrological standards.
- Because of the large investments needed and the general benefit to the greater good that is effected, the primary location of instrument equating and item bank calibration should be shifted out of individual private concerns into the public sphere.
- Investors are interested in maximizing returns over the long term, and human, social, and natural capital metrics are increasingly seen as providing information vital to achieving that goal, so shareholders in employee stock option plans and retirement investment accounts should lobby and agitate in favor of using universal and rigorous human, social, and natural capital metrology standards to guide investment policy.
- Investment banks interested in universally uniform fungible metrics for human, social, and natural capital should fund the establishment of academic centers focused on advancing the theory and practice of living capital metrology.
- Metrology agencies should institute education programs to inform
    - the public about the new potentials for transparency in human resource accounting, educational attainment, and health care outcome measurement, and
    - investment analysts and econometricians about the value of universally uniform, invariant metrics for each species of human, social, and natural capital.
- Standards groups composed of each type of stakeholder invested in the development of uniform measures for human, social, and natural should be formed to oversee their creation, development, and maintenance.
- Existing efforts in academia, government, and business aimed at establishing invariant standards for specific constructs measured via achievement tests, performance assessments, and surveys should be reviewed and synthesized with the goal of creating universally uniform metrics for each.

The broad scope of these recommendations gives pause in a manner akin to Rasch's realization that the separation theorem posed very demanding conditions on data, prompting his observation that "this is a huge challenge, but once the problem has been formulated it does seem possible to meet it" [3]. The spontaneous eruption in recent years of leaderless global movements of concerned people striving to improve the qualities of their lives, their societies, and their environments [56-58] gives hope that the energy and resources needed to meet the challenges posed will not be wanting.

6. CONCLUSIONS

Individuals, governments, and enterprises globally want to measure human, social, and natural capital in order to manage it better. Waste is the common root cause of human suffering, sociopolitical discontent, and environmental degradation [11]. Many industries have seen their profit margins minimized in recent years and are looking for new ways to reduce inefficiency. Similarly, investors increasingly recognize that consistent growth in human, social, and natural capital promises the stability needed for sustainable long term profitability.

But the implications of human, social, and natural capital metrology extends far beyond the limits of commercial interests. One often hears that said the government should be run more like a business. Given the lack of relevant metrological standards, should we really be surprised at the general inability of governments to effectively manage human, social, and natural capital? Robert Kennedy said it well 40 years ago,

> Too much and too long, we seem to have surrendered community excellence and community values in the mere accumulation of material things. Our gross national product—if we should judge America by that—counts air pollution and cigarette advertising, and ambulances to clear our highways of carnage. It counts special locks for our doors and the jails for those who break them. It counts the destruction of our redwoods and the loss of our natural wonder in chaotic sprawl. It counts napalm and the cost of a nuclear warhead, and armored cars for police who fight riots in our streets. It counts Whitman's rifle and Speck's knife, and the television programs which glorify violence in order to sell toys to our children.
>
> Yet the Gross National Product does not allow for the health of our children, the quality of their education, or the joy of their play. It does not include the beauty of our poetry or the strength of our marriages; the intelligence of our public debate or the integrity of our public officials. It measures neither our wit nor our courage; neither our wisdom nor our learning; neither our compassion nor our devotion to our country; it

measures everything, in short, except that which makes life worthwhile.

To repeat, all human suffering, social discontent, and environmental degradation can be traced to a common cause: waste. In a comprehensively designed economic system, global capital resources are not mechanically produced and consumed in the name of profits. Rather, living capital resources must be organically conceived, midwifed, and nurtured in such a way that profits are value for life: the growth of the total stock of living capital resources [11,38,43].

Humanity will fulfill its potential only to the extent that it embodies its ideals of justice and fair play in those mundane and banal metrological systems that we take for granted as a background and structure of daily life. As Alder [59] put it,

> To do their job, standards must operate as a set of shared assumptions, the unexamined background against which we strike agreements and make distinctions. So it is not surprising that we take measurement for granted and consider it banal. Yet the use a society makes of its measures expresses its sense of fair dealing. That is why the balance scale is a widespread symbol of justice. ... Our methods of measurement define who we are and what we value.

