The Passage from Entropy to Thermodynamic Indeterminacy:

A Social Science Epistemology for Sustainability

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Water wanted to live
It went to the sun it came weeping back
Water wanted to live
It went to the trees they burned it came weeping back
They rotted it came weeping back
Water wanted to live
It went to the flowers they crumpled it came weeping back
It wanted to live
It went to the womb it met blood
It came weeping back
It went to the womb it met knife
It came weeping back
It went to the womb it met maggot and rottenness
It came weeping back it wanted to die

It went to time it went through the stone door
    It came weeping back
It went searching through all space for nothingness
    It came weeping back it wanted to die

Till it had no weeping left
    It lay at the bottom of all things
        Utterly worn out   utterly clear.

Ted Hughes, How Water Began to Play (circa 1972)

1 Introduction

This essay sets out to sketch an epistemological perspective for scientific practice that might aid us in resolving these challenges of our planetary coexistence. We may call this a science for sustainability, necessarily bridging between physical science domains and the ethical and political domains of social action.

Human technological imagination has transformed almost everywhere the surface of the planet, even its weather patterns (and, some say, the ocean currents). We share, in a way that never was before, the same oceans, the same atmosphere, the same genetic heritage and the same waste disposal domains. Yet, we do not and can not control these complex ecosystems and biosphere processes upon which we all depend. If a basic principle of modern wealth accumulation is the controlled exploitation of nature (and of human labour), and yet this premise is false, then the humanist project of industrial development and mass consumption for everyone is now orienting us collectively towards a degradation of nature (and human nature) on a global scale.

In recent years the concepts of the new thermodynamics of disequilibrium systems have been used to achieve a scientific synthesis for the study of various facets of complex systems (Morin 1977; Norgaard 1984a, 1984b; O'Connor 1989, 1991, 1994a; Ruth 1993; Schneider and Kay 1994). Much of the work in application to economic systems analysis, and by extension to ecological economics systems, refers to the pioneering assertions of Nicholas Georgescu-Roegen. In this spirit, we offer here a reflection on this emergence of thermodynamics as a science of complexity, and on the problematic of complexity "as lived from the inside" — with application in the problem domain of sustainability.

2 Progress as the Liberation of Heat

The history of the market-based economic order can be read as a history of the liberation of energy — the physical energy of natural resources, and the creative energies of humanity (Cottrell 1955). Equally, it can be read as a history of dissipation and degradation -— of people as well as energy. In the instrumental, utilitarian view of nature, the non-human world is a freely available raw material just waiting to be put to use. Yet, correspondingly, the fear of natural resource depletion is as old as the idea of an expanding economy based on drawdown of God-given resources. As Jean-Paul Deléage (1989) observed, capitalism has always, in its *representation* of the accumulation process, treated nature as a non-binding constraint. For example David Ricardo at the beginning of the 19th century had been able to write of the "indestructible" powers of the land; and he could proclaim confidently that: "the brewer, the distiller, the dyer, make incessant use of their air and water for the production of their commodities; but as the supply is boundless, they bear no price" (Ricardo 1951, p.69). Yet now, we say that this is not true. We cannot treat the raw materials and "services" — source, site, scenery, and sink — furnished by nature as indestructible and/or non-scarce. And, just as Ricardo's land turns out not to be indestructible, neither is human nature immune to the assaults of the modern industrial machine.

The 19th century political economists were aware of the dependency of industrial economies on Nature's services and on agrarian sectors, and of the environmental and human degradation associated with industrial manufacturing processes. Yet they never systematically theorised the feedback dimensions of the interdependencies between industrial production and changes in the surrounding environment. Prevailing images of nature reflect the dominant motivations and orientations of each society. The interpretation of capital as embodying "stored" labour power, and of nature as holding potentials able to be unleashed to augment the productivity of human labour, was a social reality of 19th century industrialising societies. Prigogine and Stengers (1984, pp.111) have termed this world-view "a conception of society and men as energy transforming engines." On the one hand, the conception of man as worker served as a metaphor through which to comprehend the machine; and by extension, nature as amenable to transformation through labour and machine. On the other hand, the scientific concept of energy emerged out of this historically specific image of nature and contributed to its amplification. Recall Karl Marx's description of the capitalist mode of commodity production, a view quite typical of his time. In the famous description of the labour process in Part Three of *Capital I* (Chapter 5, pp. 169-177, Everyman's edition), he says:

> *"labour is a process going on between man and nature, a process in which man, through his own activity, initiates, regulates, and controls the material reactions between himself and nature."*

Man (*sic*), he says, "confronts nature as one of her own forces, setting in motion arms and legs, head and hands, in order to appropriate nature's productions in a form suitable to his own wants." The labour process is "purposive activity carried on for the production of use-values, for the fitting of natural substances to human wants." Human labour "makes use of the mechanical, physical, and chemical properties of things as means of exerting power over other things, and in order to make these other things subservient to his aims...." In this representation of the productive economic machine, the role of science was indeed simple. It furnished the knowledge base for improvements in productive efficiency and for innovations in process technology and product types. Scientific progress and economic progress (improved productivity and output growth) walked hand in hand.

Yet, the alliance between economic growth and (simple) science spawns contradictions. Thermodynamic science in the 19th century also gave an explanation, in terms of laws of nature, for phenomena that everyone already understood: that coal, once burnt, cannot be restored for re-use; that economic activity necessarily involves production of wastes. This is entropic irreversibility as defined by the Second Law of Thermodynamics. By today the question of thermodynamic irreversibility has become a truly global issue, binding in material and political terms on almost all peoples interlocked through the world-wide commodity economy or fighting for their survival on the margins of the expanding commodity economy. Science itself now informs us of the finiteness of our ecological capital, of the fragility of our biosphere as a collective habitat and life support system, and of the trade-offs between present and future associated with exploitation of forests and fisheries, with land degradation, with waste generation and associated toxicity problems.

To speak of energy in the 19th century was to evoke the immense powers of nature potentially at work for progress in industrial production. Here, the (meta-)physics of *liberation of energy* goes hand in hand with the *emancipation of the individual*, the presumed *freedom to choose* and to dispose freely of one's wealth. The West has been proud of the value it attributes to the individual. The votes of citizens against the despot; and in the marketplace the consumer sovereignly rules, OK. Modern man is free to create a history of his *[sic]* choice. "Man himself is, in this sense, liberated as a source of energy; and he becomes, by this, the motor of a history and of an acceleration of history" (Baudrillard 1990, p.105). Yet, as Marx himself remarked, if Man makes history, it is rarely the history that he has in mind. Liberty curves into catastrophe, as nature (and human nature) accommodates herself to ways that we are taking liberties with her productive powers. Behind the kaleidoscopic TV-screen facade of modern day freedoms of choice lies an *instrumental* logic by which nature -- and also people -- are reduced to the status of means to another's end. Not merely domination for appropriation of a productive surplus, rather it is a collective auto-destructive process whose result is the dereliction of human societies and ecosystems alike. Thus, the Poor "freely" confront every day their "right" to count for nothing in market society; women and wage workers every day confront the fact of their "freedom" to be of service in the projects of others, which they undertake (it is said) as matters of contractual free choice; and future generations no doubt will freely accept the polluted water, air and soil that is passed on to them.

The energy crises of the 1970s, extrapolated into "heat-death of the universe," have become diffuse cosmologies of doom. Yet, there is no danger that the world will actually run out of "free energy." Rather we have a problem of energy — and of so-called freedom — running amok. The pressing problems of exhaustion and degradation that we face are primarily the social and physical degradation such as experienced by housewives, cotton plantation labourers, and wage-workers on the factory floor, and by poultry and fish in their production-line farms. Capitalism in the 19th century was built on the "freedom" of (mostly male) industrial enterprise and on the strength of the steam engine (and child labour); and we, the participants of late 20th century (post?)industrial society, are the molecules inside the combustion chamber, rammed by the pistons, spat out the exhaust tubes.

