Discourse:
Earth System Analysis – The Scope of the Challenge

H. J. Schellnhuber

List of Frequently Used Mathematical Symbols

$\mathcal{A}$ Anthroposphere
$\mathbf{A}$ Macro-state of the Anthroposphere $\mathcal{A}$
$\mathfrak{B}$ Bundle of Paths
$\mathcal{B}$ Global Brain
$\mathbf{C}$ Coevolution Space
C Class of paths ($C[\mathbf{S}]$)
$\mathfrak{C}(\mathbf{P}_1 \curvearrowright \mathbf{P}_2)$ Geo-cybernetic Corridor from $\mathbf{P}_1$ to $\mathbf{P}_2$
$\mathfrak{D}, \mathfrak{K}, \mathfrak{R}, \mathfrak{r}, \mathfrak{S}, \mathfrak{f}$ Domains and Subdomains
$\mathcal{E}$ Overall Earth System
$\varGamma$ Manifold (Separating Domains in $\mathbf{C}$)
$\mathcal{H}$ Human Factor
L Lagrange Function
$\mathfrak{M}, \mathfrak{M}^*, \mathfrak{M}^{**}$ Pool of Control Options
$\mathbf{M}, \tilde{\mathbf{M}}, \mathbf{M}^*, \ldots$ Management Sequences ($\mathbf{M} \in \mathfrak{M}$)
$\mathcal{M}$ Executive (Management) Component of Global Subject
$\mathcal{N}$ Ecosphere (Nature)
$\mathbf{N}$ Macro-state of the Ecosphere $\mathcal{N}$
$\mathcal{P}_i$ Paradigm
$\mathbf{P}(\ldots)$ Path in $\mathbf{C}$
$\mathbf{P}$ Point in Coevolution Space ($\mathbf{P} \in \mathbf{C}$)
$\boldsymbol{\varPi}$ Trajectory in $\mathbf{C}$
Q Scalar Quality Functional
$\mathcal{S}$ Global Subject
$\mathbf{S}$ Generalized Equilibrium
t, τ Time
$\mathfrak{U}$ Accessible Universe in $\mathbf{C}$
$\mathcal{V}$ Value System of Global Subject

1. Prologue

Imagination is indispensable to scientific achievement, even more so to the emerging field of "Earth System Analysis" (ESA). Imagine ... that astronomers were warning us of a huge asteroid heading towards our planet. The collision was supposed to occur in some twenty years from now, but neither the date of the impact nor its site could be predicted with satisfactory precision at this point in time. From the already available approximate knowledge of the celestial maverick's mass and orbital parameters it could be inferred, however, that the collision energy would correspond to an explosion of at least 10 gigatons of TNT.

Let us pause for a second to emphasize two points.

First, the probability of such a strange encounter of the x-th kind is *by no means negligible*: *Lewis* [135] estimates that the mean time interval between 10-gigaton events in the history of the Earth is 70,000 years. As a matter of fact, our planet is studded with impact scars and impact-induced phenomena, such as the formation of thousands of tonnes of diamonds discovered beneath the Bavarian town of Nördlingen (*Hough* et al., 1995 [107]). This town lies within the Ries Crater, which is 24 km across and was gouged out of the rock 14.7 million years ago by a meteorite of presumably 1 km in diameter. NASA takes the threat of comet and asteroid bombardment so seriously that it recently announced the launch of a research programme costing hundreds of millions of dollars to investigate humanity's chances of coping with such a threat.

Secondly, a 10-gigaton collision would release about half as much destructive energy as an all-out exchange involving the world's entire arsenal of nuclear weapons! Clearly, such an event has to be classified as a *global perturbation*, which would shake the foundations of life and civilization on this planet to the core. The famous Cretaceous extinction some 65 million years ago, which wiped out probably more than 60% of the then-existing species, was almost certainly caused by a gigantic asteroid hitting the Yucatan peninsula (*Budyko* and *Golitsyn*, 1988 [36]). The Alfred Wegener Institute for Polar and Marine Research is currently investigating geological evidence of another major impact (*Kyte* et al., 1988 [127]; *Gersonde* et al., 1997 [87]), which took place in the south-eastern Pacific 2.4 million years ago. This 12-gigaton collision generated spring tides of more than 200 metres in height and so much dust and water vapour in the atmosphere that the Earth sank into darkness for millennia ...

Returning to our *Gedankenexperiment* we ask: how would society react to such terrifying news? The shock might initially wreak havoc almost comparable to that of the announced impact itself – stock market crashes, political unrest, a surge of religious movements and sects, etc. But finally, humankind would recover its senses and ask the scientific community to work out a comprehensive "impact analysis" which was capable of answering persistent questions like the following ones:

- What does the collision probability distribution look like, i.e. the estimated likelihood of a given region being bombarded with a given amount of energy?
- What will be the most crucial consequences of the impact? In particular, which areas and systems (natural or civilizatory) are most vulnerable?
- What options for protection, adaptation or rehabilitation are available? In particular, are there any precautionary steps (of technical, economic or political character) that should be taken immediately?
- What options for mitigating or even preventing the collision are available? In particular, is it possible to set up an international rocket programme to deflect or disintegrate the bolide?

There would be no way of answering such questions through the means of reductionist studies conducted within the narrow bounds of disciplinary eruditeness, local technocratic wisdom or the self-serving interpretations of pressure groups. The asteroid impact would trigger an entire cascade of effects that would not be stopped by any geographical, sectoral, cultural, political or social frontier. If Siberia was struck, then the stratospheric dust generated in this event would also deprive the tropical rainforests of their sunlight; if Japan's heartland around Tokyo were pulverized, then the world's economy would be heading straight for disaster.

This means that the required impact analysis would be nothing less than a genuine *Earth System Analysis* – the scientific investigation of how the infinitely interrelated complex of ecosphere and anthroposphere responds as a whole to major perturbations, and how these reactions might be favourably influenced by wise global management. With respect to its aims and scope, the so-defined research programme would be unprecedented in history. Even the notorious Manhattan Project (*Stoff* et al., 1991 [225]), which also set out to save the world (not from cosmic assault but from fascist apocalypse) and ended in opening Pandora's box, could not compare with it in any way.

The asteroid-related Earth System Analysis clearly ought to be

(i) inter-disciplinary,
(ii) inter-national, and
(iii) inter-objective.

The last qualification is of paramount importance and refers to the intricate tangle of partially conflicting needs, intentions and interests of the actors involved (ranging from individuals to multi-national coalitions). Let us give a few examples:

One plausible strategy for "de-sensitizing" the global civilizatory system with respect to bolide impact might be the world-wide dispersion of settlements, infrastructures, and industrial and agricultural production zones – as opposed to the present unabated trends of urbanization, concentration and specialization. If feasible at all, such a sweeping concept would generate a brutal geographic pattern of medium-term winners and losers and, in particular, open up new gulfs between the affluent countries of the North and the nations of the South, which crave for development.

Or consider the problem of burden sharing in creating a rocket system capable of disintegrating the asteroid just before it enters the Earth's atmosphere. Is there any "equitable" contribution scheme that takes into account all the complex disparities between the regions, cultures and social strata of this world and, nevertheless, has a chance of meeting with unanimous approval?

Finally, when it comes to weighing the option "adaptation" against the option "mitigation", are there any criteria powerful enough to warrant the right decision – a decision that is crucial to the subsistence of human civilization? Probably some bold macro-economists would be ready to determine the optimal portfolio of measures by using, e.g., a one-dimensional global damage measure as a function of the size of the largest impacting fragment. However, who will have the political mandate to fix the conversion factors needed for monetizing the damage, i.e., for collapsing all affected items of the planetary inventory – human lives, species, landscapes, power-plants, traffic systems, historic monuments, golf courses, rice paddies, etc. – onto the common dollar axis? So can we find "first ethical principles" from which these factors might be derived in a straightforward manner?

There is another element adding to the uniqueness of our fictional analysis, namely *uncertainty* about the concrete challenge to be met in the not-too-distant future. Since not even the most powerful super-computers will be able to locate in advance the precise spots where the bolide or its scattered debris will hit the surface of planet Earth, the global analysts will resort to *scenarios* such as:

- the "Pacific Crash": sea-quakes and tsunamis of unparalleled ferocity devastate the coastal zones of all riparian nations,
- the "China Syndrome": a direct hit on the Shanghai region wipes out millions of people immediately and destroys the life-support systems of the most populated country in the world, or
- the "California Split": impact-induced tectonic processes in the vicinity of the San Andreas fault separate off vital parts of the "Golden State", triggering an avalanche of world-wide economic and cultural repercussions (such as the elimination of Hollywood's fantasy machine).

Hundreds of scenarios of comparable likelihood will have to be considered, and each of them requires a tedious integrated *if-then* assessment on the continental and planetary scale. The so-defined scientific challenge is of agonizing scope, yet it might be mastered for two reasons:

First, most of these assessments might be constructed from a universal module system, whose building blocks are the answers to fundamental questions about the operation of the ecosphere-anthroposphere complex. Typical questions might concern, for instance, the stability of climate patterns and ocean currents, the vulnerability of ecosystems and coastal zones, the sensitive dependence of the global food production system on specific regions, the robustness of infrastructures with respect to natural hazards, the effectiveness of international institutions in managing trans-boundary problems, and so on.

Second, the advent of sophisticated parallel computer hard- and software (*Akl*, 1997 [2]) in combination with recent progress made in scientific modelling of complex systems might allow the establishment of *virtual impact laboratories*. Renewable artificial earth systems could be exposed there to various simulated crash scenarios in order to study the potential consequences. As a matter of fact, these cyberspace experiments should be the most powerful tool for generating entire ensembles of assessments within a reasonable stretch of time.

