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Why is emergy so difficult to explain to my environmental science friends?¹

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Abstract

Communication problems concerning the emergy concept, in an environmental science context are described. Problematic areas identified, are 1) the different use of the energy concept, where adding up energies of different kinds are not accepted, 2) the size of tidal and deep heat emergy compared to solar energy, 3) the solar energy being represented by rainfall or land cycle, and 4) the view on value and connection to economics. Pedagogic experiences are shared regarding 1) how to communicate the energy hierarchy concept, 2) the communication benefits of decoupling the hypotheses of the energy hierarchy, maximum empower and pulsing, and 3) communication to economists regarding the emergy concepts relation to economics. Some larger contextual reasons influencing the communication are also identified as 1) the important paradigm shift in ecology during the 1970s, from a holistic ecosystem ecology to a reductionistic population and community ecology, and 2) the dualistic view of quantity and quality regarding the four main types of flows existing in systems (energy, mass, money and information), where useful qualitative measures seem to be missing as a complement to the quantitative measure of information in bits. The main recommendation from this paper is that even more carefulness is spent on explaining that the emergy concept relies on the theory of the energy hierarchy, with the implication that the energy concept is used in a slightly, but very important, different way than by most scientists.

Keywords: ecosystem ecology, emergy, tidal energy, deep heat energy, pedagogy, energy hierarchy, maximum empower, pulsing, paradigm shift

¹ An earlier version of this paper was published in the proceedings of the conference Emergy Synthesis 5: Theory and Applications of the Emergy Methodology. Fifth Biennial Emergy Research Conference, at the Center for Environmental Policy, University of Florida, Gainesville, Florida, USA, January, 2008. This paper is not meant as an alternative to “the Florida approach” to introduce the emergy concept, but if you have (like I had) some problems with understanding and accepting parts of the theory behind the concept, my observations may hopefully be useful. If you have embraced the concept, but have problems reaching out to your friends (like I had), feel free to try my experiences how to navigate around that problem.

1 Introduction

Emergy is a concept developed by HT Odum and co-workers, in the context of ecosystem ecology, during the last 40-50 years [1]. In principle it is a further development of the old food chain and energy pyramid of trophic levels developed in the 1940s by Raymond Lindeman [2,3]. Since then new measures (emergy one of them) has been developed for the energy hierarchy formed in the energy pyramid, and with the emergy concept the application has been expanded to include abiotic factors such as wind, rain, etc., as well as human artefacts as cities, nations etc. The basic principles of the emergy concept were present already in HT Odum's first textbook from 1971 *Environment, power and society* [4], and described in a more popular form in *Energy basis for man and nature* [5]. In 1983 the emergy concept was almost fully developed and presented in the textbook *Systems ecology: An introduction* [6]. Up to this year the concept was presented under other names, but from 1985-87 the word emergy was emerging in the literature (in 1986 the word "enmergy" was used in the book *Ecosystem Theory and Application* [7]), and from the journal paper in *Science* in 1988 [8] it has been the established term used. In 1994 a revised version of the *Systems ecology: An introduction* [6] textbook was published with a new name: *Ecological and general systems - an introduction to systems ecology* [1]. In 1996 the main methodology source for emergy accounting was published: *Environmental accounting. Emergy and environmental decision making* [9]. In 2001 the emergy concept found its probably so far best popular presentation in the book *A Prosperous Way Down: Principles and Policies* [10], and in 2007 the circle was fulfilled with the second edition (posthumous) of HT Odum's first book, now with emergy as the major backbone: *Environment, power and society for the twenty-first century* [11]. Other publications mentioned to show the width of the usefulness of the concept are *Emergy and evolution* [12] and *Ecology and economy: "Emergy" analysis and public policy in Texas* [13].

This paper is summing up 20 years of the authors experience in communicating the emergy concept in different contexts, from internal seminars at the Division of Ecotechnics/Ecotechnology at Mid Sweden University, over informal student evening discussion groups, to conference presentations etc.

In the first section of the paper problematic areas to communicate are described. In the second section pedagogic experiences how to meet and dissolve the problematic areas are presented and described. In the last section, other, deeper, reasons for the biased communication are suggested and discussed. The context of the experiences presented are the time period 1997 to 2019, mainly in Sweden, but to some extent also international.