What is the use-value of the hole in the ozone layer? What human wants are satisfied by the production of nuclear wastes? What is the final "product" in the process of biological change being unleashed by modern genetic recombination technology (Wills 1994; Funtowicz & Ravetz 1997) Contrary to what Marx portrayed, the final product risks disappearing in the process (O'Connor 1994c). Susan Griffin (1978, p.134) evokes the same thing poetically:

> *"Barely seen, soundlessly surrounding him, with hardly a breath of evidence, all he has burned, all he has mined from the ground, all he cast into the waters, all he has torn apart, comes back to him. He is haunted. Carbon monoxide, sulfur dioxide, beryllium, arsenic, peroxyacetylnitrate, formaldehyde, do not desert him. Dioxin, DDT, will not let him forget. Lead, mercury, live in his dreams. Strontium sticks in his bones. The equation for oxygen stays in his mind but he cannot breathe what he used to call air. The equation for water stays in his mind, but there is nothing he can drink that will not poison him...."*

We no longer have a simple equation between science, progress, and economic growth. The uncertainty, the diffuse dread of accidents and contamination, and the sharpening of distributional conflicts means a change in the roles that can be hoped, and reasonably required, for science inputs to social problem solving and policy decisionmaking. It now becomes paramount that *we are acting and observing from within complex natural-social systems, and these are not amenable to control along the lines of classical paradigms of mechanics, engineering design, or even cybernetic regulation.* A new epistemology for science is needed that is suited to these new Western preoccupation with the integrity of the life process itself.

3 An Epistemology for Complexity

To highlight the blind spots of the industrialist conception of production that underlies contemporary political economy and ecosystem management, and to offer some seeds for an alternative, we may draw on elements of contemporary open systems analysis and the thermodynamic theory of irreversible processes. Fight fire with fire. Thermodynamic science is the child of a particular time and place, spawned in the heart of the 19th century industrialisation process of Western Europe. It is par excellence the science of production. Yet, the fact that thermodynamics is a (by-)product of industrial society lends it a double-edged pertinence: first, no doubt, as a tool of ideology; and second (as we will try to employ it), as a tool of immanent critique — the science of Quality in production and by-production.

We draw here on a distinction suggested by Herbert Simon (1969, 1973) and developed in a different way by Isabelle Stengers (1987), between two conceptions of the explanation sought in science. The first, that we can call *Laplacian*, takes for its reference point and ideal, the formulation of a single set of equations describing "perfectly" the behaviour of the system in question over time (see Laplace 1795). That is, one seeks a description at the "most fundamental" level, usually supposed to be the most microscopic one, from which all macro-level phenomena are then able to be deduced. A "complicated" system may thus be deemed ultimately determined in its behaviour, where in practice (due to limitations of knowledge, lack of precision, lack of computing power) we are unable to provide a description that captures this underlying determination. The ideal of scientific explanation is to achieve -- even if only locally, partially, and imperfectly -- the same sort of determinacy that is visible to Laplace's omniscient demon.

The second, that we can designate *"complexity"* (Stengers 1987; O'Connor 1994a, 1994b), aims at the formulation of laws that express regularities characterising many distinct levels of hierarchical structures and their inter-relations. The presumption is that reality displays an irreducible complexity of structure -- a hierarchical, dynamically meta-stable, and mutable character being confronted at whatever level it is interrogated.

This view of *complexity* is the antithesis of reductionism, but it does not give rise to a simplistic holism either. Reality is amenable to scientific analysis along a variety of spatial and time-scales, according to a variety of investigative methods. In any domain, we may describe as "simple", those systems and models that, for the horizons considered, are determinate in their explanatory ambition. However, explanatory models in the simple category are not deemed to be approximations to the underlying (complex) reality, nor as partial and local analogues of some more complete description in the predictive sense envisaged by Laplace. Rather, they are a very special case, an impoverished mode of description that abstracts away from the enriching indeterminacy of our reality. This is possible and appropriate only for limiting situations, such as making a cup of tea or driving on the motorway. Something very different from *mere simplification* is involved in giving a deterministic type of description. The movement from the general (complex) to a special (simple) case amounts to a *banal* ambition (Baudrillard 1983). It means to forget about the possible social adventure initiated by the cup of tea. To say that a "simple" mode of explanation is applicable is tantamount to saying that we can, in the given situation and for the purposes of analysis, *forget about the complexity of the phenomena we are dealing with.*

The vision of modern Western science from its origins has been one of the study of the world from the point of view of simplicity. Descartes attempted to reduce physics to matter in motion, and psychology to the reactions of mechanisms and particles. The accepted model for reasoning was geometry, and later functional analysis; and the aim was to enable the control of the whole natural world by routine operations, like those of the mechanic. It may be inferred that simplicity is intimately linked to prospects of prediction.

Ever since then, developments in science have been counted as advances if they further articulated that paradigm of simplicity. A simple system may be characterised by its scientific properties (e.g., linearity of its defining equations); but it is most useful to see simplicity in pragmatic terms of possibility of effective capture by routine operations. Systems are simple if they are knowable in the sense of prediction. And thus, there are some systems whose behaviour is not "simple" in this technical sense (such as those studied by chaos theory), and yet which do not pose any real challenge to the classical programme of science. To be sure, some systems are genuinely complicated, perhaps having many variables, or non-linear operations, so that they defy the neat, formal solutions of the paradigm of mathematical physics. Yet, we may consider them as still within the class of essentially simple systems. The difference between simple and complicated systems is only one of degree; in the case of a complicated system, not enough is known for analytical representation with predictive precision, so some skill and judgement are required for its effective capture. But from God's point of view -— from which we are, sadly, infinitely far removed (according to Laplace in 1795) — the predictability would be complete.

The term "capture" is of course highly anthropomorphic; it comprehends both theory and practice, and is relative to the goals of those studying or manipulating the system. Typically, in the practice of science, a simple system is the sort provided for students' exercises; a project requiring original thinking will involve a system that is complicated at first sight (but then, perhaps, can be rendered simple!). Yet we know that no system is "purely" simple; for any real system (material or intellectual) has a history, embedded in social processes of creation and use. But pragmatically we can say that many systems, including both biophysical and socio-economic, are certainly conceived as simple in this sense; and rendering operational this norm of simplification is the goal or much applied social and economic, and ecological, science.

A feature of contemporary ecological management problems is that in scientific practice we can *almost never* forget about the complexity -- both social and biophysical -- of the phenomena being dealt with. Moreover, we would like to say, on social and ethical planes we *should not want to neglect this complexity.* For it is synonymous with the possibilities of love and passion.

So, within complexity and as an enrichment of it, we want to place also the dimension of *reflexivity,* of self-awareness of action-within-a-system (or ecosystem). We thus distinguish between systems that are simple, complex, and reflexive (see Funtowicz and Ravetz 1994, and O'Connor *et al* 1996; where the term "emergent complexity" was used for reflexivity). We will further suggest that just as Energy mainly characterises systems from the point of view of simplicity, and Entropy/Exergy from that of complexity, there is a third property, which we will call Quality, mainly characterising reflexivity. (Note nonetheless that all concepts apply in some degree to any rigorous systems analysis, at whatever level).

With Quality, we will make explicit the connection between the disciplined study of thermodynamics and its poetry (see also Funtowicz and Ravetz 1997). More particularly, our approach to reflexivity allows us to develop a philosophical foundation for a new form of scientific practice, appropriate to the needs of a world in which simplicity is a memory of a bygone age, and in which reflexivity characterises all the systems that we need to understand and manage, this new scientific practice is based on the tasks of quality assurance in the historically new contexts of applied environmental science and ecological-economics systems management.