* * *

Keeping in mind that any sort of Earth System Analysis will have to rely heavily on the two techniques just described, let us now turn back to the real world at the threshold of the third millennium of the Christian era. Although there is no immediate threat by cosmic tramps, the future of the planet looks almost as black as in our collision fantasy: *Global Change* is all about us – a breathless frenzy of expansion of western industrial patterns, lifestyles and technological knowledge to transmute the very character of the Earth System. The crisis thus induced between nature and humanity expresses itself in a number of fully-developed or emerging phenomena such as:

- the depletion of stratospheric ozone as opposed to the regional enrichment of tropospheric ozone,
- the diffusive spread of physical, chemical and biological pollutants (e.g. mercury) all over the planet,
- the accelerated degradation of humanity's soil resources,
- the global reduction of biodiversity and ecological functions as a consequence of anthropogenic transformations of forests, range- and wetlands,
- the ruining of pristine as well as cultivated landscapes by urban sprawl and rural exodus, and above all,
- the civilizatory modification of the global climate that will trigger an avalanche of environmental impacts.

All these trends are facets of a non-fictional collision, namely the self-generated clash between the biogeophysical Earth System and its own evolutionary offspring – a thermodynamic singularity sometimes called *Homo sapiens sapiens*. The mega-syndrome "Global Change", which will be described in some more detail below, is the very real threat we will have to cope with! This threat, of course, differs in various fundamental respects from the asteroid scenario. We name just a few of them.

Firstly, Global Change is not a predicament inflicted upon humanity by obscure divine or cosmic forces – it is the planetary emanation of trillions of individually expedient decisions of billions of deceased or living actors at all levels of social organization. Therefore, in principle, Global Change may be retarded, modified, or steered according to certain paradigms if the collective will for doing so can be organized. Formally, this boils down to a (very hard) problem of *multiple self-referential control*.

Secondly, Global Change is not hitting humanity in the form of a sudden shock – it is rather a highly interrelated bundle of gradual co-developments. Only occasionally may certain elements of this dynamic pattern cross critical thresholds or points of no return, thereby unleashing abrupt and disastrous impacts on natural or civilizatory systems. It is well known that such insidious processes are most difficult to handle.

Thirdly, Global Change does not have to be as detrimental as an asteroid impact – taken all in all, the long-term benefits for humankind may very well dominate. Even anthropogenic global warming might be turned into positive effects if the right adaptation strategies (e.g. optimal food production and distribution) were chosen and implemented. But note that our civilization is not even passably adapted to the present climate!

Earth System Analysis is generally one of the "Grand Challenges" to scientific endeavour in the decades to come. Its main task will be to provide tools for *managing Global Change* in order to secure an *acceptable long-term coevolution of nature and civilization*. In other (more fashionable) words, Earth System Analysis should yield a good deal of the information and methods required for defining and materializing "*Sustainable Development*".

However, isn't this ambition – or even the very notion – of top-down control of the planetary coevolution hubris of the worst kind? Isn't it precisely this type of thinking, still coveting the intellectual heritage of the

Age of Enlightenment, that paved the way to the deep crisis we are at present facing? The answer is Yes – and yet there is no real alternative to judicious management of the global commons! Humankind is modifying the Earth System anyway at a breathtaking pace - the crucial question is whether this transformation should continue in the familiar, effectively planless way or whether we should at least strive to influence the course of the overall process according to common trans-national objectives. (In fact, the first and most important test regarding the feasibility of Earth System Analysis and control will be the materialization of the AGENDA 21 of the Earth Summit in Rio (*UNCED*, 1992 [239]).

W. *Clark* [43], who is one of the early visionaries regarding global environmental management, has introduced a somewhat naive yet powerful allegory: planet Earth as a vast garden cultivated by humankind. Without doubt this garden cannot be shaped and maintained "à la française", i.e., according to detailed plans based on rigorous scientific principles like Euclidean geometry. The global garden has to be managed rather like an English park, which is allowed to develop "naturally" at the micro- and meso-levels within the boundary conditions of a carefully designed macro-structure.

We have to accept that the "environment" or even "the wilderness" are not just human conceptions, but to some extent actually social constructions, at least at the local and regional scale. This intricate issue is thoroughly discussed in a recent book entitled "Uncommon Ground. Towards Reinventing Nature" (*Cronon*, 1995 [49]). Now the time has finally come to extend the gardening to the planetary scale – if only to counteract anthropogenic global despoliation that, ironically, results in part from the measures taken to protect limited-area environments (e.g., constructing high smoke-stacks or trading toxic waste).

But what about the daunting complexity of the system to be managed, what about its chaotic, i.e., unpredictable behaviour as a consequence of ubiquitous non-linear processes and interactions? Is it, therefore, not highly probable that all efforts to control the ecosphere at large will only exacerbate the present crisis between nature and civilization?

A serious effort to respond to this sweeping argument against any type of global environmental management, put forward in particular by conservationist organizations, will be undertaken in one of the later sections. Let us make here just two preliminary comments. First, people have been successfully managing entire landscapes (like Tuscany or Punjab) for millennia, although these regional systems behave in many physical, biological or cultural respects in no less intricate a way than the planetary one. Second, the ignoristic argumentation may very well be turned around: all the predictions about environmental catastrophes lurking around the corner or the statements about the dynamic malevolence of the ecosphere have to be exposed to the uncertainty considerations introduced above as well. Thus *positive* surprises like the existence of as yet unknown self-stabilizing mechanisms within the ecosphere, which may greatly facilitate Earth System control, cannot be ruled out. As a matter of fact, Lovelock's geophysiological theory (better known under the somewhat misleading label "GAIA Hypothesis") is reasoning precisely along these lines (*Lovelock*, 1991 [141]).

* * *

The rest of my essay is organized as follows: in Sect. 2 the present anthropogenic environmental crisis is briefly reviewed with special emphasis on its novel *character* due to globality. In the following section this crisis is conceived as a *cybernetic task* for the emerging "Global Subject". Plausible *guiding principles* for the so-defined control problem are formulated in Sect. 4. In Sect. 5 *simulation modelling* is featured as the indispensable prerequisite for global environmental management. Sect. 6 is devoted to the question of how control schemes for complex systems like the ecosphere can be efficiently *implemented* in spite of major cognitive deficits. A short Epilogue will conclude our *tour d'horizon*.

As indicated by its title, my contribution primarily attempts to provide a very rough outline of what Earth System Analysis is all about: what are the main topics, the – few – appropriate methods, the pertinent questions and the possible answers.

My specific hope is that the precursor of a consistent and comprehensive programmatics for this intellectual enterprise might transpire from the discourse. This programmatics should help to enrich the slowly materializing research agenda for the science of planet Earth (see, for instance, *NASA*, 1988 [162]; *Pickering* and *Owen*, 1994 [183]; *Moore* et al., 1996 [156]; *Munn* et al., 1996 [159]; *Williamson* and *Liss*, 1996 [250]; *Turco*, 1996 [234]) and to guide the further development of the latter toward a science of Global Sustainability.

2. Global Change: Quantity Turns into Quality

Environmental crises are ancient concomitants of the history of humankind. As a rule, crises of this type were caused by "natural" spatiotemporal fluctuations in the dynamic equilibrium of the ecosphere, especially by astrophysical disturbances, tectonic events, climatic excursions or biological disasters such as new types of pest plagues, for example. These fluctuations had a direct effect on the quality, quantity and distribution of the natural media that were indispensable for civilization, and they therefore indirectly acted as history- and culture-forming factors. The scientific investigations on the historical significance of weather and climate antics are especially varied (see e.g. *Brown*, 1992 [35]; *Hole*, 1994a [104]; *Hole*, 1994b [105]) – there is, in fact, hardly any bygone, advanced civilization the downfall of which had not been or could not be connected in some way with these factors.

A series of environmental crises were, however, not due to the whims of sovereign nature, but instead to the goal-oriented, yet in the long run disastrous activities of human societies themselves. There is also a great deal of speculation on this, though rarely of substance. Did, for example, the American Indian tribal nation of Anasazi really ruin, with lasting effect, its cultural landscape surronding Mesa Verde (Colorado) through overuse of the available resources in the form of biomass, soils and fresh water supplies? In contrast, other historical examples are scientifically assured, for instance the deforestation of the states of the former Roman Empire, which was driven by ship building and which spread outwards from the coasts, with its spectacular ecological consequences. Or the great environmental crisis in Western Europe after the middle ages (especially in Germany, France and Great Britain), where the forests disappeared for the most part by the mid-18th century as a result of charcoal production for the steel and iron industry and where the soils were exhausted by the traditional three-field farming (see e.g. *Montanari*, 1995 [155]; *Bork*, 1988 [28]). Remarkably, the innovative thrust of the Industrial Revolution delivered the way out of the crisis; among other things, this revolution gave rise to the systematic use of coal as a substitute for wood and the large-scale deployment of artificial nitrogen fertilizer in agriculture.

What distinguishes these cases of historical environmental destruction from the present-day situation that is complained about with force and verbosity in the official documents of the *UNCED* (1992) [239]? Many factors could be named here, but we want to concentrate on the most elementary of all these differences, namely the "order of magnitude" of the effect on nature: earlier crises were, in the final analysis, always local (i.e. non-planetary) phenomena that were not capable of triggering a drastic and lasting change in the *basic character of the Earth System.* As far as the *time dimension* is concerned, the subsequent "renaturalization" of anthropogenically degraded areas through exchange movements with the "outside world" that has remained intact has frequently been possible up to now. This process is sketched in Fig. 1.