2 Problematic areas to communicate

2.1 The energy concept

Energy is a phenomenon very familiar to all scientist in natural science and engineering, and in many scientific branches energy calculations are performed in a standardized way. However, going deeper into the energy concept it turns out to be a more complicated question than most scientists expect. Vaclav Smil in his book *Energies* writes that it is "...a

hard question to answer..." what energy is [14]. "If forced to choose...", Smil continues, "...I would opt for David Rose's evasive answer: Energy 'is an abstract concept invented by physical scientists in the nineteenth century to describe quantitatively a wide variety of natural phenomena'" [14]. Energy of different types (phenomena) are well defined and they can all be expressed in joules (or calories, kWh or similar). The use of the common unit joule (J) gives the impression that they are the same, and can easily be compared to each other. Often, this works fine for many types of energies, as is the experience from many fields of engineering, and energy calculated within the so called energy sector. However, HT Odum had a more strict approach to this, probably based on the experience that different kinds of energies could not be replaced by each other in the ecosystems he was investigating. Rather solar energy has its integrity as well as the osmotic energy in water has its. And, to take one of HT Odum's more extreme examples, snake movement energy is different and cannot be replaced by other energies. Odum therefore used the approach of expressing different kinds of energies from how they were produced. So, electric energy from a coal power plant could either be expressed as electric energy or coal energy. To make the difference explicit Odum added the word *equivalent* to the unit (other words were used by Odum in the earlier publications). So 1 J of electricity could either be expressed as 1 electricity equivalent joules (eej) or as the 4 J of coal it took to produce it: 4 coal equivalent joules (cej). Or each one of the 4 coal joules could be expressed as 0.25 eej. To compare different types of energies, one type was chosen as the type to express it in. The most general kind of energy turned out to be the solar equivalent joule (sej). Therefore sej is the most common unit used today in energy calculations.

HT Odum's explanation why energy can be added up in engineering and the energy sector was that it works as long as the different types of energies are from approximately the same energy hierarchy level [9]. It is since long known that in nutrient chains most of the energy is lost going up one trophic level, and that the nutrient webs form energy pyramids of producers, herbivores, predators, and top predators. Odum called this an energy hierarchy. From an energy point of view it is not useful to add up all the energies at all levels at the same time. Then almost all the energy will be found at the producer level, and only that level would be needed to measure. Even the big dinosaurs contained only a fraction of the energy the food they consumed contained. It makes more sense to sum up the energy at each trophic level. So, adding up herbivore energy makes sense, even if they are of different qualities as cow, horse or goat. Adding up grasses of different species and also with herbs and bushes also makes sense in ecological investigations. However, adding up the energy in goats and herbs from the same system gives very little more information, than just measuring the energy in the herbs. A notation must be made though: the above examples are only valid as long as we talk about living matter. As soon as we discuss dead organic matter in the system, they will of course have a similar value. The energy content per cubic centimeter in dead plants, herbivores, carnivores, and top consumers are approximately the same (of which the detritivores can testify!). In the living phase we will anyhow never find as many joules of top predators as herbivores in any system (at least not in joules per year).

The problem and confusion connected to the above described, is that even in textbooks of ecology or environmental science the energy concept will be explained only from the dead matter perspective used in physics and chemistry, and never (or rarely) from the systems perspective. Even when discussing the trophic pyramids the discussion will stop at the energy values assessed when burning the dead organic matter producing heat energy. Heat energy is always the lowest quality of energy in any system.

Another problem is that other environmental assessment methods (than emergy analysis) are often better known to the listener or reader, as life cycle assessment (LCA), ecological footprints, or different Factor X approaches as Factor 4 or Factor 10. They all use the common approach of adding up energies of different kinds. When it then comes to emergy evaluations it is often assumed that emergy is based on the same type of calculations, which as seen above is not the case. Emergy accountings instead use a correction factor (called transformity) correcting the traditional energy value (often the heat value) for its position in the energy hierarchy. This is similar to the correction factor used in exergy accounting, with the difference that the exergy correction factor corrects the heat value for its ability to do physical work, and not for hierarchical differences in the system (actually emergy accountings most of the time want to correct the exergy value for its position in the energy hierarchy rather than the energy value. Odum preferred to use the term “available energy” instead of exergy [9]).

So, to sum up the communication problem with the energy concept, it is a question of how different kinds of energies can be summed up. Most listeners or readers are used to the summing up method of different kinds of energies used in physics, developed for heat engines during the 19th century. In emergy accounting energies from different hierarchical levels are not summed up without first being corrected for their position in the energy hierarchy. Both approaches are valid within the context they were designed for. However, this difference is often not recognized but instead many get confused by trying to understand emergy accounting with “heat engine” energy understanding.