In traditional science, if we may simplify a little, quality assurance was considered to be accomplished by largely internal means (viz., methodology: reproducibility of results, experimental tests, falsification, etc.), within a relatively homogenous peer community, with reference to established norms of theoretical coherence and reliable measure (and thus, basis for replication). But now, when dialogue is oriented on issues such as climate change, the creation and exploitation of genetically modified organisms, and the production and disposal of toxic wastes, these internal scientific norms are insufficient to establish the validity of science applications.

Environmental issues are characterised by a plurality of perspectives and often by conflicts of principle as well as of economic interests, and here the quality assurance of scientific inputs requires the self-aware (and possibly conflicted) participation of an “extended peer community”. The scientific tasks themselves can no longer effectively be conceived as simple discovery and application. Rather these are embedded in institutional, ideological, ethical and societal contexts, which condition both the various actors and also the conceptual objects of enquiry that are studied. The scientists themselves must become reflexive. For we can no longer maintain the previously taken-for-granted background assumptions of the simplicity of problems and the exclusive legitimacy of scientific rationality. Scientists, like all other participants in the dialogue, must reflect on their own condition and practices, as one among the several interests and legitimate forms of judgement and action that make up the social order. In these post-normal conditions, science operates as it were in a multi-cultural environment; its criterion for success can no longer be a an idealised simple Truth, but rather a realistic complex Quality.

4 Energy, Entropy and Exergy

As it is traditionally introduced in science teaching, the Energy concept is presented as an objective feature of the natural world, whose laws are independent of human activity. It is measured through physical variables which themselves are defined in mechanical terms ("heat", "work" and then "force"); and its fundamental property is given by the First Law, stating its conservation through all changes of form. In our terminology, this amounts to conveying this theory as if it were a simple conceptual system. Yet, this is an oversimplification. Starting with Mach (1942), historians and philosophers have shown that the concepts and their names have rich histories, in which (apparent) clarity emerged only fitfully from confused practice, incomplete theory, and poetry.

Energy's lineage is from one of the many senses of "force", in this case a "living force" or *vis viva* associated with moving bodies. As this was clarified in the early nineteenth century, the constancy of conversion-factors between different sorts of "motive force" became noticed, and then a Greek word was imported to describe that basic substance which remains unchanged in quantity through all its changes in form.

The conservation of energy was first seen as an equivalence among conversions, such as work coming out of heat in a steam engine, or coming out of the "potential energy" of gravity in a water wheel. But also, while some conversions seemed capable of conversion either way (as between mechanical and electrical energy), the conversion from heat to work seemed irreversible. Although the energy remains unchanged in quantity, it is somehow degraded in quality. In the steam engine, which was the first technological model for the science of thermodynamics, this degradation shows up in the fact that the exhaust heat is at a lower temperature. Yet the complexity of the phenomenon is perhaps more easily visualised through the rustic example of the water-wheel. Think of the falling water caught by a large wheel, which turns on its axle, drives a shaft, and thereby runs a mill; there the energy coming from the waterfall is eventually dissipated as heat, noise, water turbulence, and wear-and-tear on materials. Although the energy is conserved, and necessarily still exists, it can no longer be applied to useful work. It is "different"; and this difference in the energy requires another concept for its characterisation.

The difference was first described in terms of "Entropy" (literally, directionlessness), and mathematical arguments showed how, under certain conditions, a reaction converting heat to work would always increase this rather strange quantity. The scientist who first gave a clear formulation to this Second Law promptly proceeded to do poetry with it. Clausius generalised from the properties of idealised heat engines to those of the entire universe. To a popular audience he told a story of a "heat death" occurring some time in the unimaginably distant future, when the entropy will have risen to its maximum possible. Less poetically, J.W. Gibbs produced a comprehensive theory of the modes of conversion of energy. He distinguished between Entropy and another function, "free" or available energy, later called Exergy. The two are related in a simple inverse fashion in the simple reactions described above; but in other respects, particularly in modern thermodynamics, they are quite distinct. Several names appear in the literature to designate concepts that are virtually identical to Gibbs' Free Energy (see Faucheux & O'Connor 1998, chapter 6, for a review). *Availability* and *available energy* designate the potential energy capable of doing mechanical work. *Potential energy* designates the amount of stored energy that may undergo "depletion" during the work process. *Exergy* is a name that designates the ability of energy sources or combinations to do mechanical work. So, while details vary with the exact conditions of measurement, they all correspond with exergy as a metric which evaluates energy forms according to their capacity to do mechanical work under designated environmental conditions. Exergy thus derives from differentiation within a configuration of materials (i.e., system and environment) able to be exploited to do mechanical work. These may be differences at sub-atomic level (fission and fusion potentials), at inter-atomic and molecular levels chemical potentials), temperature differences (thermal potentials), spatial separation of masses (gravitational potentials), and so on. As Grübbstrom (1985) put it, “The cause of the opportunity to extract work lies in the initial differences between characteristics of the objects rather than the initial characteristics as such.” On a planet covered by kerosene seas, oxygen in rock cavities would be regarded as the energy source.

These “exploitable differences”, whatever their forms, define the space for the emergence of life. Fire earth water air. Water, energised by the sun, falling as rain and flowing with gravity's ups and downs, is the fundamental resource of organic life. Ecological economic activity, as all life, unfolds as so many small eddies, flows and recyclings in the planet's water cycles, an open history within the bounds of exergetic potentials. There are no general thermodynamic laws that enable us to predict this history. Rather, as Georgescu-Roegen proposed, human ecological economy appears as a “free” activity within the overall bounds of entropic irreversibility. Further, any particular life activity involves an interweaving of many different thermodynamic potentials, being exploited and rearranged according to diverse time-scales and spatial scales.

There are also aspects of purpose and meaning. What happened to the potential energy of the water as it went over the original waterfall, before the waterwheel was built there? We see that it is correct to say that while scientifically all Energy conversions are equal, anthropocentrically some are more equal — that is, useful — than others. The water wheel establishes a structuring in the body of water's flows. As the water is caught in the wheel's shaped blades, it collects in parcels and by the force of gravity produces a steady rotational force which is transmitted to the shaft. Gently lowered by the wheel, the water has little kinetic energy as it is released, and it splashes softly in the pool below. By contrast, in the unimproved waterfall the water tumbles down, more or less broken up by the lip of the retaining wall, perhaps being further disturbed by air resistance and wind, and it finally crashes into the pool at the base, forming chaotic eddies before being carried off downstream.

In systems analysis perspectives, considerations of structure help us to locate the multiple dimensions of Exergy in the analysis. We may broaden our scope somewhat, and consider the waterwheel itself as part of the energy-flow pattern. Clearly, someone used energy (or rather, exergy) in creating a structure that had not been there before. The structure was then used in the modification of the process of the descent of the water, so that the maximum of useful energy was extracted during it. In the unimproved waterfall, the water arrives at the bottom with a big dose of kinetic energy, ready to splash and eddy; but in the domesticated situation the water leaves the waterwheel with scarcely any "free" (available) energy. The waterwheel extracts and passes on the maximum of exergy from the falling water, only by having, itself, absorbed some exergy in its construction and maintenance. Thus we are reminded that energy is not about simple degradation, but involves purposes, structures and renewal as well. This aspect of exergy as the renewal of activity enables us to suggest a poetry for thermodynamics, for the eddies and flows of life, completing the characterisations already in terms of energy and entropy.

5 Economic systems considered from the point of view of simplicity

The 19th century concept of energy as conserved and dissipated did not simply fall from the sky like Newton's apple. Rather, to speak of energy was to evoke the immense powers of nature potentially at work for progress in industrial production. The emphasis was on nature as source (for useful energy) and as sink (for the dissipated energy). Man lived, and progressed, by tapping into -- and indeed hastening, augmenting, hurrying on -- this one-way flow of entropic degradation. But just so, the glowing representation of nature's forces also had its dark side, in this phenomenon of energy dissipation. Not only is the yield of useful work from any energy source absolutely constrained, but all productive processes result in a using up of energy available to do work, meaning there is a net loss of available energy for future use. This result, the irreversibility of entropy production, gave rise to the spectre of "heat death." If classical thermodynamics imaged nature and society on the model of the steam engine, then nature was "a reservoir of energy that is always threatened with exhaustion" (Prigogine & Stengers 1984, p.111); this also was a metaphor for Georgescu-Roegen's melancholy.