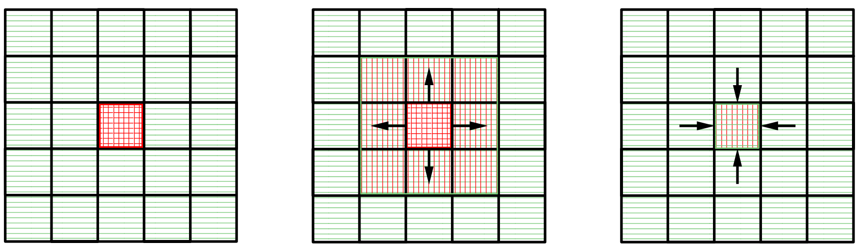


Figure 1. Successive stages in the "Healing Process" (in German: "Renaturierung") of a degraded environmental cell. **(a)** Local degradation. **(b)** Outward migration of actors, polluting substances, etc. **(c)** Inward migration of ecosystems, unpolluted media, etc.

The scheme described is similar to the natural healing of a minor wound in the tissue of the human body, in the process of which a permanent scar may remain. The time constants for the "healing" of heavilydamaged ecotopes are very different and depend on the respective geographic conditions. In most of the historical cases, however, the "fallow time" enforced by nature was significantly longer than the planning horizon of the degraded cultural communities, so a direct resettlement of the renaturalized areas did not take place.

On the other hand, there is also a series of examples of anthropogenic environmental destruction that has led in the past to nearly irreversible damage, locally or regionally. This applies above all to instances of intervention by civilizations that brought about the complete loss of the fertile soil layers and, with that, consequential effects such as karstification and desertification (*WBGU*, 1995 [83]; *Blaikie* and *Brookfield*, 1987 [26]; *Bork*, 1988 [28]). If the spatial order of magnitude of historical events of this type is put into proportion with the magnitude of the overall Earth System, however, it is then clear that these limited environmental crises cannot interfere in any crucial way with the qualitative functions of the ecosphere – such as large-scale atmospheric and oceanic circulation, the global water cycle, planetary biogeochemical cycles, macro-dynamics of the biomes, etc. In particular, the average values of the key planetary parameters (for instance the CO_2 content of the atmosphere or the pH value of the oceans) remain almost unchanged by anthropogenic disturbances of this type: the Earth System behaves vis-à-vis that intervention like a thermodynamic reservoir with quasi-infinite inertia (see e.g. *Callen*, 1985 [38]).

If we want to stay within our "geo-physiological" picture introduced above, then limited, irreversible, historical environmental degradations are comparable to the loss of non-vital body parts (for instance, a fingertip or a tuft of hair) – in other words with damage that can be functionally compensated for nearly completely.

We will try to summarize in this discourse, over and over again, the most important findings in an *extremely simplified* mathematical form. Just as a caricature frequently has a greater recognition value than a photograph, these symbolic representations can help to maintain the overview of the important connections in the analysis. Accordingly, we will describe the basic dynamics of the Earth System in general through a system of only two coupled ordinary differential equations that can depend on various parameters! The historical situation discussed above can then be formalized with regard to its global aspects as follows:

$$\begin{aligned} \dot{\mathbf{N}}(t) &\equiv \frac{d\mathbf{N}}{dt}(t) = F_0(\mathbf{N};t), \\ \dot{\mathbf{A}}(t) &\equiv \frac{d\mathbf{A}}{dt}(t) = G_0(\mathbf{N},\mathbf{A}). \end{aligned} \tag{1}$$

Before we interpret the actual message of this system of equations, we have to first explain the symbols used. t naturally stands for the *time variable*; a suitable origin $t = 0$ has to be chosen. $\mathbf{N}$ designates the *macro-state* of the *ecosphere* $\mathcal{N}$, thus the total natural environment of significance for humanity consisting of atmosphere, hydrosphere, lithosphere and biosphere. Along the lines of *Lovelock* [141], $\mathbf{N}$ is therefore simply to be identified with the state of the planetary "super-organism" Gaia.

$\mathbf{A}$ designates the *macro-state* of the *anthroposphere* $\mathcal{A}$, thus all of humanity along with all of the products of its civilization such as settlements, infrastructures and factories.

Note: Within the framework of this classification, cultivated ecosystems such as a wheat field, for example, are part of $\mathcal{N}$. A constituent of $\mathcal{A}$, for instance a stone house, arises through a specific processing of components of $\mathcal{N}$; this part will usually disintegrate again in the course of the centuries into mineral components and thereby return to the domain of the ecosphere. In other words, no *separate* conservation principles apply for $\mathcal{N}$ and $\mathcal{A}$ – this fact, recognized by Anaximander of Miletus 2600 years ago (see e.g. *Schmitz*, 1988 [210]), cannot be better expressed than through the biblical words referring to human beings themselves: "you have come from the earth, you will become earth once again ... ".

Eq. 1 describes the temporal development of the Earth System; as with the simplest dynamic systems, the first time derivatives of the individual macro-variables can be essentially calculated as functions of the momentary state of all variables. The corresponding mathematical operations are designated here as F_0 and G_0.

It must be emphasized at this point that our system of equations does not represent an outrageous and absurd simplification of the real dynamics, but instead an *extremely condensed description* of the same: $\mathbf{N}$ and $\mathbf{A}$ do not necessarily have to be equated with well-defined, real variables; those symbols may very well represent multi-dimensional, geographically explicit fields or even probability distributions. In a similar way, deterministic or probabilistic tensor operators can be concealed behind the symbols d/dt, F_0 and G_0 without further ado. We always have trust in Occam's Razor in the following, however, and will keep our symbols as simple as permitted for the transport of the content.

Let us now come to the actual message for the historical environmental situation as coded in Eq. 1: The temporal evolution of human civilization first depends on its actual, current state, but also directly on the respective macro-state of the ecosphere (which may pass through a glacial as opposed to a warm period, for instance) with all of its local consequences – the historical human is at the mercy of GAIA to a great extent. By way of contrast, the anthroposphere has *no* influence on the dynamics of the ecosphere on the planetary or continental scale. The latter dynamics first depend on GAIA's current macro-state, but also on external disturbances such as the perpetual modulations of the Earth-Sun configuration (*Milankovitch*, 1930 [153]), or the passing of cosmic dust fields through our planetary system (*Muller* and *MacDonald*, 1997 [158]). On the grounds of these "externalities", F_0 is an explicit function of time and (1) is not an autonomous dynamic system. Note that the dependence of the anthroposphere on extraterrestrial influences is mediated by the ecosphere, because only the excursions of $\mathcal{N}$ are directly perceptible for people. The main message of Eq. 1 is, though: The global development of GAIA is *decoupled* from the development of civilization in the pre-industrial age; the historical human had no influence on the overall operational process of the Earth System.

If one wants to illustrate this situation with a simple physical system, then the parametric double pendulum outlined in Fig. 2, with a heavily asymmetric mass ratio, comes under consideration. The behaviour

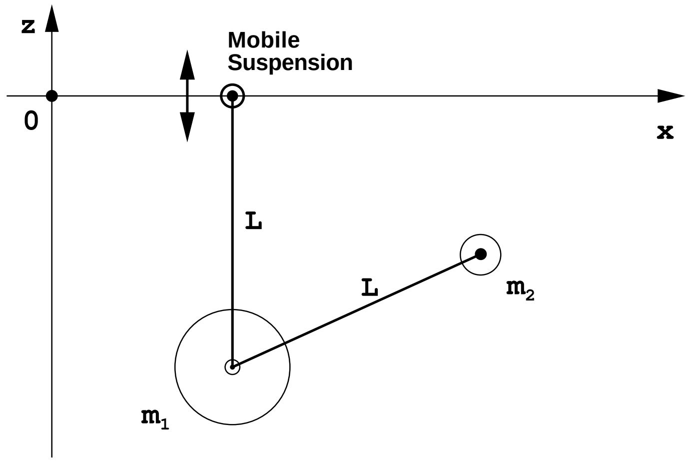


Figure 2. Planar double pendulum, moving under the combined influence of the gravitational forces $\mathbf{F}_i = -m_i g\hat{z}, i = 1, 2$, and a temporal modulation of the pivotal suspension. g denotes the constant acceleration due to the Earth's gravitational field, the two rigid links have identical length L. We initially assume that the first mass is clearly dominating the dynamics, i.e., $m_1/m_2 \gg 1$.

of such a system is best characterized by its "phase space portrait", which reflects the dynamics of the canonically-conjugated variables as defined by Hamiltonian theory (see e.g. *Lieberman* and *Lichtenberg*, 1983 [136], *Abraham* and *Marsden*, 1977 [1]). Under the assumption that the parametric drive at the suspension point (symbolizing the variation of the external influence on the Earth System), as well as the mass m_2 (symbolizing the influence of civilization on the ecosphere), is practically negligible, the following picture results for the corresponding quantities q_1 ("position") and p_1 ("momentum") of the first pendulum (Fig. 3):

* * *

Let us consider, in contrast, the present-day relationship between nature and civilization: The totality of anthropogenic perturbations of the ecosphere can no longer be compared in any way with the historical influence as regards *intensity* and *geographic extent*. The corresponding current state of the global environment is reviewed in detail in thousands of articles and monographs, although occasionally in a contradictory way; we merely make reference in connection with this to the annual reports of the World Resources Institute (*WRI*, 1986 [256]), the Worldwatch Institute (*WI*, 1984 [258]) and the German Advisory Council on Global Change (*WBGU*, 1993 [82]), and to the book series of the Scientific Committee on Problems of the Environment

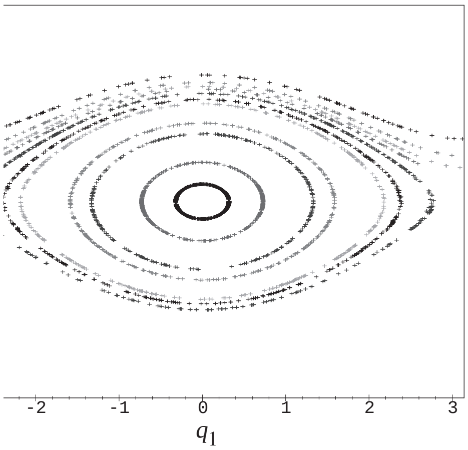


Figure 3. Phase space portrait for the motion of the (almost) unperturbed dominating mass in the double pendulum system depicted in Fig. 2. Each contour corresponds to a given (practically conserved) initial energy of the system component considered. The analyticity of the graph indicates the perfect regularity of the dynamic behaviour observed.