2.2 Size of tidal and deep heat emergy

Sunlight is the totally dominating incoming source of energy to the biosphere. $5.61 \text{ E}24 \text{ J/yr}$ ($\text{E}24=10^{24}$) of solar radiation is received at the upper atmosphere and when 30% albedo is assumed, this gives a net energy absorbed by the Earth system of $3.93 \text{ E}24 \text{ J/yr}$ [15]. Compared to this the tidal energy received from the moon was estimated to $5.2 \text{ E}19 \text{ J/yr}$ [16] which is only 0.001% of the incoming solar energy. The third independent energy source reaching the biosphere is deep heat energy from the Earth's crust. Odum [15] used the estimations from Sclater et al. [17] of $1.98 \text{ E}20 \text{ J/yr}$ from crustal radioactivity and $4.74 \text{ E}20 \text{ J/yr}$ from heat flow from the mantle, giving a total of $6.72 \text{ E}20 \text{ J/yr}$ which is only 0.017% compared to the incoming solar radiation. However, when converting these three independent energy sources to emergy flows (emergy per time is called empower) the proportions of the values change very much: Solar emergy absorbed $3.93 \text{ E}24 \text{ J/yr}$; Tidal energy absorbed $3.83 \text{ E}24 \text{ sej/yr}$; Crustal heat sources $8.06 \text{ E}24 \text{ sej/yr}$.

The discrepancy between the energy values and the emergy values creates mistrust regarding the emergy method. Fortunately, it has in general no implication at all for the emergy evaluation of the system. Emergy evaluations use a baseline for the calculations in the same way as the ecological footprint method use a baseline [18]. The current baseline in ecological footprint calculations is 11.9 gha (global hectares), but other baselines have occurred: 51 gha and 11.2 gha. Comparing results based on different baselines is not a fair comparison. In emergy accounting the most commonly used baselines have been 9.44 E24 sej/yr [9] and 15.83 E24 sej/yr [15]. Recently Brown and Ulgiati [19] updated the baseline to 15.2 E24 sej/yr. In emergy accounting the baselines can easily be recalculated to each other. So, for the reader who is very sceptical to the deep heat and tidal emergy values, the baseline can be set to only include the sunlight, giving 3.93 E24 sej/yr. Comparing that evaluation to other can easily be done, just by using the baseline correction factor.

2.3 Rain or land cycle representing sun energy

In emergy accounting it is normal procedure to use the largest of the local renewable flows to represent the others to avoid double counting. This since for example both wind and rain are secondary flows driven by the solar insolation. Depending on what ecosystem is evaluated sun, rain, wind or land cycle are the most common candidates. In energy terms of course the sun insolation is the largest item, but when correcting for the current estimates of position in the energy hierarchy of rain (chemical energy potential, or gravity energy potential), rain will often be the largest flow in many systems. In some places even the land cycle flows are the largest, following the high position in the energy hierarchy by the geological sedimentary cycle compared to solar insolation. Communicating this is often problematic, since it is un-intuitive to the students that the emergy in rain can be larger than the emergy in solar radiation. However, the rain and wind must be positioned higher up in the energy hierarchy of the biosphere since both are solar driven. It is possible to calculate how much solar energy it takes to produce a joule of rain or wind energy. The land cycle is driven by the combined work of the three independent energy sources described in the previous section, solar, tidal, and deep heat. This is even more obvious if the evaluated ecosystem is affected by the large sea currents or ocean waves. Going deeper into this also the wind and the rain are affected by the tidal and deep heat forces. The flows of sun, rain, wind and land cycle should not be seen as single flows, but rather representing the total biospheric work allocated to the investigated system. Brown and Ulgiati [19] labels it “geobiospheric work”.

2.4 Value – connection to economics

In his 1996 book, *Environmental accounting*, HT Odum [9] claims that emergy is a better measure of value than money, and therefore calls emergy a measure of the “real wealth”. It must be remembered that Odum here means a systems value – an ecocentric value – while monetary valuation based on market valuation is the value to single persons – “the economic man” – and an anthropocentric value [20]. Ecologists and environmentalists can usually understand this approach. However, the few environmental scientists with economic background that the author has met have problems accepting Odum’s “real wealth” concept. Some even have problems with the concept of “ecosystem work”, arguing that only humans can do work, not ecosystems.