Yet, the material "limits to growth" are only one half of industrial society's ecological contradiction, and arguably the less troublesome half. The other half relates to the side-effects and by-products of modern life. Thermodynamics, the science of conservation and transformation of energy, establishes the *necessity of inter-actions between systems and their environments as the precondition of continuing transformation activity.* And, under conditions far-from-thermodynamic-equilibrium, these interactions are not merely fuels and dissipations, they mean the emergence of structures, collisions and restructuring: an historically open co-evolution (Norgaard 1984; Gowdy 1994; Morin 1977, 1980; O'Connor 1991). We move, then, from steam-engine thermodynamics to an open systems thermodynamics as the science of reciprocal system-environment transformations. We *live with/in nature*, a relation of intimacy and mutual (in)compatibility. Water in its many dispositions and transformations is a paradigm of this intimacy and coevolution.

How could all this be considered “simple”? More precisely, how can science and economics take a “simple” view of these things? Consider the following ideological process of “simplification” applied to thermodynamic open systems. In particular cases, a system may be said to be thermodynamically dominant in relation to its environment, or vice versa, in one of two senses (O'Connor 1990, 1994b).

(a) *strong thermodynamic dominance*, where there is maintenance of complete control over the organisation and dynamic behaviour of its co-system. This is not the norm in the world. It is, however, the norm in casual "scientific" discourse. Much popular wisdom about scientific method relies on conceptualising systems in this way, e.g., experimentation based on a "control" or "reference" system relative to which the impacts of selected changes in "inputs" are tested. Also, this is the conceptualisation which underlies the economist's traditional conception of a production process.

(b) *weak thermodynamic dominance*, the case where the productive activity of the co-system is not completely controlled by the system, but where system-environment interactions are regulated so that the latter has insignificant perturbing effects on the structural organisation and evolution of the system. One can imagine a system which successfully "exploits" its environment without changes in environmental organisation having any significant "feedback" effects on system activity.

Now consider the example of an industrial production system, represented using a multi-sectoral model and a vector of final consumption, said to be “growing at 5% per annum” and fuelled by the controlled exploitation of minerals, oil, natural gas, timber from tropical forests and so on. This is a *simple* model in our epistemological sense. Similarly, if demographic growth is zero, we may infer that the economy is characterised by 5% growth in GNP/capita per annum, which is a *simple* indicator of economic progress. This might be contrasted with more “complicated” notions about development as involving qualitative changes in habits, social values, patterns of human interactions and improvement in the “quality of life” and so on.

The measurement of economic progress at “macro-economic” scale by single-dimension indicators such as GNP/capita, and the representation of production processes at micro-economic level by equations representing maximum output as a function of input quantities (the economists’ production function), are sometimes regarded as the paragons of “scientific” economics. Yet, they can alternatively be construed as examples of “special” situations where, through the conventional way of looking at things, complexity (and reflexivity) can be put aside. Applying our (unconventional) perspective of complexity, and making allusion to the wide category of environmental problems (accidents, by-products, side-effects, and so on), we can readily see how, in effect, a whole raft of controllability assumptions underpin the corpus of the “simple” modern theory of economic production and growth.

(1) *Controllability of a production process.* Usually a production technique, or a spectrum of feasible techniques, is represented through relating specified ratios of inputs of economic resources (i.e., inputs of materials and energetic services directly controlled by economic agents) to specified levels of outputs of economic resources. Full control is presumed over the combination and reaction of the inputs. This amounts, in effect, to the assumption of strong thermodynamic dominance by production managers over each process of commodity production. The inputs are transformed according to determinate rules or know-how, so that the process can be conceived as leading to determinate output results. Perfect functionality is the norm. Unpredictability is attributed to error or accident.

(2) *Dominance over the environment.* Further, it is presumed that complete control can be and is maintained in relation to all non-economic (environment) processes, insofar as these latter are interactive with economic processes. The environment provides stable conditions as a site for economic activity; and at or around a given site, natural resources can be freely appropriated up to the limits of their availability. Nature has been "domesticated," as it were. Economists call this the "free gift" assumption applied to the environment. Similarly, economists have traditionally assumed "free disposal," i.e., that wastes and excess outputs from economic production processes can be assimilated by the environment as a "sink" without affecting the economic production processes themselves. This amounts, in effect, to an assumption of weak thermodynamic dominance of an economic system over its natural environment (i.e., no significant uncontrolled feedback implications from environment to economy). It is what C. Perrings (1987, p.4) calls, in axiomatic language, the "weak environmental assumption" in

economics, namely: "that an environment exists; that it is not completely dominated by the economy, but that it plays only a benign and passive role."

(3) *Independence of production processes.* It is further assumed that, as a general rule, the technique of each individual process can be expressed without explicit reference to levels of activity of other economic processes within the system. However, by definition the complement of processes to any chosen production processes within an economic system, comprises the latter's physical environment. So repression of reference to process-environment interdependencies requires the premise that environmental effects on production process activity are known and/or constant for any particular context. Given the dialectical symmetry of the situation, this means assuming reciprocal weak thermodynamic dominance of each process over all others: that they do not perturb each other, or even that they are independent of each other.

The picture we get of production is that the production managers and economic policymakers can regulate the system's inputs, parameters and environmental conditions with a view to obtaining a pre-determined output from a "black box" process. Paradigms would be the steam engine and the factory assembly line. In earlier work (O'Connor 1989, 1994b), this ensemble of presumed control properties has been called the *"industrial production épistémé" (IPE).* The term *épistémé* (used in the sense of Michel Foucault) connotes a particular manner of knowing reality. The control assumptions amounts to a particular mode of conceptualising production activities. The adjective "industrial" signals that this manner of representation of production emerged into prominence in the context of the development during the past two centuries. It is characteristic of Western "industrialised" societies; other societies have understood production and technology, or the action of transformation of material reality, in quite different ways.

6 The Qualitative (and Quantitative) Thermodynamics of Life

Is it possible to envisage, rather, a "complex" ecological economics — one that would place on centre stage the exploration of action and coevolution in what Georgescu-Roegen labelled the domain of entropic (and exergetic) indeterminacy? We think so; and open systems thermodynamics can yield us some clues.

Among the creators of the science of thermodynamics were men who had strong commitments both to the improvement of industrial practice and to the cultivation of the philosophy of nature. By some of them (though not all), thermodynamics was interpreted as an expression of a materialistic philosophy, which was intended to show the way that the world is and has to be. With its foundation in theory and experiment, it was convincing. But still, there was an apparent exception to the universal law of degradation of energy and structure in all transformations: life. It could be explained away, as a temporary and local aberration; yet given our own unavoidably anthropocentric perspective, it could hardly be called insignificant!

It took about a century before thermodynamics began to catch up with life; and that happened only when an implicit restriction on previous thermodynamic theories was relaxed. This was the assumption that the processes studied were all at or near "equilibrium" -- or, more particularly, that processes should and could only be studied *from the point of view of* states of thermodynamic equilibrium. As Prigogine & Stengers (1977) put it, the study of irreversible processes from the point of view of their disappearance! (Like the study of life from the point of view of dissected dead frogs.)

Without this methodological convention, the mathematical tools then available could simply not have been applied; but with the assumption of equilibrium or the adoption of equilibrium as the exclusive reference point, the science of thermodynamics was restricted in its scope, to the description of only those systems where the forces driving a reaction are very nearly balanced by those resisting it. In recent decades scientists have been developing new methods for characterising and for studying reactions far from equilibrium. For these, we might imagine the waterwheel example, but in accelerated time-frames, so that the waterwheel needs nearly constant maintenance. Then we have a system in which energy is attenuated (from that of gravity to rotational motion, wear-and-tear, and waste heat), producing the maximum of exergy *en route*, but requiring a parallel set of energy-exchanges. If the repair work is not done properly, the wheel will (for example) start to leak, and more water escapes and less exergy is extracted. If for some reason maintenance is not kept up, then eventually the wheel will stop.