(*SCOPE* [215]). Humanity has now long since outgrown the role of a free rider in the Earth System and has become a *global actor*.

As evidence for this assertion, a series of rather spectacular figures can be given that have meanwhile become a part of the environmental folklore. We will quote a few of these, without dealing more closely with the relevant sources and their reliability.

– Since the start of the Industrial Revolution, the atmospheric CO_2 content has increased by more than 25% because of human activities.
– In the course of the last Spring seasons in the southern hemisphere, episodes of practically complete disappearance of the stratospheric ozone layer over the Antarctic came about.
– The so-called arctic haze, a specific photochemical smog, reigns over a range of up to 9% of the Earth's surface.
– Approx. 8% of the global freshwater flow is used for purposes of civilization.
– Approx. 11% of the ice-free areas of the continents are farmland.
– Since World War II, close to 30% of the fertile soils have been lost through mostly anthropogenic erosion.
– Movements of minerals due to civilization already exceed today, in volume, the global mass movements due to natural forces.
– Humanity now manipulates more than 50% of the net primary terrestrial production caused by green plants.
– The surface of the tropical forests is reduced by 1% annually because of forestry and agriculture.
– Human activities lead, intentionally or indirectly, to the extinction of about 50 species per day.

A limitation or an end to this "list of successes" cannot be foreseen for the time being, since the driving factors are more likely to still be gaining in momentum: for example, it can be assumed that the world's population will approximately *double* by the year 2050 vis-à-vis today's status. The world's economy could even increase its extent *five-fold* by then, if the average growth rate since 1930 of 3% per year is maintained. This would – ceteris paribus – mean an increase of the use of fossil fuels by around 20% per decade worldwide. Such a development almost has the character of a force of nature, especially if one considers that only one fifth of the world's population lives today in relative affluence (guaranteed satisfaction of the basic needs with regard to nutrition, drinking water, accommodation, health, education and mobility). Only a gigantic global campaign on the scale of AGENDA 21 (*UNCED*, 1992 [239]) would be able to perceptibly change this development; realistically, one should instead try to reduce its environmental impact as effectively as possible – but more of that later.

In summary, humanity has intervened *on the scale of the system* in the operation of planet Earth, i.e., the modern anthropogenic modifications no longer vanish – other than the historical ones – in the global limit. The changes in the ecosphere due to civilization can be roughly classified according to:

(i) Content (physico-chemical fabric of the atmosphere, bio-chemical state of soils and bodies of water, etc.);

(ii) *Form* (texture of landscapes, topology or connectivity of ecosystems, etc.);
(iii) *Composition* (make up of species, balance of terrestrial biomes, etc.);
(iv) *Artificiality* (distribution and state of minerals, etc.).

Categories *(i) – (iv)* naturally do not describe any strictly disjunctive quantities, but instead multiply overlapping problem areas that coalesce to bring about *"Global Change"*.

Our classification simultaneously supplies, in a certain way, a ranking with regard to the degree of severity of the human intervention. All actions of substitution or sealing up of natural areas with settlements and/or infrastructure are, as an example, to be subsumed under the most serious Category *(iv)*. The relative share of such areas of "artificial nature" is rapidly increasing world-wide with shanty-town building, urban sprawl and landscape fragmentation. The progressive conversion of the rain forest ecosystem into savannas, steppes or farmland in practically all tropical zones, for instance, falls into Category *(iii)*. The planet is thereby robbed of an "organ" that is important, among other things, for the hydrological cycle; as a consequence, the "geo-physiology" significantly changes. Category *(ii)* contains, in contrast, seemingly milder forms of environmental modifications, for instance measures for the regional development of rural areas (in Germany, this has become notorious under the name "Flurbereinigung", i.e., land consolidation). Interestingly, the anthropomorphism of landscapes can be directly determined through the fractal dimension derived from aerial photographs (*May* and *Sugihara*, 1990 [147]). Finally, the intervention of civilization frequently viewed as being harmless is part of Category *(i)*. This intervention in general only leads to slight shifts in the average values of certain environmental parameters, e.g. of the average lead content of coastal sediments.

In fact, modifications of all four categories can contribute to significantly transforming the dynamic character of the Earth System – its *"operating mode"*. We want to discuss this briefly, using examples for the less obvious Categories *(i)* and *(ii)*. The *first Category* includes especially changes in large-scale key parameters such as the global share of CO_2 in the atmosphere, which only represents a marginal admixture with regard to volume. The 3-atom CO_2 molecule has quite specific quantum-mechanical resonance characteristics in the infrared range, however, which make it a potent heat reflector. The progressive anthropogenic increase of the CO_2 content is therefore leading to a continuous revision of the radiation budget of planet Earth and thereby – with a high probability – to a qualitative modification of the complex atmospheric circulation pattern, which in the end represents a sun-driven, dissipative state far from thermodynamic equilibrium (on this, see especially *IPCC*, 1996 [108]).

A different geo-physiological control parameter is the salinity of the North Atlantic. This variable has a decisive significance for the formation of heavy deep water to the south of Greenland, which is mainly responsible for driving the "Conveyor Belt" of world-wide thermohaline oceanic circulation (*Broecker*, 1995 [33]). The saline content, in turn, can in principle be influenced by anthropogenic changes of the entry of fresh water into the North-Atlantic basin (e.g. through direct modification of the continental outlets or through climate-caused modification of the precipitation conditions). A series of intensive computer experiments (see, among others, *Rahmstorf*, 1995 [189]; *Manabe* and *Stouffer*, 1993 [144]) supply clear indications that even relatively slight manipulations of the freshwater valve could lead to new types of patterns of thermohaline circulation. In particular, it is not difficult to bring about a complete shutdown of the Conveyor Belt in the simulation – an event that has otherwise been realized many times in the earlier history of Earth and that has always had natural causes up to now.

A related computer experiment may also be interesting, in which the hydrological cycle is *not* changed, but the salt in the world's oceans is completely removed. The Conveyor Belt does not then come to a standstill, remarkably; it reorganizes itself, though, in an Atlantic and a – practically decoupled – Pacific vortex (*Ganopolski* and *Schellnhuber*, 1997 [81]).

The *second Category* of globally-effective environmental changes due to civilization includes above all the sum of the topographic rearrangements of the Earth's surface. This process has, for instance in Central Europe, now transformed nearly all of the original natural biogeotopes – a fact that can be easily verified by inspection during an appropriate business flight. A cultural landscape with intermixtures of small areas of forest, meadows, wetlands and farmland fulfills other ecological functions, however, than a macro-structured area – even if the relative total weights of the various landscape components are identical. This problem has been researched very little and is even less understood (*Prentice* et al., 1993 [188]; *Baker*, 1995 [13]; *Mosier* et al., 1997 [157]). Nevertheless, it can be assumed that the texture of the "planetary garden" has a significant influence on the hydrological, climatological and above all biological characteristics of the overall system: geometry and interlinking of the habitats presumably determine the abundance pattern of the regional species and thereby also the ecological elasticity or resilience of the respective domains. Within the framework of an extended "Daisy-World Model" (*Watson* and *Lovelock*, 1983 [246]) , the connection between landscape fragmentation, biological diversity and self-regulation can be explicitly studied (*von Bloh* et al., 1997 [243]).

How the strength of key parameters as well as geometry control the dynamic mode of a dissipative system can be visually demonstrated through the legendary Bénard convection experiment (see Fig. 4). This system now represents one of the icons of modern non-linear dynamics, because it serves as a model case for a series of convective phenomena in nature (see e.g. *Ebeling* et al., 1990 [63]; *Lanius*, 1995 [129]), on the one hand, and has formed the starting point for the Lorenz equations and thereby for the discovery of the first "strange attractor", on the other hand (see, e.g., Chapt. 4).

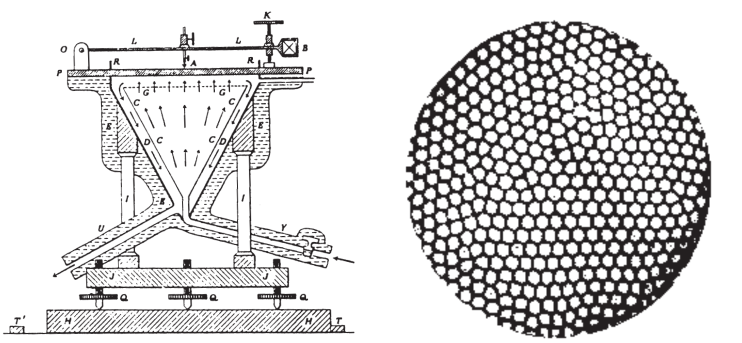


Figure 4. The famous Bénard experiment demonstrating pattern formation in a dissipative dynamic system. **(a)** Typical experimental set-up. A layer of viscous fluid confined by two planar slabs is heated uniformly from below. As long as the resulting temperature gradient across the layer is sufficiently small, the heat is transported exclusively by diffusion processes at the molecular level. **(b)** If the temperature gradient transgresses a critical threshold, then a hexagonal convective pattern emerges as a self-organized macroscopic model of heat transport (pictures taken from *Wittig*, 1983 [253]).