Metrologists [60-61] know better than most that no units of measurement are born fully formed as universally available and uniform common indicators of quantity [32-36]. The transparency built into systems for the exchange of capital value is not easily obtained. But as long as we go on assuming either that we already have adequate metrological standards for human, social, and natural capital, or that such standards are impossible to achieve, our methods of measurement will inadequately define who we are and what we value.

REFERENCES

[1] Andrich, D. (1988). Rasch models for measurement. (Vols. series no. 07-068). Sage University Paper Series on Quantitative Applications in the Social Sciences). Beverly Hills, California: Sage Publications.

[2] Bond, T., & Fox, C. (2007). Applying the Rasch model: Fundamental measurement in the human sciences, 2d edition. Mahwah, New Jersey: Lawrence Erlbaum Associates [http://homes.jcu.edu.au/~edtgb/book/].

[3] Rasch, G. (1960). Probabilistic models for some intelligence and attainment tests (Reprint, with Foreword and Afterword by B. D. Wright, Chicago: University of Chicago Press, 1980). Copenhagen, Denmark: Danmarks Paedogogiske Institut.

[4] Dawson, T. L. (2004, April). Assessing intellectual development: Three approaches, one sequence. Journal of Adult Development, 11(2), 71-85.

[5] Smith, R. M., & Taylor, P. (2004). Equating rehabilitation outcome scales: Developing common metrics. Journal of Applied Measurement, 5(3), 229-42.

[6] Fisher, W. P., Jr., Eubanks, R. L., & Marier, R. L. (1997). Equating the MOS SF36 and the LSU HSI physical functioning scales. Journal of Outcome Measurement, 1(4), 329-362.

[7] Masters, G. N. (2007). Special issue: Programme for International Student Assessment. Journal of Applied Measurement, 8(3), 235-335.

[8] Lunz, M. E., Bergstrom, B. A., & Gershon, R. C. (1994). Computer adaptive testing. International Journal of Educational Research, 21(6), 623-634.

[9] Barzel, Y. (1982). Measurement costs and the organization of markets. Journal of Law and Economics, 25, 27-48.

[10] Bigo, V. (2007). Explaining modern economics (as a microcosm of society). Cambridge Journal of Economics, advance access publication [http://cje.oxfordjournals.org/cgi/content/abstract/bem058].

[11] Hawken, P., Lovins, A., & Lovins, H. L. (1999). Natural capitalism: Creating the next industrial revolution. New York: Little, Brown, and Co.

[12] Fischer, G. H. (1995). Derivations of the Rasch model. In G. Fischer & I. Molenaar (Eds.), Rasch models: Foundations, recent developments, and applications (pp. 15-38). New York: Springer-Verlag.

[13] Wright, B. D. (1997, June). Fundamental measurement for outcome evaluation. Physical Medicine & Rehabilitation State of the Art Reviews, 11(2), 261-88.

[14] Andersen, E. B. (1977). Sufficient statistics and latent trait models. Psychometrika, 42(1), 69-81.

[15] Wright, B. D. (1977). Solving measurement problems with the Rasch model. Journal of Educational Measurement, 14(2), 97-116 [http://www.rasch.org/memo42.htm].

[16] Fischer, G. H. (1981, March). On the existence and uniqueness of maximum-likelihood estimates in the Rasch model. Psychometrika, 46(1), 59-77.

[17] Luce, R. D., & Tukey, J. W. (1964). Simultaneous conjoint measurement: A new kind of fundamental measurement. Journal of Mathematical Psychology, 1(1), 1-27.

[18] Cohen, L. (1979). Approximate expressions for parameter estimates in the Rasch model. British Journal of Mathematical and Statistical Psychology, 32, 113-120.