The waterwheel example does not incorporate heat and chemical energy-exchanges. But biochemical far-from-equilibrium systems are similar, in that everything happens as if they are extracting as much useful work as they can from the (available) energy, by increasing its flow along gradients, or pathways of decreasing intensity, so that what is emitted at the end is of as low an intensity as possible. A dramatic experimental example of this is in the Bénard cell, in which a mass of water, as it absorbs heat will (under certain conditions) organise itself into separate columns where hot water rises and cooler water falls, smoothly and efficiently. Equally dramatic is the ecological example of a forest, whose emitted heat is at a much lower temperature than that of grassland or of land without vegetation (Schneider & Kay 1994).

In the case of "life" as we know it on Earth, the main source of intense high-quality energy is the sun (there are a few other sources such as geothermal heat and chemical potentials in specialised organism cases). Speaking generally, the energy no longer usable in the metabolic cycle is emitted as low-grade heat, just as in the original steam engine. Living systems employ a variety of materials and structures which enable their chemical reactions to proceed and reproduce. Complexity is created in photosynthetic processes by a harnessing of the intense input energy, and is then destroyed to provide feedstocks for the various cyclic reactions. The sun is an "absolute" with respect to the earth-system, as we do not affect its source (although we can very much affect the energy transmitted from it to ourselves); and also because its time-scales of change are much greater than those of human history and biological evolution. But in between the “absolute” source and the “absolute” sink (deep outer space) there is much dance and play.

In our waterwheel example, we have already observed that there is a human intervention. Let us situate this intervention in a social-ecological perspective. A watershed defines a “natural” unit, or sub-unit, for ecosystem analysis. There is water inflow from precipitation, and then the flow patterns are determined by landforms, rock porosity and fractures, human interventions (dams, pumps and pipes, canals, etc.), and woven into the habitats of hillside, swamp, riverbank and aquatic species. The water may be considered as a valuable input for industrial, agricultural and urban consumption. Who “owns” the water? If water flow is diverted for irrigation, for factory use, for power plant cooling or for urban drinking supply purposes (for example), or if the continuity of flow is interrupted through dams, reservoirs and other forms of storage, the pre-existing “natural” forms of life may be put at risk. Dike and dam systems can stabilise minor floods, yet may not be able to master the “100 year” ones (which can thus be all-the-more devastating, because maybe people have built on the flood-plains downstream from the dams). Barrages may permit the harnessing of the water’s gravitational potential energy through a waterwheel or, later, a turbine generator producing electricity. But, if the dam is too high, river species such as salmon cannot swim upstream beyond the dam; and so the upper river ecosystems are species-impoverished which may have repercussions for recreational and aesthetic attraction. (As an example, a recent study has been carried out by colleagues, on the possible futures of the Loire water system in France, see Noël & Tsang 1997).

So, a great variety of possibilities exist for the exploitation of “water potential”, along the paths by which water falls from “high” to “low” quality. And there is also another sort of problem of water quality. Water can become “dirty” or contaminated along its way. Water that has become “used” for economic purposes such as a leather tanning or dairy factory, or that has passed through a fertilised field or a rubbish disposal site, may flow onwards into other “natural” systems -- but now in a polluted condition. This can menace the viability of non-human life forms, can impose opportunity costs for other potential economic uses, and can pose direct problems for human health, and so on. The water is “degraded” in its quality.

Life turns out to have its own thermodynamic structure; but the characterisation we are developing iis very much richer than, and different from the temporary and controlled phenomenon imagined by the science that took its inspiration from the steam-engine. The popular term "edge of chaos" well expresses the contradictions involved in sustaining the special conditions enabling life’s existence. The sun is a necessary condition for life, but not at all sufficient: a complex structuring of the loops and cascades down and around thermodynamic potentials is also required. Further, the sun’s rays can destroy as well as nourish; and the sorts of transformations that support life can equally bring death. Seen from another angle, water is a necessity on earth for all life, yet its quality is easily (and, we might add, necessarily) degraded, before it can (perchance) be renewed.

What is the right course of action in the “management” of the renewals, transformations and degradations of water fire earth and air in their interdependent qualities? Here reflexivity is essential, along with complexity of the resource systems. Of all the life potentials that might be realisable, which ones will come really to be? Who decides? Someone must; or rather some concatenation of influences must: for there is no solution that is uniquely “natural” or “right” or “rational” or “best”. There is no algorithm for social-ecological choice that will command universal assent.

With the maturing of the exergy concept in the analysis of complex systems, energy flows can no longer — no more than water flows — be depicted as occurring along simple downhill paths. Down and up are intertwined. Since our concern is with sustainability, we will suggest that Quality, in some sense to be explord, is created, or maintained, in our anthropomorphic sense, when water management decisions work for the permanent renewal of these cycles of water transformation that support life. In this definition, complexity of structures is entwined with ambiguous (or multiple) significations of the resource management process. In what sense can we say how Quality in decisions is to be found? Perhaps it can through water uses that maintain the memory of waters' origins while the also realise new forms of life (links to cultural heritage, sense of place, local identity, historical consciousness, and so on?). Perhaps it can be through finding management procedures that reconcile objectives of assuring long-term future water quality with water use demands of the present day? Perhaps through affirming the joys of one life form to be sustained while acknowledging with grief other possibilities left aside? (This is not a traditional cost-benefit analysis.) these are dimensiopns of human meaning and significance to be explored.

Thinking of life and economic activity as a process of emergence, decay and renewal through time of both material forms and meanings, the decisions for management of flowing water systems can be understood as a problem of the distribution of sustainability (O'Connor 1997a, 1997b). For example, the regulation of access to water and the control of water quality can be posed in terms of distinct (yet often interdependent) “needs for sustainability” and of the vulnerabilities of the different habitats and forms of life to changes — controlled or uncontrolled — in the terms of access and quality. How may the various candidates for sustainability — for example terrestrial and aquatic ecosystems in “natural” or human-modified form, agricultural systems, rural and urban communities in their physical settings — be assessed in relation to each other? In a typical watershed management situation the maintenance of (say) bird populations and riverbank rural economies through flood management assuring year-round flows, would serve *different communities of interest* from (say) damming and piping the water for urban supply. These are not easy things to compare.

In complex self-transforming systems, the “simple” flow and stock measurements that traditional science comprehends must be interpreted with reference to “functions” and purposes and, more particularly, the concatenation of purposes, timescales and spatial scales of organisation and change. The use of energy and ecosystem models for policy cannot be one of simple determination of quantities and directions of flow. The technical reasons for this can be seen in the difficulties of measurement of flows in particular cases, and also as the impossibility of imputing a partition of energy flows where streams diverge. As a matter of practical experience, quantifying the exergy and water transformations, flows and degradation, through all branching and interweaving of ecological-economic activity, cannot always be done to any useful degree of accuracy. What appears to be at first (as in the case of the waterfall) an uncomplicated branching of energy (falling water, plus axle, that in turn becoming energy in machines, and then friction and heat), turns out to resist complete quantification. When the energy coming into a complex system is immediately taken up in living biological processes and the produced artifacts of living communities, close quantification of all transformations becomes strictly impossible. Although useful aggregate estimates can be and are routinely made, every particular action of transformation of energy in the natural world is complex in our sense, and profoundly ambiguous in its contribution to (or against) a sustainable coevolution.