In the extensive literature on this physical phenomenon it has been laid out in detail how the convection pattern ("software") is determined by the system parameters ("hardware") such as temperature gradient and preparation of the experimental arrangement. The overall spectrum of patterns and dynamic states that can be generated here by proper tuning is extraordinarily rich (see e.g. *Bergé*, 1990 [20]).

The Bénard experiment does not just show how sensitively the motion of a complex system reacts to small, but macroscopic, variations of the boundary conditions. It further conveys the insight that sharply-defined "critical" values can exist for the key parameters of such a system; the character of the dynamic pattern – thus the operating mode – abruptly changes when they are exceeded: *quantity then suddenly changes into quality!* For example, when the fundamental system quantities are known, the temperature gradients at which the cylindrical convectional motion sets in and when it is finally replaced by a truly complicated flow pattern can be exactly calculated. The emergence of structural transformations or phase transitions as a result of the continuous variation of certain system parameters is generally described by the so-called catastrophe theory (*Saunders*, 1980 [205]).

One of the most burning questions of modern environmental research is therefore whether there is a possibility that *critical thresholds* likewise exist in the much more complex Earth System for certain global conditions that can be modified by nature, God, humanity or whatever. The knowledge of such threshold values would be all the more important if so-called *"points of no return"* were involved – exceeding them would induce practically irreversible transformations of the ecosphere's character. The scientific discussion on this question has unfortunately been speculative to a great extent up to now, because the available information regarding data and processes are just as inadequate for a satisfactory answer as today's computer resources for running simulation models. We have, without doubt, here run up against one of the main research fronts in future Earth System Analysis.

Various environmentally relevant threshold values have already been postulated or discussed, especially in connection with the estimation of the potential consequences of anthropogenic climate change: we just mention the presumed minimum temperature of 27 °C for the top ocean layer as a necessary condition for the formation of tropical hurricanes, or the temperature value of approx. 15 °C as a switching point between the methane-generating and the almost methane-free reaction path during the microbial decomposition of organic material in soils. These two examples belong to the class of process thresholds determined by the laws of nature, however, not to the really relevant *system thresholds*. A genuine criticality analysis for planet Earth will look instead for answers to questions of the following type:

– Above which value of the atmospheric CO_2-concentration will the ENSO phenomenon (*Philander*, 1989 [182]; *Latif* et al., 1994 [130]) become permanent (or, conversely, shut down)? (*Meehl* et al., 1993 [151]; *Knutson* and *Manabe*, 1994 [123])?
– At which level of anthropogenic biotope disintegration in the temperate latitudes do the annual, transcontinental migrations of certain animal species collapse?
– What minimum extent (diameter) does the tropical rain forest need to subsist as an ecosystem in its remaining refuges, and what consequences would its disappearance have on the global water cycle?
– What percentage of the Earth's surface may be sealed up, without destroying the homeostatic (self-stabilizing) functions of GAIA (Lovelock, 1991 [141])?

These questions have been asked quite naively here and will presumably not find sensible answers in this form. More sophisticated versions of questions of this type will play a dominant role in future global environmental research, though!

If we formally summarize the present-day dynamic relationship between nature and civilization on the planetary scale similarly to the way this has been done in the historical case (see above), we obtain the following system of equations:

$$\begin{aligned} \dot{\mathbf{N}}(t) &= F_1(\mathbf{N}, \mathbf{A}; t), \\ \dot{\mathbf{A}}(t) &= G_1(\mathbf{N}, \mathbf{A}). \end{aligned} \tag{2}$$

All symbols have the same meaning as in (1); only the index of the functions F and G was replaced, in order to indicate the new type of situation. The structural difference to Eq. 1 is the *dynamic quasi-symmetry between the global quantities* **N** *and* **A**: the anthroposphere has now become an active component also at the system scale and therefore represents a significant driving force for coevolution.

In the mechanical example of the parametric double pendulum, this would mean that the mass m_2 of the second pendulum is no longer negligible vis-à-vis the mass m_1 of the first one, thus $m_1 > m_2$ or even $m_1 \approx m_2$. If we draw up again a phase space portrait of the non-linear model system under this modified prerequisite as a counterpart to Fig. 3, a qualitatively clearly different picture results (Fig. 5).

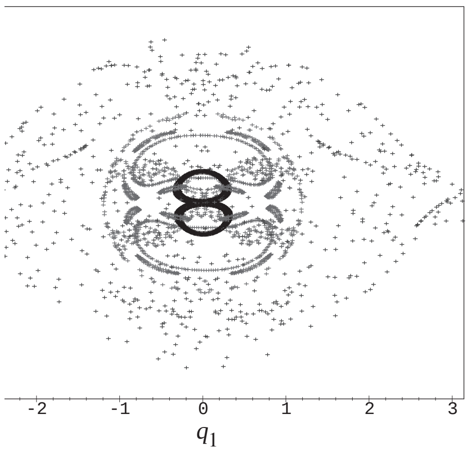


Figure 5. Phase space portrait for the motion of the first mass in the double pendulum system of Fig. 2 for the mass ratio $m_1/m_2 = 1$. Note that the qualitative character of the graph has changed completely in comparison with Fig. 3: the non-analytic texture now heralds chaotic dynamics.

Because of the fact that the second pendulum itself now has an influence on the overall movement, the dynamic character of the system is transformed: with the loss of the analytic nature of the phase space texture, the door is opened for deterministic chaos (*Arnold* and *Avez*, 1968 [8]).

In a similar way, the dynamics of the Earth System have become significantly more complicated since humanity emerged as a global system component – even if comparisons with models that show signs of chaos appear to have no substance at first. We will return again to this point later. This section will be concluded, however, with a few thoughts on the geographically explicit realization of Global Change as characterized above, and on the implications of this spatial phenomenology.

The modern anthropogenic redesign of our environment achieves its global effectiveness through two types of spreading mechanisms that are basically different, namely through *short-range diffusion processes* and *long-range induction processes.* All forms of direct, physical or biogeochemical transport of ecologically relevant substances or entities from sources associated with civilization are part of the *first type:* gases that enhance the natural greenhouse effect or that affect the ozone abundance, aerosols and dusts, heavy metals and organic pollutants, radioactive substances, artificial genetic material, etc. These items spread out in a front-like way through strictly local processes that achieve most diverse expansion velocities and horizons. As an example, particles infiltrating the stratosphere are transported more quickly, by several orders of magnitude, than toxic herbicides in groundwater.

The possibility of diffusive dilution of local emissions of pollutants formed the basis in the 1960s and 1970s for a regionally effective, but globally disastrous environmental-policy principle that can be rewritten as the "strategy of the high smokestacks". (For this, see also the current discussion of the "High-Smokestacks Syndrome", *WBGU*, 1997a [85]). The finite nature of the Earth System necessarily implies that the substances "thrown away" remain within the aura of the anthroposphere and, in fact, often even return to the direct emitters through complicated paths within the food webs. The attempt at the "global homogenization" of the environmental load by civilization may even be substantially more damaging for humanity as a whole than a regional "confinement" at the expense of the party causing it.

The reason for that is twofold. On the one hand, the "homeopathic dilution" of environmental modifications reduces their individual and social *perceptibility* enormously, and the illusion of an unspoiled nature is prolonged, particularly in the geographic centres of the disturbance. Until direct perception of the continually-developing global changes finally comes about, several decades will be lost in general for an effective, international mitigation policy with clear-cut regional specifications.

On the other hand, it is precisely the uniform distribution of originally concentrated pollution that can significantly increase its negative *overall impact.* As an example, the homogenization of landscape fragmentation due to urban sprawl, thoroughly damaging the diversity and vitality of the self-organized balance of species, could be named. Thus the "migration resistance" of these landscapes is significantly increased, or to put it the other way round, the biological mobility as a prerequisite for reactive adaptation movements is dramatically lowered.

We want to demonstrate these elementary effects with a simple electrotechnical example and, in the process, also throw some light on the popular, but infrequently explained statement "*The whole is more than the sum of its parts*". Our object for demonstration is a circuit that essentially consists of N parallel branches (Fig. 6 a). Each of these parallel, conductive segments is supposed to have an internal resistance of the magnitude ε/N. According to Kirchhoff's rules, then the total resistance R_0 amounts to

$$R_0 = \frac{\varepsilon}{N^2}, \tag{3}$$

and, with a given applied voltage U, the following current flows:

$$I_0 = \frac{U}{R_0} = U\frac{N^2}{\varepsilon}. \tag{4}$$

Now an additional resistance of the fixed overall magnitude ρ is to be introduced to the circuit; the portioning and distribution of the "perturbative" entity still remains to be determined. Resistor arrangements that allow for strong (or even maximum) currents are especially sought after. We consider a perfectly homogeneous distribution of ρ on the parallel branches (Fig. 6 b) and an extremely non-homogeneous distribution loading down a single branch (Fig. 6 c) as extreme cases.
In the *homogeneous case*, we find that the total resistance R_h is given by