3 Pedagogic experiences

3.1 The energy hierarchy

Explaining the energy hierarchy is, of course, fundamental in explaining the emergy concept. Starting this explanation with the picture of the energy memory concept [9], where energy is a record (memory) of previously used-up energy by e.g. a tree, an eagle, a city, or a population of lemmings, has its limits from the author's experience. After some trial and error the author discovered that picturing the energy hierarchy with a triangle was the fastest way to introduce the energy hierarchy concept. The emergy measure, in sej, can then easily be shown as measure of the width of the base of the triangle, and the transformity a measure of the height in the hierarchy (figure 1). The cognitive picture of the energy hierarchy will then rather be what it takes to balance a system at a dynamic steady state rather than the path of historical energy memory. The picture contains one major simplification, and that is the assumption of no storages in the system storing energy flows from previous years and releasing some of them during the year (or other time unit) of the actual investigation, which of course will happen in almost any real system (storage of seeds, dead wood, food, oil etc).

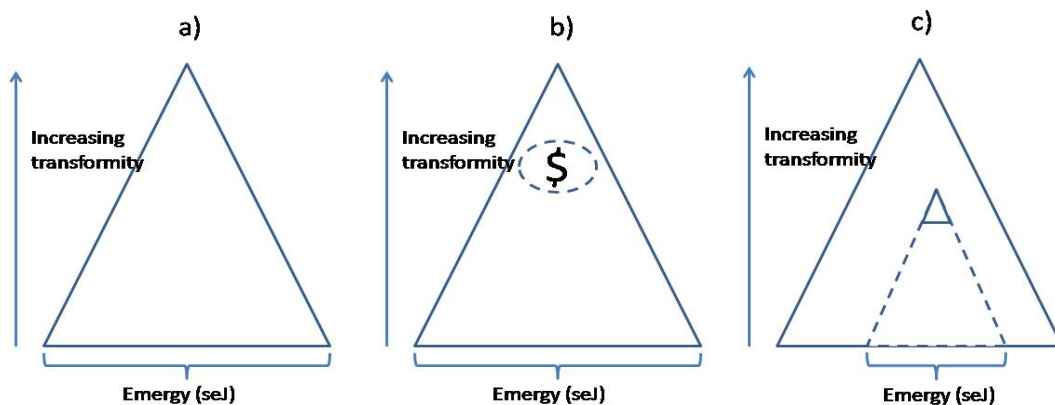


Figure 1. a) energy hierarchy, b) energy hierarchy with monetary flow at a certain hierarchical level, c) embedded subsystem.

The balancing steady state picture also makes it easier to meet the type of critique from e.g. Hornborg [21] of the old car having a higher energy value than the new one, since more ("energy memory") have been invested in it in the form of maintenance and historical operation resource use. The triangle figures give way to an explanation where emergy represents what is needed to maintain the feature car (or the "car-system") including its life cycle, rather than comparing a car early and late in its life cycle.

3.2 Decoupling of the hypotheses of energy hierarchy, maximum empower and pulsing

HT Odum's "emergy world" has three separate hypotheses that are interconnected: 1) the energy hierarchy, 2) maximum empower, and 3) pulsing. In the emergy literature from HT Odum and co-workers the starting point is always the maximum empower concept,

which probably reflects the chronology in how HT Odum developed the emergy concept [22]. The pulsing concept – there are pulsing behaviour in almost all real systems – is also connected to the maximum empower concept, as pulsing is probably maximizing empower, but has not been proven so yet [23]. The experience for the author of this paper is that the early communication benefits from the three concepts being decoupled, and the energy hierarchy is presented first. The reason for this is the experience that as soon as the maximum empower concept has been introduced, the discussion almost immediately becomes polarized, for and against the maximum empower concept, spreading mist around the emergy concept. The energy hierarchy concept on the other hand is quite easy to explain and very noncontroversial among most listeners. They can relate easily to the hierarchy concept. The authors own introduction took the same road. To accept the emergy concept I had to reject the maximum empower concept for some years (and still view it as a likely but yet not proved hypothesis).

3.3 Connection to economics

The authors experience is that the Odum 1996 [9] view of monetary flows (higher up in the energy hierarchy, see figure 1b) being the result of physical flows (lower in the energy hierarchy), is not accepted nor rejected by most people, whether with scientific background or not. Even though dealing with money every day most people have very little theoretical understanding of what money is. People with economic education are generally sceptic to the Odum 1996 view. A better approach towards this group is to introduce the Odum 1984 [24] view of energy and economy possibly being different tracks, however possible to connect, see figure 2. Money distribution can be observed forming hierarchical patterns, and assuming proportionality between the monetary hierarchy and the energy hierarchy of physical flows, is a way to accept the conversion factor between the physical and monetary hierarchies. This alternative explanation gives a possibility to introduce the sej/\$ conversion factor without challenging the economic science view on money, and still let it be open to accept the energy-economy connection.