This new vision of complexity in degradation and renewal is the basis for understanding life as quite other than a scientifically inconvenient exception to the majestic Second Law. We see the emergence, loss and renewals of Quality as a major dimension in the work of shaping the planet. We find webs of energy transformation, the ebbs and flows of water transformation, along with those of material transformation, with multiple paths in and out of any nexus, with intensification as well as remission, and finally with a causality that is very far from linear. Even to speak of cycles (physiological and environmental) is often an over-simplification. If we want to escape from the metaphorical confines of the Industrial Revolution, and have an evocative image of Energy for the age of reflexivity, we might think of wave in the ocean surf, where form is created and dissipated simultaneously, in a process where determinism and chaos together play.

Thus energy in the environment becomes like any other environmental variable, subject to deep uncertainty and unpredictability. Quality renewal is synonymous with indeterminacy. The study of ecological-economic systems in their Free-energy (Exergy) and Qualitative dimensions involves addressing systemic events which can to some extent be explained only in retrospect (as is the case with many disasters). In studies of this sort, where linear causal thinking cannot master the problems, we see the outlines of one more dimension of what would be a science of reflexive systems. In such a reflexive scientific practice, for example Post-Normal Science, complexity is respected through its recognition of a multiplicity of legitimate perspectives on any issue; and reflexivity is realised through the extension of accepted "facts" beyond the supposedly objective productions of traditional research. Also, the social participants in the process are not treated as passive learners at the feet of the experts, being coercively convinced through scientific demonstration. Rather, they will form an "extended peer community", sharing the work of quality assurance of the scientific inputs to the process, and arriving at a resolution of issues through debate and dialogue.

With an historical perspective on the whole process, we can say that traditional science focused on the problems it could solve. But with the issues of risks and the environment, we now have scientific problems thrust upon us whose very statement involves reflexivity as well as the full complexity of biological and ecological systems. These are problems that we do not know how to describe yet very well (for example risks with cloning and genetic engineering), let alone resolve. For these, we need a new conception of science, comprehending reflexivity. For the establishment of the genuineness of scientific knowledge, traditional unreflective methods and approaches to science, based on the assumption of simplicity and equating knowledge to predictability, are inadequate. Traditional philosophies of science are somewhat irrelevant. We will suggest that Post-Normal Science (Funtowicz and Ravetz 1993, 1994a, 1994b), with its emphases on uncertainties, value-commitments, plurality of perspectives, dialogue, and quality, provides a way forward.

In Post Normal Science, a shared and incessant problématique of Quality replaces Truth as its organising principle. The task is no longer one of accredited experts discovering "true facts" for the determination of "good policies". Rather it involves an extended community, which evaluates and manages the quality of scientific inputs and scientific results; these are provided for complex decision making processes whose goals are negotiated from conflicting perspectives and values. What we want to show now is how this notion of Quality in science is an aspect of a wider problematic of Quality as the reflexive dimension of complex evolving systems.

7 A Passion Play : Quality, Poignancy and Grief

The enrichment of the thermodynamic concepts to include Exergy enables us to comprehend processes of renewal, such as life. For reflexive systems, with their mixtures of meaningfulness and absurdity, of radical creativity and innovation together with radical instability and decay, a further dimension in the characterisation is desirable. For this purpose we have evoked a notion of Quality — related to meaning(s) associated with histories and actions and processes — as a completion of the other three principles, as always applying at other dimensions of the observed phase space, but uniquely characterising reflexive systems.

Let us try to frame some of the dilemmae and challenges of sustainability in terms of Exergy and Quality. The history of industrialisation can be read in the terms of technological progress, mastery of nature and the successful harnessing of water and free energy for productive gain. And it can be read as a history of dissipation and degradation, of people as well as energy. Energy and Entropy. The two readings can simultaneously be true. Which one seems the more compelling depends a lot on a person's point of view. Industrialism has, officially, been premised on a simple model of production, in which nature is measured up as a useful resource, according to an instrumental logic where human labour and technology are applied to achieve the desired end. The captains of industry in the 18th and 19th centuries (and, in some parts of the especially Third World, still in the 20th and 21st century) built capitalism on the strength of slave labour and the steam engine. This is the way it looks from the outside, the manager's overview of the thermodynamic black box. Looking from the inside, within this industrialist regime, we, the participants of this society, are like the water in the generator turbines, the molecules within the engine's combustion chamber, rammed by the pistons, liquidated and gasified, spat out the exhaust tubes.

The instrumental view of nature and of human relations — the metaphysic that everywhere permeates capitalism and the idealism of "liberal" society — chooses not to heed the many voices of poetry and passion that we find in nature and ourselves. Instrumental reason has preferred to gauge people and things for their utility in self-interested pleasure and accumulation goals. It took a simplified idea of freedom and free energy, one that amounts to denial of most of what we know of reality — the touches, ecstasies and agonies, and dramas that life unfolds. The loves, the hates, dislocations and impossibilities of being in this world. What it is like, not just to use and take and dissipate, but also to be used, eaten, consumed, corrupted, transformed, loved, caressed, bulldozed, erased, taken away. To live love from the inside: earthy rich desirous hot, fierce loamy dark, adrift and whole. To be the coal, the glow-worms, the roots and stones, pebbles, welding arcs and butterflies in the matrix of material life.

When we (re)place ourselves (ideologically speaking) inside the disequilibrium process, we are led to reframe our views of how Energy works in sustaining (and transforming) the system of life on earth. Some aspects are simple: Coming from its absolute source outside, Energy proceeds through its successive transformations as it drives cycles of material change, producing work of various sorts and in the process sacrificing its intensity, and thus (if you wish) its own invariant Quality. As it goes from being intense solar radiation, passing through various chemical forms, and eventually becoming background heat, it retains its Quantity (First Law) but is degraded in thermodynamic Quality through the increase of Entropy (Second Law).

Then, as evoked in the new thermodynamics, the phenomenon of renewal of structure is accounted for in terms of the workings of Exergy, moving energy along gradients of generally decreasing intensity but involving all sorts of loops and detours. This renewal-dissipation-reorganisation-degradation (Morin 1997, 1980), where there is ambiguity — a sort of metaphysical hesitation — between "order(ly)" and disorder(ly), is our entrée into complexity. Indeed, the ambiguity of the unfinished symphony, of polyphony, of tensions, clashes of different possibilities, resolution and onwards flows, which we can see in the phenomenology of evolving "dissipative systems" (Prigogine and Stengers 1977), is also the experience of everyday life. Quality renewal is synonymous with indeterminacy. Here, the phenomenology of Exergetic transformations — the cascadings and loops of exergy Quality — provides an analogy for what we might call anthropomorphic or existential Quality . Here also, in the historical movement of meanings, forgettings, institutions, social conventions and cultural forms, we can imagine a sort of flowing onwards from a Source, where the but dialectically interacting with its own sort of Entropy and being renewed by infusions of its own sort of Exergy. Persistence of Quality, whether in its exergetic or existential dimensions, in a pure or fixed form is impossible; indeed original Quality is so ephemeral, that the tension between its emergence and its diffusion produces one of the great contradictions of civilised life. But on the analogy of Exergy, existential Quality can also be maintained and renewed, meanings created and re-created, as meanings and purposes always "on the edge of chaos" find their way through space and time. This weavings of meanings with materiality is our characterisation of reflexive systems.

Energy transformations in society are governed not just by thermodynamic laws but by social purposes, production objectives and rules of access, use and exchange. So also, Quality as a social category, evokes and requires its own governing. We have said that Quality has got something to do with our understanding of the possibilities and significance of action when the choice is not a simple one. As such, Quality as a shared and incessant problématique, is a social category that links up with older notions such as Justice and the problem of Right Action. The old Latin motto, *Quis custodiet custodes ipsos?* (Who guards the guardians?) is a reminder that control cannot be complete at any given hierarchical level, but iterates upwards without a definite end. Inevitably there will be debate over the criteria and procedures to be adopted for Quality assurance; this is an abstract characterisation of political conflict, social tensions, human misunderstandings, cultural differences and so on. We can also think of more specific instances. After immersion in the raw practice of quality assurance in some particular technological or scientific field, one becomes aware of the difficult of establishing universally agreed or applicable criteria, and one might be tempted to view the whole process as an exercise of subjectivity (viz., discourses of cultural relativism, cultural no-bridge, solipsism and so on). But this would be to over-simplify the Quality problem. Simply expostulating "subjectivity" is to ignore the discernible constraints of the external world, however unnameable, and the discernible influences of history and of public morality, in the weaving of the tapestries of individual and social meaning. (For an account of some threads in these tapestries, see for example Glacken 1967).