$$R_h = \frac{\varepsilon + \rho}{N^2}, \tag{5}$$

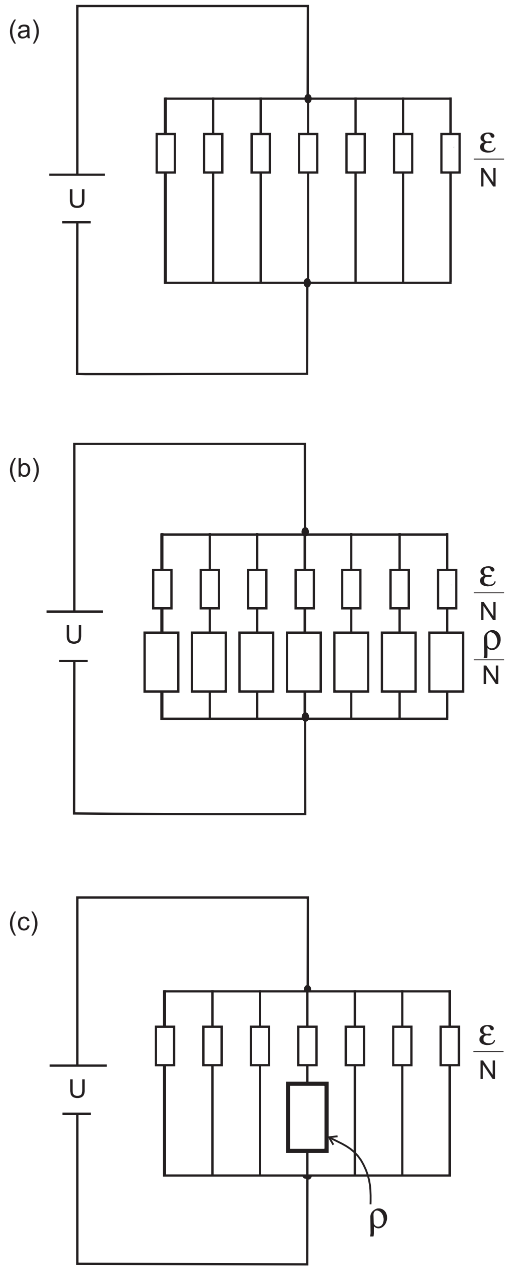


Figure 6. Variants of an electric network for demonstrating the dependence of overall system performance on distributional topology. **(a)** Basic configuration. **(b)** Homogeneous allocation of total incremental resistance ρ to all parallel links. **(c)** Inhomogeneous distribution as a result of allocating ρ to one single link.

so the electric current amounts to

$$I_h = \frac{UN^2}{\varepsilon + \rho}. \tag{6}$$

In the *inhomogeneous case*, in contrast, the following applies:

$$R_i = \left[\frac{N(N-1)}{\varepsilon} + \frac{N}{\varepsilon + N\rho}\right]^{-1}, \tag{7}$$

$$I_i = \frac{UN(N-1)}{\varepsilon} + \frac{UN}{\varepsilon + N\rho}. \tag{8}$$

Thus for the ratio between I_i and I_h, the inequality

$$\frac{I_i}{I_h} \geq \left[\frac{UN(N-1)}{\varepsilon}\right] \Big/ \left[\frac{UN^2}{\rho}\right] = \left(\frac{N-1}{N}\right)\frac{\rho}{\varepsilon} \approx \frac{\rho}{\varepsilon} \quad \text{for large} \quad N \tag{9}$$

holds. So, under the prerequisite $\rho \gg \varepsilon$ already used for this estimation, we observe that

$$I_i \gg I_h. \tag{10}$$

Therefore, if one wants to keep the current as high as possible, it makes sense to distribute the additional *resistance as non-homogeneously as possible!*
Let us now make two further assumptions:

- The reduction of current by the arbitrarily-distributed incremental resistance may only be realized *locally*, i.e., through observations at the parallel branches of the network. The *perception threshold* is reached when the current in the individual branch drops below the value $\frac{1}{10}\left(\frac{UN}{\varepsilon}\right)$.
- The circuit serves to drive another system, the function of which is no longer fulfilled if the *total current* falls short of the *critical value* of $\frac{1}{2}\left(\frac{UN^2}{\varepsilon}\right)$.

Select $\rho = 4\varepsilon$, for instance. In the *homogeneous* case, we then have

$$I_h^{local} = \frac{1}{5}\left(\frac{UN}{\varepsilon}\right), \tag{11}$$

$$I_h = \frac{1}{5}\left(\frac{UN^2}{\varepsilon}\right), \tag{12}$$

i.e. the flow disturbance caused by the additional resistance is not noticed locally, although the total current is already sub-critical!

In the *inhomogeneous* case, things are precisely the other way around. For the individual branch loaded with the additional resistance, we obtain, under the prerequisite $N > 2$,

$$I_i^{local} = \frac{1}{4N+1}\left(\frac{UN}{\varepsilon}\right) < \frac{1}{10}\left(\frac{UN}{\varepsilon}\right) \quad , \tag{13}$$

while the total current amounts to

$$I_i = \left(N - 1 + \frac{1}{4N+1}\right)\left(\frac{UN}{\varepsilon}\right) \geq (N-1)\left(\frac{UN}{\varepsilon}\right) > \frac{1}{2}\left(\frac{UN^2}{\varepsilon}\right) \quad . \tag{14}$$

Thus the perturbation can already be verified locally, although the overall system is still super-critical!

Conclusion:
The homogeneous distribution of the load not only leads to poorer system performance in general, but moreover veils the crossing of critical thresholds.

* * *

Let us return to the general implementation mechanisms of Global Change. By no means all of the elements of ecosphere change are caused by the diffusion processes described above: note, for example, that the world-wide phenomenon of accelerated soil degradation (see, *WBGU*, 1995 [83], and the references therein) is hardly progressing through the physical expansion of fronts. Environmental changes of this type – and also those driven by diffusion in a certain way – are more likely the result of profound “Global Change of the Anthroposphere”, which is essentially mediated through *long-range effects.* This “action at a distance” is particularly realized by the tele-communication (in the broadest sense) of information, technologies, economic incentives, lifestyles, political convictions and value systems, as well as by the physical tele-transport of persons and materials within the framework of the world-wide flow pattern of goods, services and traffic.

Because of this it is possible, for example, that booming East Asian regions will move into direct economic competition with traditional industrial territories of Europe, that the campesinos of the drought-stricken Brazilian Northeast move to the coastal shantytowns in droves, allured by the elusive prospects of an upper-class life as conveyed by the ubiquitous "telenovelas", or that in South Jordan fossil groundwater under the blazing desert is squandered for a bizarre non-sustainable plantation culture, which supplies table grapes to London in the winter via air freight. As a whole, the various long-range effects induce innumerable local instances of intervention in the natural budget, which bring about *global patch structures* of environmental change or of environmental degradation in the end.

If one wants to symbolize this form of ecosphere transformation through a statistical phase transistion, the phenomenon of *nucleation* comes into consideration, whereas the diffusion-driven environmental changes can more likely be categorized as *infection* processes. Fig. 7 outlines the different phenomenologies of these two basic mechanisms of stochastic state substitution.

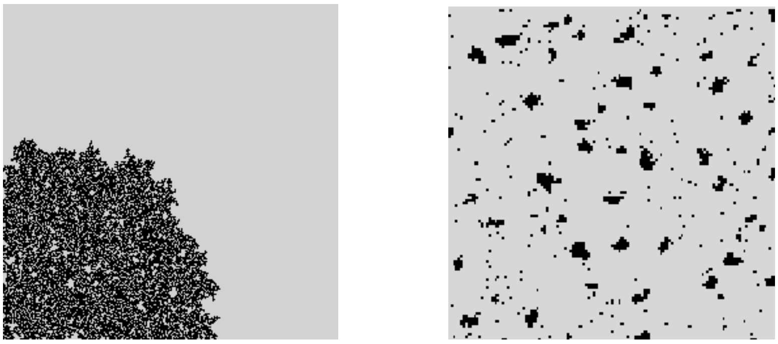


Figure 7. Fundamentally different spatial patterns resulting from distinct ways of performing a phase transition. **(a)** In infection processes, the two phases are separated by connected invasion fronts. **(b)** In nucleation processes, one of the phases appears as a patchy structure embedded within the other phase.

The nucleation of a new type of phase can only take place, though, if the conditions for existence of this phase have already been fulfilled in a sufficiently large domain. Only sporadic impulses from outside are then required – e.g., the introduction of condensation nuclei for the artificial generation of rain – in order to put the polycentric transformation into operation. In the case of Global Change, the preconditions for the world-wide transition to the modern technical-commercial society and for the accompanying ubiquitous rearrangement of the ecosphere have developed over the long term, in part over centuries – but the catalyst of tele-interaction has now converted this potential into an extensive conflagration in a short period of time!

This process cannot, by the way, be studied better in any region than in the marginalized Northwest of Spain, where the ancient cultural landscapes of Cantabria, Asturia and Galicia have been virtually pulverized since the end of the Franco regime and the entry of the nation state into the European Union. The remains of traditional land-use areas still jut out like sinking islands from an ocean of rapidly-growing, profoundly incoherent commerce and settlement structures.

The insight into the topological nature of Global Change does not just have academic value, it supplies hints and indicators, among other things, on how this change could be controlled or how its most crass effects could be reduced. Whereas diffusive spreading processes are typical *surface phenomena* that can be limited or screened off by local or regional measures, in the case of the main mechanisms of Global Change (as described above) *bulk phenomena* are involved. The latter may only be significantly influenced by the well-specified preparation of the global – economic, socio-cultural, political – conditions. Particularly the instruments of tele-interaction come under consideration, which helped to orchestrate the modern crisis in the Earth System. The elaboration of this thought represents one of the main aspects of the following section.

3. Global Environmental Management: The Physics and the Metaphysics

Isn't it strange that both the state of affairs and the cause of the stratospheric ozone loss were discovered "just in time" to be able to (presumably) ward off a really threatening development for the majority of the Earth's population? Imagine that the chemists of the Industrial Revolution were already in a position two centuries ago to manufacture substances similar to CFCs on a large scale and to subsequently dump them into the atmosphere through various types of uses. How would one have tried to explain at that time, however, the unavoidable impacts of this act – destruction of the ozone layer, even over the temperate latitudes, significant increase in the UV-B radiation, vast amounts of physical, genetic and economic damage to the societies that have been exposed? Similar to the case of the greatest natural catastrophe of Western civilization up to now, the plague of 1347 - 50, the scholars presumably would have offered an entire spectrum of obscure causes – from a mysterious "miasma" to the apocalyptic punishment by God ...