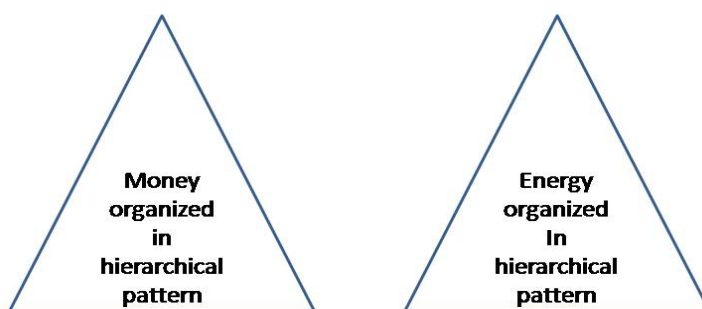


Figure 2. The view on money from Odum 1984 [24] where proportionality is assumed between a hierarchy of money and a hierarchy of energy, giving way to use the sej/\$ ratio.

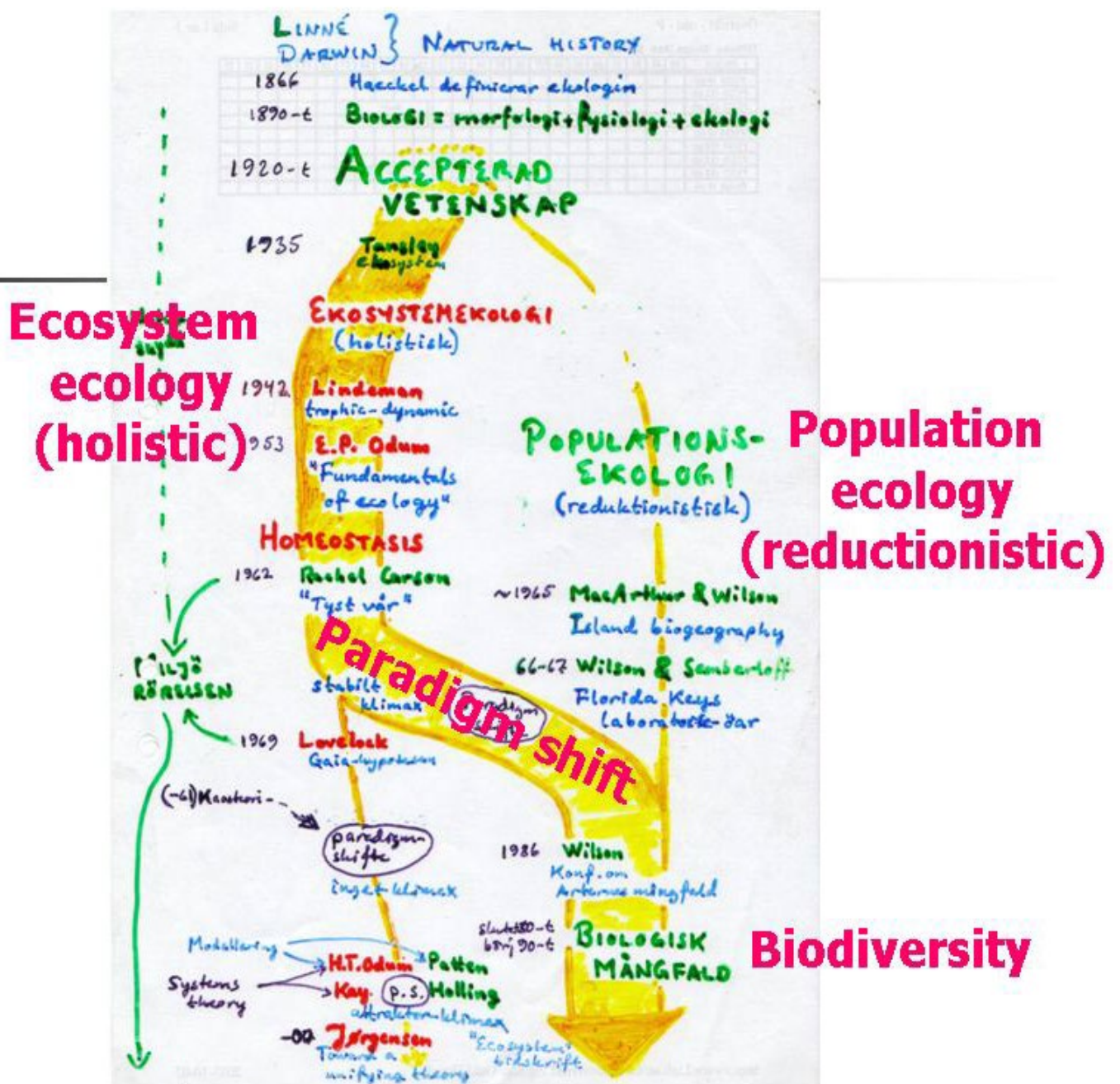


Figure 3. The history of ecology up to the millennium shift interpreted by the author of this paper from Worster 1994 [3].

4 Other reasons

4.1 Paradigm shift in ecology during the 1970s

A larger scale explanation of communication problems regarding the emergy concept can be found in the emerging flora in recent years of books covering the history of ecology. Figure 3 is the authors summary of Donald Worster's description of the history of ecology [3], showing the important paradigm shift occurring in the field of ecology during the 1970s. After this paradigm shift the reductionistic population and community ecology has totally dominated the ecology field. Active ecologists in the older holistic ecosystem ecology paradigm were very low in numbers during the 1980s and 1990s. Environmental scientists working with ecologists are educated in the reductionistic paradigm, and often has no knowledge of the recent development in ecosystem ecology [25-28], and find new concepts as emergy, ascendancy [29], environs [30], and eco-exergy [31-33] problematic to understand. And maybe even more important: not established terms in the field of ecology.

4.2 Measures yet to be invented

From a system science point of view, there are only four main types of flows in systems, yet known to science. These are flows of energy, material, information and money. Money can be seen as a special type of information flow, and this fits well into the main road of quantity-quality thinking that characterized the work of HT Odum, and has been beautifully formulated by Giannantoni [34] in his book *The maximum em-power principle as the basis for thermodynamics of quality*. In table 1 the four types of flows are arranged in the frame of quantity-quality [35].

Table 1. The four main types of flows arranged in the frame of quantity-quality [35].

Quantitative	Qualitative
Energy, J	Exergy, J Emergy, sej
Mass, kg	Type of atom- & molecule, kg Material, kg
Money, number of items	Money, US\$
Information, bit	- (missing) Value, US\$?