Today, just as we observe that energy flows cannot (no more than water flows in living ecosystems) be depicted as occurring along simple downhill paths, neither can social change be depicted as occurring along a simple dimension of Progress (movement onwards and up) or even of conservation (maintenance of a status quo). We life life on a raft that endures in turbulent seas. The Quality is found in the art of navigation, the joys of life on board, the memories past, the learning and the passage through adventure and calm. Consider in this light the norm of "sustainability" as a problem of Quality. Sustainability of what, why and for whom? Over the past few centuries in Europe, and at an accelerating pace in recent decades, we have been avowing the moral significance, as an anthropocentric attribute, a Quality, to ever-larger domains of Nature. This is part of a "crisis" of modern society — the problem of "Man's relation to Nature" (see Nasr 1968; White 1967; Salleh 1997, among many others). In many non-industrial societies the flow of significance was from god(s) to humans, or from Nature to humanity (this has been called paganism and "animism"). In Western humanist society, it is Man (sic) who ascribes significance to nature. And, in modern times, this signifiying project becomes noticeably more complex. Starting with the liberation of "human nature" in the forms of slaves, the privileged classes of men exercising public authority began to acknowledge a moral status and dignity for other classes of human nature such as women, children, persons of colour and aliens. The repercussions for politics and even for the traditional demarcations in the halls of knowledge have been quite far-reaching. And by now the Western dominant ideology of "rights" and "legitimate voices" has been further broadened to embrace not only pets and higher mammals, but trees and generations of all species as yet unborn, culminating in Gaia herself.

Such an indefinitely expanded moral solidarity, extending an anthropocentric Quality to the cosmos, has some serious contradictions. In this modern "rights" based society, pain and death are not seen as phases in the loss and renewal of Quality. A strong reaction is to push out these parts of life, as needing to be reduced as much as possible, always and everywhere. We may consider the economists' predilection for the Pareto-improvement criterion of "no loss". A policy will be judged as good and non-controversial if some parties gain and there is "no loss" for anyone — or, more controversially, if through well-chosen compensation measures there is the "potential" for a no-loss situation to be attained. Yet this "Pareto rule" is useless in all of the important ecological-economics decision-making situations, where sacrifices by some parties are inevitable, for example foregoing present day convenience in the use of toxic materials, in recognition of future generations' interests.

The call for "conservation" is an understandable reaction to the scale of wanton destruction of human and non-human cultures alike over the past two centurues. Yet, the commitment to a universal spreading of anthropocentric Quality, if expressed as a vague generalised sustainability concern, encounters the contradiction of indeterminable boundaries:. Can we sustain all life values? Cetaceans are nice, but virus and mosquitos and bacteria too? The impossibility of resolving this particular contradiction can lead to sentimental ecological activism (Doris Lessing 1984). Pain and death are the inseparable concomitants of enjoyment and life. Living "on the edge of chaos" requires being able to make sense of loss — to be able to accept loss and death, with compassion, courage, respect and grief, as part of their total interaction with their related "other" species.

Thus, we suggest that attempts to conserve a simple Quality for individuals, unchanged and free of contradiction (such as the economist's notion of a person's utility), manifests within our affluent societies as an inability to cope with pain and death. It can lead to grotesque results. Safety, comfort, convenience, and above all entertainment have become the overriding goals of consumer technological design. In the technologies of the person, this tendency has the consequence of the commodification of beauty, youth and life itself (either the delaying of death or the technological production of offspring). Runaway technologies, driven by marketed sentimentality, are now producing true "cyborgs" in which wholly new sorts of being are created. A parallel development is in the high-technologies of spectacle, in which ever more vivid and enthralling experiences provide the illusion of escape from the limitations of body and humanity as well. (Ravetz & Sardar 1996).

Technological advances permit the construction or more and more vivid virtual realities, and also sharpen our capabilities for calculated and uncalculated interventions in real human and non-human systems. In both "virtual" and "real" respects, the technological innovation thus also heightens the stakes of the uncontrolled and incalculable dimensions of social-ecological system change. Both objectively and subjectively we find ourselves very far from any sort of equilibrium. As Susan Griffin (1978, p.134) remarks, our prowess establishes a new pathos.

> *"He has gone to the very root, he says, of existence. He has deciphered the secrets. .... At his hands, the molecules change, and changed and changing they enter his skin, hide in what he eats, secrete themselves in his tissue, alter the molecular structure of his body. He goes*

inside the heart of life, he says. He takes apart the form of matter itself, he strips energy from mass, he splits what is whole, he takes this force for his own, he says. But what he has split does not stop coming apart. Fractures live in the air, invisible fractures come into his body, split his chromosomes, unravel the secrets of life in him."

Our knowing about this disequilibrium (which is hardly ever a steady-state) is a problem of complexity, grounded in our materiality. That is to say, our knowing is obtained in the fracturing of that materiality, ambiguous knowledge of what we can do and how we can provoke our own undoing. Pamela Zoline (1978, pp. 99-120), in a short story titled "The Heat Death of the Universe," evokes in a pathetic irony the interveaving between dissipation of Exergetic Quality and disintegration of existential Quality. She chronicles a day in the demise of a suburban U.S. housewife, capturing bleakly the sense of what it can be like to live inside a suburban sub-eddy of over-ratiocinated thermodynamic degradation. Her protagonist Sarah Boyle is described as "a vivacious and intelligent young wife and mother, educated at a fine Eastern college, proud of her growing family which keeps her busy and happy round the house." At the routine of morning breakfast:

"*With some reluctance Sarah Boyle dishes out Sugar Frosted Flakes to her children, already hearing the decay set in upon the little milk-white teeth, the bony whine of the dentist's drill. ... One bowl per child. ...*

The box blasts promises: Energy, Nature's Own Goodness, an endless pubescence. On its back is a mask of William Shakespeare to be cut out, folded, worn by thousands of tiny Shakespeares in Kansas City, Detroit, Tucson, San Diego, Tampa. ... Two or more of the children lay claim to the mask, but Sarah puts off that Solomon's decision until such time as the box is empty.

A notice in orange flourishes states that a Surprise Gift is to be found somewhere in the package, nestled amongst the golden flakes. So far it has not been unearthed, and the children request more cereal than they wish to eat, great yellow heaps of it, to hurry the discovery. Even so, at the end of the meal, some layers of flakes remain in the box, and the Gift must still be among them.

There is even a Special Offer of a secret membership code and magic ring; these to be obtained by sending in the box top with 50c.

Three offers on one cereal box. To Sarah Boyle this seems to be oversell. Perhaps something is terribly wrong with the cereal and it must be sold quickly, got off the shelves before the news breaks. Perhaps it causes a special cruel cancer in little children. As Sarah Boyle collects the bowls printed with bunnies and baseball statistics, still slopping half full of milk and wilted flakes, she imagines in her mind's eye the headlines, 'Nation's Small Fry Stricken, Fate's Finger Sugar-Coated, Lethal Sweetness Socks Tots'."