Today, humanity is actually changing its habitat on a global scale, as described above – not just the reflection properties of the stratosphere. However, to the same degree that the redesign of the planetary environment progresses, science and technology are generating better and better preconditions for channeling this development along acceptable paths. In particular, modern civilization is in a position to contemplate its own activities of unleashing the forces of "nature" against itself and to comprehend the mechanisms and consequences of these processes – to a great extent. Because of this, the global actor gains a new type of identity and becomes a "*Global Subject*", who is starting to define its (her/his) self-conscious role in the Earth System. These fundamental observations are to be briefly discussed in the following.

The prerequisite that is perhaps the most important for the emerging self-consciousness of the Global Subject is its rapidly-growing ability *to conceive the planetary system in its entirety.* According to the great philosopher (and natural scientist) I. Kant, nature is just what a human mind composes from consensual affections according to its own rules (which, in turn, arise from the "transcendental synthesis of apperception"; see, for instance, *Kant*, 1991 [115]). Thus the design of that nature is necessarily shaped by the characteristics of our perception apparatus. This apparatus defines, like an optical lens system, the construction laws for the image of the outside world to emerge from innumerable particular impressions.

The Kantian approach has its merits, even though the realist will meet it with a great deal of scepticism. As an example, note that the phenomenon of "climate" is without any doubt an ("apperceptive") construct from the observations of the atmospheric states actually prevailing in space and time. We do not want to discuss here whether a "social construction" could even be involved in the case of climate (*Stehr* and *v. Storch*, 1997 [222]).

However, the senses of an individual person are in no way sufficient to perceive, for example, the status quo and development of the *world* climate, or generally any global changes in the environment. Who has ever observed "the ozone hole" or even watched the "extinction of species"? Nevertheless, terms of this type have now become standard elements of everyday conversation, and children portray these phenomena with crayons, just as they drew flowers and butterflies in those good old days. For humanity as a Global Subject perceives the Earth System with the senses of the world-wide "scientific-medial complex". Part of the main modules of this complex are all types of monitoring equipment (satellites, aeroplanes, stratospheric balloons, deep-sea vehicles, drilling devices, weather stations, etc.), the planetary hierarchy of computers and data storage, the explosively growing electronic networks, such as the World Wide Web, all public and commercial means of communication (television, radio, newspapers, magazines, books, etc.), and naturally the agents of this complex who may occasionally appear like the abbots, monks or lay brothers and sisters of a bizarre order – hundreds of thousands of co-operating members of the scientific system who attempt to fit together, interpret and translate for the public the results of the global fact-generating machine to the best of their knowledge and (usually) belief, as well as crowds of media representatives who further popularize the products of the scientists, convert them into "news" and frequently degenerate them into canapés for infotainment. The so-produced flood of correct or distorted information on the state of the globe invades the most obscure corner of human civilization; it regenerates in the daily rhythm and it seems to expand and accelerate incessantly during this process.

There is already a wealth of practical applications for those new types of artificial sensory organs of humanity that penetrate deeply into the area of everyday affairs: just think of the optimization of fertilizer use in agriculture through precision orientation with the aid of the Pentagon's "Global Positioning System", or the control of environmental criminality via remote sensing.

Fully immersed in the electronic ether of the scientific-medial complex, the individuum may further develop into "l'homme symbiotique" (*de Rosnay*, 1995 [56]), into part of a planetary super-organism that will never attain the horrific maturity of the fictional Solaris ocean (*Lem*, 1991 [133]), though. The emergence of this form of collective consciousness is accompanied by a series of negative phenomena, however, in particular "*global hallucinations*". Some of the notorious highlights of ecological folklore belong to this class of collective "disturbances in consciousness", for instance the unshakable expectation of the biological "collapse" of certain oceanic basins (like the North Sea), the invocation of the "imminent climatic catastrophe" or the almost hysterical fear of anthropogenic ground-level ozone, the damaging effect of which cannot compete with that of cigarette consumption in any way. By way of contrast, truly terrifying developments such as the soil degradation in the agricultural centres of the Earth or the over-exploitation of the most productive fishing grounds world-wide are only gradually moving into the consciousness of the Global Subject.

The contemplation of the Earth System in its totality is best done from a real or an artificial *distance*, which lets the planet shrink to an object of manageable dimensions for the purpose of investigation. Today's geographic information systems (GIS) which allow all essential system aspects to be illuminated via thematic maps are most instrumental in this shrinking process. As an example, we sketch in Fig. 8 the texture of land use and land degradation that humanity has impressed on the terrestrial biosphere since the last Ice Age.

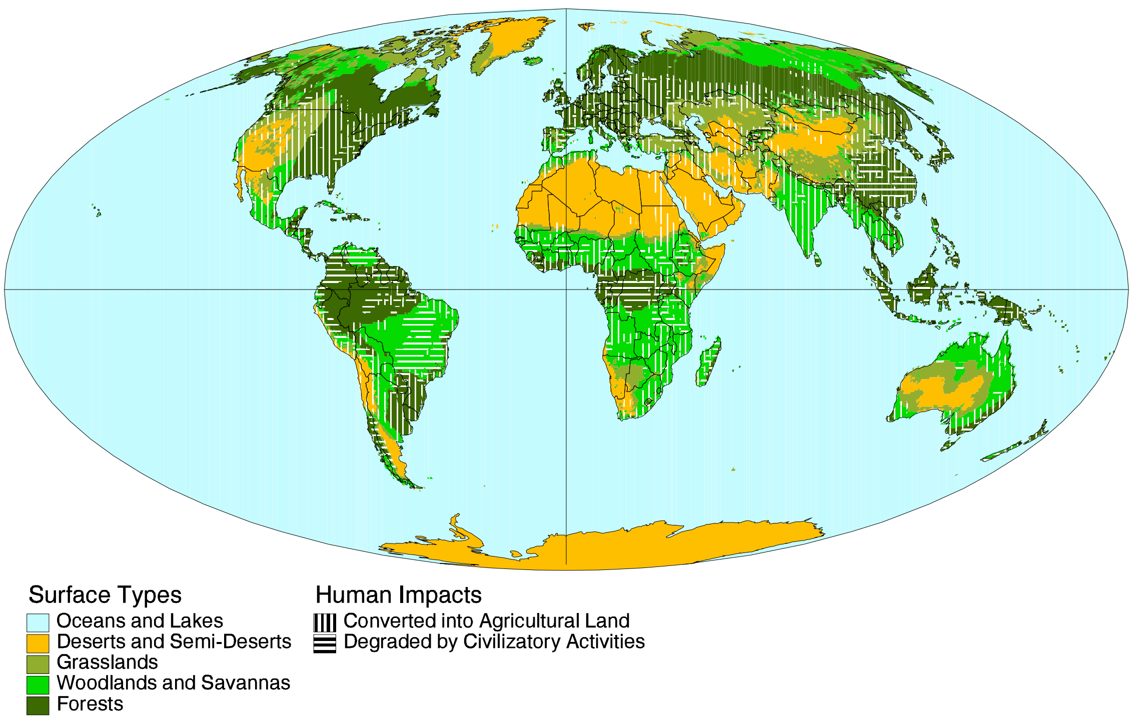


Figure 8. Anthropomorphicity of the Earth's terrestrial surface (M. Plöchl, M. Lüdeke and M. Cassel-Gintz, Potsdam Institute for Climate Impact Research, unpublished).

Fig. 9, in contrast, conveys a real (although GIS-processed) vista of a segment of the Earth's surface: the interweaving and mutual penetration of ecosphere $\mathcal{N}$ and anthroposphere $\mathcal{A}$ can be clearly recognized here.

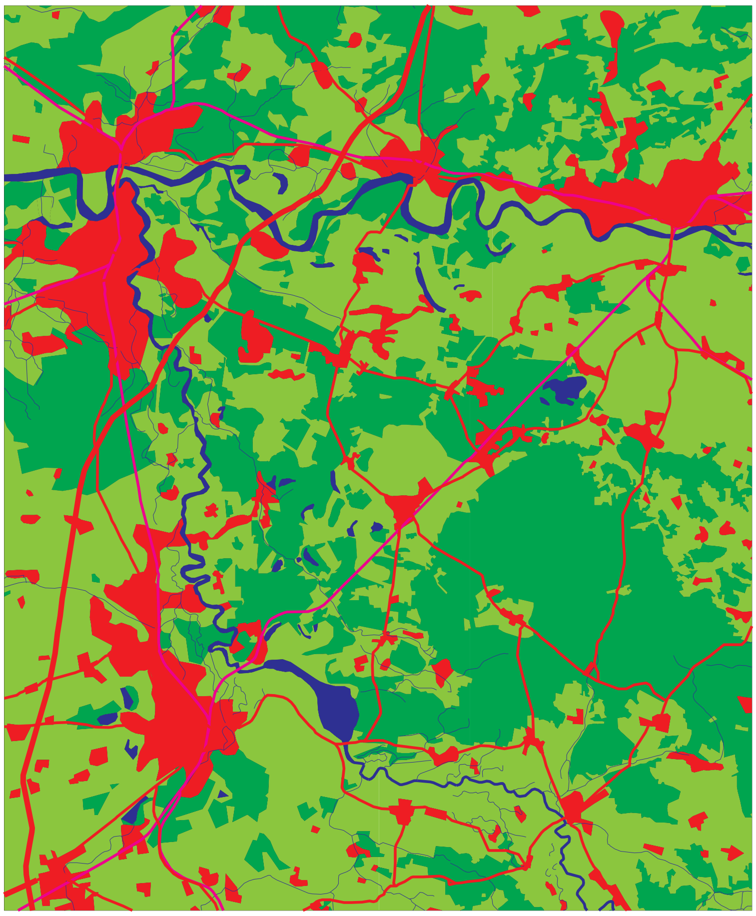


Figure 9. GIS-processed satellite image of a sector of the Earth's surface (Dessau-Wittenberg region). The components of the ecosphere (especially forests, meadows, fields and bodies of water) are coloured in *green* or *blue*; the components of the anthroposphere (especially settlements and traffic paths) in *red*.