[19] Andrich, D., Lyne, A., Sheridan, B., & Luo, G. (2006). RUMM 2020: Rasch unidimensional models for measurement. Perth, Australia: RUMM Laboratory Pty Ltd [www.rummlab.com.au].

[20] Linacre, J. M. (2008). A user's guide to WINSTEPS Rasch-Model computer program, v. 3.65.0. Chicago, Illinois: Winsteps.com.

[21] Fisher, W. P., Jr. (1988). Truth, method, and measurement: The hermeneutic of instrumentation and the Rasch model [Diss]. Dissertation Abstracts International (University of Chicago Dept. of Education, Division of the Social Sciences), 49, 0778A.

[22] Choi, S. E. (1997). Rasch invents "Ounces." Rasch Measurement Transactions, 11(2), 557 [http://www.rasch.org/rmt/rmt112.htm#Ounces].

[23] Moulton, M. (1993). Probabilistic mapping. Rasch Measurement Transactions, 7(1), 268 [http://www.rasch.org/rmt/rmt71b.htm].

[24] Pelton, T., & Bunderson, V. (2003). The recovery of the density scale using a stochastic quasi-realization of additive conjoint measurement. Journal of Applied Measurement, 4(3), 269-81.

[25] Burdick, D. S., Stone, M. H., & Stenner, A. J. (2006). The Combined Gas Law and a Rasch Reading Law. Rasch Measurement Transactions, 20(2), 1059-60 [http://www.rasch.org/rmt/rmt202.pdf].