As mentioned above one of the major problems in communicating the emergy concept is that the average scientist find the quantitative measure of energy sufficient and only think implicit of quality aspects of energy. When it comes to mass, the opposite is the rule: we are so used to identify different qualities of materials at the everyday scale, and different atoms and molecules on the microscopic scale, that we would never dream of just adding them up easily (except in a few cases as e.g. cargo in an aeroplane). The same goes for money. We get amused when the child adds up coins whether they are 10 cents or Euro coins. The information measure, bit, has become familiar to us in the computer age, and

many of us easily relates to kilobytes, and gigabytes (1 byte = 8 bits). However, the situation is similar to the energy measure. Our intuitive understanding of information is “useful information”. However, the bit measures only the information content, whether it is useful or not. We can nowadays probably measure how many bits are shouted at night in the rainforest, but we have no measure of how much important was said! Intuitively we have the same opinion of energy: that it is something useful that can do work (which is actually exergy). To the authors knowledge a measure of qualitative information is lacking. The EmBit may be a candidate. Or the concept of exformation as described in the book *The user illusion: cutting consciousness down to size* [36,37], which features seems much correlated to emergy thinking.

5 Conclusions

The main reasons identified why the emergy concept has been difficult to communicate in a Swedish environmental science context are:

- The energy concept is used in slightly another way than most people and scientists are used to.
- The ecology concept is used in another way than many people and scientists are used to.
- The concept of value is used in a different way than in economic science (very easy, however, to get acceptance from natural scientists regarding this).
- The maximum empower concept is controversial among many and often blocks the possibilities to explain the energy hierarchy, which defines the emergy concept.
- The important differences between qualitative and quantitative aspects of the basic types of flows in the biosphere are too often not expressed explicit enough. A qualitative measure of information seems to be needed.

It may be a larger problem than realized that the use of the energy concept is slightly different, but at the same time still close to the most common (“normal”) use. The environmental science friend does not realize the sudden change of basic use of the energy concept. In this view the problem is rather psychological than a problem of understanding or different opinions.

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