Something is out of balance. There is no sense of enduring Quality here, no sense of participating in life's renewal. What is made plain by the story, along the way, is that the "average housewife" understands perfectly well the social and economic meanings of degradation, increasing disorder and entropic irreversibility (ibid., p.104):

"Sarah Boyle writes notes to herself all over the house; a mazed wild script larded with arrows, diagrams, pictures; graffiti on every available surface in a desperate/heroic attempt to index, record, bluff, invoke, order and placate. On the fluted and flowered white plastic lid of the diaper bin she has written in Blushing Pink Nitetime lipstick a phrase to ward off fumy ammoniac despair. 'The nitrogen cycle is the vital round of organic and inorganic exchange on earth. The sweet breath of the Universe.' On the wall by the washing machine are Yin and Yang signs, mandalas, and the words, 'Many young wives feel trapped. It is a contemporary sociological phenomenon which may be explained in part by a gap between changing living patterns and the accommodation of social services to these patterns.' Over the stove she has written 'Help, Help, Help, Help, Help'."

These moments of annihilation and decomposition, material and subjective at the same time, are among the effects of simple-minded instrumental reason that ordinary men and women face during every day. But the moments of raw anguish and disarray that are part of a life of caring and grief, are also possible moments of Quality and profound insight. As Ariel Salleh (1994, 1997) has argued, the positive side of such experiences may be an intimate recognition of our human identity with nature, of our living within nature -- and from that, the possibility of an ethic grounded in the experience of this reciprocity. Out of the often anguished sentiments of exploitation and injustice, of the loss and dissipation of Quality in these throes of modern life, there can emerge within the interstices of the (post-)industrial machine's unreason a knowledge basis and motive for social transformation. The new experiments of “life on the far side”, the tribal improvisations of urban and rural marginal populations in their “informal” social networks, are perhaps, at least in some cases, among the attempts to create new existential and material Quality (however transient it may be) out of the decompositions of the old (Roszak 1975).

Sarah Boyle's everyday experience hints at quite different dimensions of economic life from those represented in the economist’s production function or the technician’s model of a steam engine. We are destined, each of us, to the confusion of service to others. As Hegel wrote in 1807, with a certain ecological foreboding, if we want to analyse everything in terms of a metaphysics of utility, then the place to start is with the admission that "usefulness" is an implacably reciprocal relationship. Materially speaking, everything depends on everything else; and so (says Hegel 1807/1977, pp.342-343):

> *"Just as everything is useful to man, so man is useful too, and his vocation is to make himself a member of the group, of use for the common good and serviceable to all. The extent to which he looks after his own interests must also be matched by the extent to which he serves others, and so far as he serves others, so far is he taking care of himself: one hand washes the other."*

What new forms and meanings, what new Quality can we bring to the fact of life of each being in the service of each other, that each individual and human society be a member of the group, "of use for the common good and serviceable to all"?

8 Conclusions

Heavy body, large and old:
old as day.
Time to have known the folding of mountains
now moldering into tired hills.
Chalky bluffs precipitate into valleys tree-groined in shade,
Where aged trunks and roots gnarled in shadow
Are mingled to the ancient loam,
and rivers flood echoing dark red to the sea.

Tired? Sated, perhaps:
Grown weary with much life, and with entropy's play.
Worn? Certainly; and perhaps worn out,
yet hale.

Blood runs dark and brooding under wrinkled skin,
Nursing ancient bones through still-coursing streams.
Eternal in her green, forest shaded haunts of a lost age,
Weary, none the less she is well:

living weight of time.

Martin O’Connor, Old Body (1987)

Our Quality, in the realm of consciousness as well as in the physical, is increasingly embodied in sophisticated matter-energy systems, and silicon chips, rather than in inherited living cultural forms. Our civilisation thus depends on massive throughputs of Energy, transformed at a frantic rate by an enslaved technological Quality, and producing physical Entropy and social meaninglessness at an accelerating pace. The “dissipation” thus manifests partly in the lower, material dimensions, as "wastes" or "pollution" that threaten to poison or choke our industries, cities, and selves, and partly in the higher dimensions as the loss of "quality of life", a staleness of social existence. The combination of “lower” and “higher” shows up in a constantly threatening degeneration of the functional quality of the support systems, both material and social, on which we all depend. The injections of Exergy, in the form of every more complex systems intended to prevent or remedy these structural ills, carry their own costs, and can eventually overload the societal system and contribute to its collapse, as in the case of declining civilisations like Rome (Tainter 1988).

Through the poetry of thermodynamics we search out a new appreciation of prospects for a style of natural science that affirms complexity and is appropriate for the constant re-emergence and diffusion of Quality. In this, the reflexivity of our relationship with Nature is accepted, and the stresses of life at the edge of chaos are understood as part of the human (social) condition. The assumptions of simplicity are recognised as abstractions (often useful but always limiting), and the human presence in the scientific project, as a thread of the life project, is affirmed through the recognition of systems uncertainties, social contradictions, tensions and decision stakes.

It might seem to be a pessimistic view of things, to deny the Enlightenment project of deploying Science and Democracy to bring all of mankind to a guaranteed permanent state of plenty and peace. Yet, that simple vision of a puzzle-solving science is now so badly compromised, with so little prospect of rejuvenation that we may really consider it to have (at least for now) lost all its Quality. What alternative source can there be for compassion and commitment? As we have seen, the dialectical tension between Quality and its own Entropy is never-ending, but it can sometimes be brought to higher levels of awareness. Such an awareness can be an antidote to the despair and apathy of post-modernity as well as to the banality and barbarism of technology-based consumerist culture.

Humans' actions in their habitats are purposeful in many respects. Yet we do not merely take and use according to instrumental designs. Also we give and provide, furnishing or inflecting the "initial conditions" for other people, other system changes, the co-evolutions alongside. The kernel of our environmental predicament is the incalculability of an indeterminate coexistence. The message of modern physical and life sciences is not unambiguously that more knowledge about nature's forces means better control; rather science raises new and sharper questions about the indeterminacy attached to our interventions and attempts at control. The ecological crisis is a crisis in our social and moral conception of technology and its uses. It is also a crisis of our conception of the nature of human action and human choice. Ecological interdependency is felt in the dilemma of our incessant involvement, individual and collective, in the making and unmaking of life opportunities for others, now and in times to come. We make the journey together through conflicts, concessions and compromises, alliances both willing and unwilling, adventures and unlikely liaisons, ruptures and grief.

Politics in this post-normal world has to be understood in its large original sense: the problems of governance and collective purpose. Moving beyond a simple version of the "precautionary principle" that would merely announce the incorrectness of imposing irretrievable risks on others, we need to affirm inextricable involvement, each one of us, in the lives and deaths of others. Each of our choices affects, sometimes in small ways, sometimes in big ways, the prospects for the coming into being, for the sustaining, for the ceasing, or for the non-being, of specific other lives, social forms, and ecologies. Our science of complexity deals with phenomena of conflict and ambiguity, and so its epistemology necessarily rests on the willingness to entertain conflicting perspectives and to let them confront each other -- the conflicts and contradictions being resolved (though not necessarily "solved") through a commitment to dialogue (Funtowicz & Ravetz 1994a, 1994b).

When we place ourselves in time and within the disequilibrium processes evoked by the new thermodynamics, the turbulence in its reflexive dimensions connotes phases of pain and loss; yet it also connotes the indeterminacy of a love affair, the ambivalence of seduction, treachery and honour, the reciprocity of a dinner party, hospitality amongst guests, rage and calm. Participants may make great sacrifices out of commitment or compassion; and they may have commitments beyond price, which cannot be negotiated or arbitrated away (except perhaps at the price of their own lives). The water resource conflicts of the Middle East furnish a striking example; yet the same sorts of questions about conflict and compromise are evident in the obstacles in the way of (re)assuring water quality within Europe.

Concessions, freely given or forced, may be the price of continuing to be in some sort of community; but at any time consensus may give way to coercion, and dialogue to conflict. So this is not an optimistic philosophy, with a vision of everyone being a winner through progress and simple rationality.

But it comprehends grief, not only the ordinary sort attendant on pain and death, but also the reflective sort arising from our knowledge of our limitations and of the lives that we did not create.

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