[26] Ramsay, J. O., Bloxom, B., & Cramer, E. M. (1975, June). Review of Foundations of Measurement, Vol. 1, by D. H. Krantz et al. Psychometrika, 40(2), 257-262.
[27] Rentz, R. R., & Bashaw, W. L. (1977, Summer). The National Reference Scale for Reading: An application of the Rasch model. Journal of Educational Measurement, 14(2), 161-179.
[28] Fisher, W. P., Jr. (1997). Physical disability construct convergence across instruments: Towards a universal metric. Journal of Outcome Measurement, 1(2), 87-113.
[29] Fisher, W. P., Jr., Harvey, R. F., Taylor, P., Kilgore, K. M., & Kelly, C. K. (1995, February). Rehabits: A common language of functional assessment. Archives of Physical Medicine and Rehabilitation, 76(2), 113-122.
[30] Fisher, W. P., Jr. (1999). Foundations for health status metrology: The stability of MOS SF-36 PF-10 calibrations across samples. Journal of the Louisiana State Medical Society, 151(11), 566-578.
[31] Smith, R. M., Julian, E., Lunz, M., Stahl, J., Schulz, M., & Wright, B. D. (1994). Applications of conjoint measurement in admission and professional certification programs. International Journal of Educational Research, 21(6), 653-664.
[32] Latour, B. (1987). Science in action: How to follow scientists and engineers through society. New York: Cambridge University Press.
[33] Wernimont, G. (1978, December). Careful intralaboratory study must come first. ASTM Standardization News, 6, 11-12.
[34] Fisher, W. P., Jr. (2000). Objectivity in psychosocial measurement: What, why, how. Journal of Outcome Measurement, 4(2), 527-563.
[35] Wise, M. N. (1995). Precision: Agent of unity and product of agreement. Part III--"Today Precision Must Be Commonplace." In M. N. Wise (Ed.), The values of precision (pp. 352-61). Princeton, New Jersey: Princeton University Press.
[36] Mandel, J. (1978, December). Interlaboratory testing. ASTM Standardization News, 6, 11-12.
[37] Fisher, W. P., Jr. (2008). Reducible or irreducible? Mathematical reasoning and the ontological method. In M. Garner, K. Draney, M. Wilson, G. Engelhard, Jr. & W. Fisher, Jr. (Eds.), Advances in Rasch measurement, Vol. 1 (p. in press). Maple Grove, MN: JAM Press.
[38] Fisher, W. P., Jr. (2008). Bringing human, social, and natural capital to life: Practical consequences and opportunities. In B. Duckor, Brown, K. Draney & M. Wilson (Eds.), Advances in Rasch measurement, Vol. 2 (p. in press). Maple Grove, MN: JAM Press.
[39] Seiler, E. (1999). The role of metrology in economic and social development. Computer Standards & Interfaces, 21, 77-88.
[40] Andriessen, D. (2003). Making sense of intellectual capital: Designing a method for the valuation of intangibles. Oxford, England: Butterworth-Heinemann.
[41] Hand, J. R. M., & Lev, B. (Eds.). (2003). Intangible assets: Values, measures, and risks. (Oxford Management Readers). Oxford, England: Oxford University Press.
[42] Hulten, C. R. (2004). The "architecture" of capital accounting: Basic design principles. In D. Jorgensen, J. S. Landefeld & W. D. Nordhaus (Eds.), Conference on Research in Income and Wealth, April 16-17, Washington, DC. Chicago: University of Chicago Press.
[43] Anielski, M. (2007). The economics of happiness: Building genuine wealth. Gabriola, British Columbia: New Society.
[44] Kærgård, N. (2003, 2-4 May). Georg Rasch and modern econometrics. Presented at the Seventh Scandinavian History of Economic Thought Meeting, Molde University College, Molde, Norway.
[45] Fisher, W. P., Jr. (2008). Rasch, Frisch, and two Fishers: A social history of the econometric origins of some widely used psychometric models. The European Journal of the History of Economic Thought, in review. [Rasch Measurement SIG, American Educational Research Association Annual Meeting, New York, March.]
[46] Magnus, P. D. (2007). Distributed cognition and the task of science. Social Studies of Science, 37(2), 297-310.
[47] NIST. (1996). Appendix C: Assessment examples. Economic impacts of research in metrology. In C. o. F. S. Subcommittee on Research (Ed.), Assessing fundamental science. Washington, DC: NSTC [http://www.nsf.gov/statistics/ostp/assess/nstcafsk.htm#Topic%207; accessed 10 June 2008].
[48] Frisch, R. (1930). Necessary and sufficient conditions regarding the form of an index number which shall meet certain of Fisher's tests. Journal of the American Statistical Association, 25, 397-406.
[49] Allen, R. L. (1993). Irving Fisher: A biography. Cambridge, Massachusetts: Blackwell.
[50] Barber, W. J. (2005, January). Irving Fisher of Yale. American Journal of Economics & Sociology, 64(1), 43-55.
[51] Dimand, R. W. (1998). The quest for an ideal index: Irving Fisher and the making of index numbers. In M. Rutherford (Ed.), The economic mind in America (pp. 128-44). New York: Routledge.
[52] Hochstein, A. (2001, December 1). A Keynesian view of the Fisher separation theorem. Atlantic Economic Journal, 29(4), 469.
[53] Hillinger, C. (2007). Measurement in economics and social science (Tech. Rep. No. 2007-19). Department of Economics: University of Munich.
[54] Lawson, T. (2006). The nature of heterodox economics. Cambridge Journal of Economics, 30, 483-505.
[55] Boumans, M. (2005). How economists model the world into numbers. New York: Routledge.
[56] Brafman, O., & Beckstrom, R. A. (2006). The starfish and the spider: The unstoppable power of leaderless organizations. New York: Portfolio (Penguin Group).
[57] De Soto, H. (2000). The mystery of capital: Why capitalism triumphs in the West and fails everywhere else. New York: Basic Books.
[58] Hawken, P. (2007). Blessed unrest: How the largest movement in the world came into being and why no one saw it coming. New York: Viking Penguin.
[59] Alder, K. (2002). The measure of all things: The seven-year odyssey and hidden error that transformed the world. New York: The Free Press.
[60] Busch, T. (1989/1964). Fundamentals of dimensional metrology (2nd ed.). Albany, New York: Delmar.
[61] Pennella, C. R. (1997). Managing the metrology system. Milwaukee, WI: ASQ Quality Press.