In fact, though, not only the regional dovetailing of the structures of $\mathcal{N}$ and $\mathcal{A}$ is visually evident. As already expressed by Eq. 2, *the metabolisms of nature and civilization are dynamically coupled today at the scale of the Earth System*. The anthroposphere maintains its "metabolism" by perpetually sucking up raw materials from the ecosphere, consuming them and expelling them again in a mostly devalued or distorted form (*Harrison* and *Jeffries*, 1976 [98]; *Baccini* and *Brunner* (1991) [9]). Because of this, the metabolism of the "host organism" $\mathcal{N}$ is significantly perturbed.

The main topic of Earth System Analysis is the medium-term to long-term *coevolution of* $\mathcal{N}$ *and* $\mathcal{A}$ on a global scale (see also, *Pitt* and *Samson*, 1997 [184]). This coupled development can be formally represented by a path in the physical *coevolution space* $\mathbf{C}$, which is spanned by the state variables $\mathbf{N} = (N_1, N_2 \ldots)$ and $\mathbf{A} = (A_1, A_2 \ldots)$ of $\mathcal{N}$ and $\mathcal{A}$, respectively (see Fig. 10).

Thus, the coevolution path $\mathbf{P}(t) \equiv (\mathbf{N}(t), \mathbf{A}(t))$ describes the future succession of evolutionary stages of the global $\mathcal{N} - \mathcal{A}$ tandem as initiated by the current state $\mathbf{P}_0 \equiv \mathbf{P}(0) \equiv (\mathbf{N}(0), \mathbf{A}(0))$. We denote by $\mathbf{P}_T(t)$ the *path segment* that unfolds until the time $T > 0$, thus

$$\mathbf{P}_T(t) \equiv \mathbf{P}(t) \mid_{[0,T]} . \tag{15}$$

We now come to a decisive point in our analysis: despite the extreme formal reductions that have been carried out, the representation of the dynamics of the human-environment system up to now basically seems to be correct. But this representation suggests the conclusion – entirely in the spirit of a physics-oriented view of the world – that the future coevolution $\mathbf{P}(t), t > 0$, is *determined* (in principle at least) by the "initial condition" $\mathbf{P}_0$ and the "dynamic equation" (2).

This statement would only have to be qualified in so far as the time development described by Eq. 2 does not solely have to comply with the deterministic rules of the natural laws involved, but is also influenced by *genuinely non-deterministic* elements. We are not refering here to stochastic aspects of the dynamics, which result from information deficits regarding quantities and processes that are principally deterministic. What

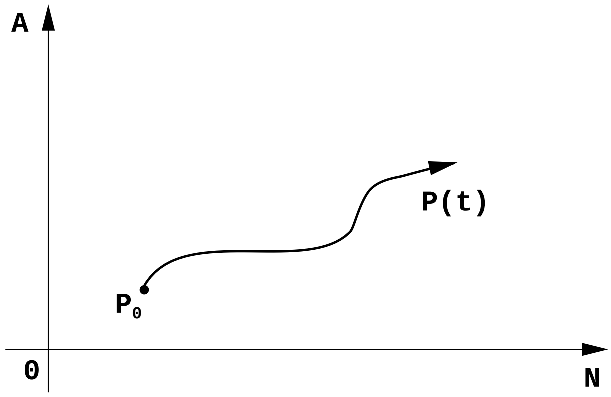


Figure 10. Two-dimensional caricature of the coevolution space **C**, the points of which represent possible states of the global human-environment system. For illustration, a segment of a hypothetical coevolution path $\mathbf{P}(t)$ is drawn in.

is rather meant is the *a-priori indefiniteness* of the future intentional potpourri of billions of humans, which induces the overall behaviour of the anthroposphere. On the other hand, it is conceivable that this ensemble of individual actors and volitions can be taken as a thermodynamic system, the average behaviour of which can be precisely described by means of suitable macro-variables. Macroeconomics, like no other scientific discipline, illustrates the glory and misery of such an approach, in particular with its mathematical pricing and welfare theory à la Walras and Pareto (*Walras*, 1874 [245]; *Pareto*, 1917 [172]; *Samuelson* and *Nordhaus*, 1995 [204]). Consequently, Eq. 2 could fully prove its validity as a time-development rule for global, thus macroscopic, quantities, although in the sense of a probabilistic description.

Under these conditions of "predestined coevolution", however, only the role of prospective contemplation and retrospective documentation would remain for science. The task of organizing the best possible local adaptation to an inexorable development – in a way that is similar to how organizers of open-air events react to the weather forecast – would fall to politics. Such a fatalistic attitude is naturally blatantly inconsistent with the mentality that has brought about the desire for global environment and development (E & D) policies and has thereby installed, among other things, the system of international environmental conventions (*WBGU*, 1996 [84]). The fundamental axiom of this gigantic initiative is the conviction that the coevolution of the $\mathcal{N}$ - $\mathcal{A}$ system does *not* unfold in a globally deterministic way, but can instead be "positively" influenced, may even be *controlled*. An autonomous willpower is required for this, though, which intervenes *from "outside"* in the physical human-environment metabolism according to a top-down strategy.

This intention for E & D design will be brought about by the very "Global Subject" whose basis of existence has been outlined at the start of this section. The Global Subject *transcends* the sum of the physical-individual desires and impulses of all elements of $\mathcal{A}$ as a result of a self-referential process. The collective target structure emerges through million-fold communication, perception and evaluation of personal value-systems as a synergistic control quantity (for physical metaphors like mean-field theory see e.g. *Negele*, 1982 [164]; *Haken*, 1983 [96]; *Baxter*, 1990 [16]; *Landau*, 1996 [128]). One element of this target structure might, for instance, be the intention of limiting anthropogenic warming of the Earth's atmosphere to a maximum of $2\,°C$ – a project that would profoundly shatter and revise the respective manoeuvring spaces for individual action regarding energy consumption, mobility, etc. in every respect.

This means, however, that in the Earth System – besides $\mathcal{N}$ and $\mathcal{A}$ – yet another entity exists, which manifests itself in a "*metaphysical dimension*", so to speak. Fig. 11 provides a synopsis of the overall situation in cartoon form.

Traditionally, the metaphysical space is occupied by "God" or a comparable, poorly-defined trans-human subject of volition, to whom a controlling or just a maliciously-interfering influence on $\mathcal{N}$ and $\mathcal{A}$ is ascribed. We shall not commit ourselves on the existence of such an entity and will restrict ourselves instead to the observation that humanity is today confronted with itself in the form of a seemingly exogenous force unleashing the powers of nature. Thus, if in the analysis one considers the Global Subject as an operator of international E & D strategies, then the composition of the Earth System can be – purely formally – represented as follows (the used letter type refers to *entities*, not state variables):

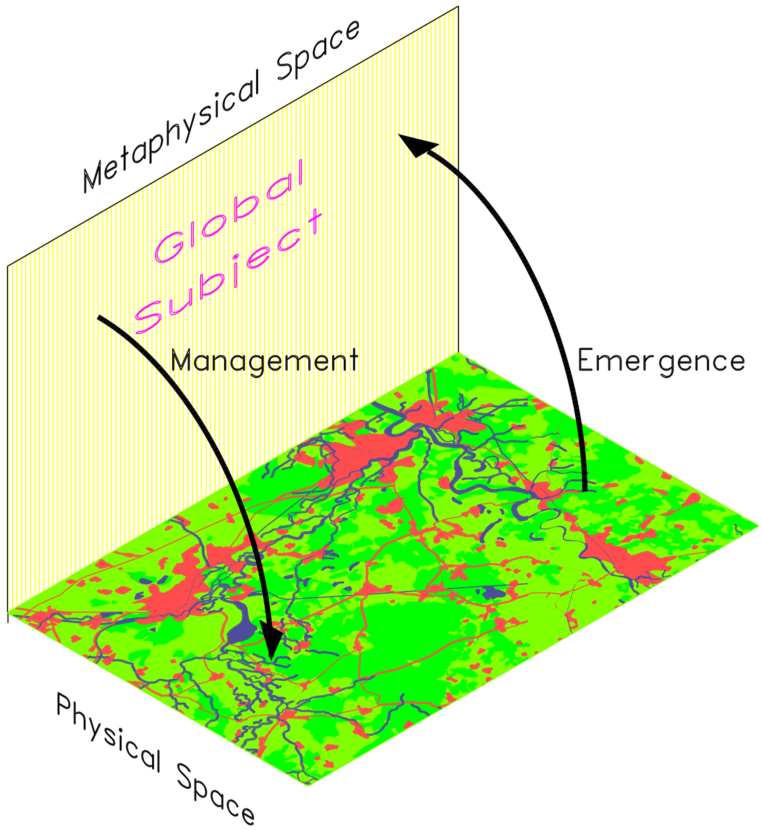


Figure 11. The physical and the metaphysical dimensions of the Earth System, which are "orthogonal" but mutually constitutive.

$$
\begin{array}{rcl}
\mathcal{E} = (& \mathcal{N} \; , \; \mathcal{H} &) \\
 & \downarrow \qquad \downarrow & \\
(\mathfrak{a}, \mathfrak{b}, \mathfrak{c}, \ldots) = \mathcal{N} & & \mathcal{H} = (\mathcal{A}, \; \mathcal{S}) \\
 & & \qquad \downarrow \\
 & & \qquad \mathcal{S} = (\mathcal{B}, \mathcal{V}, \mathcal{M}).
\end{array} \tag{16}
$$

This "formula" is to be read like this: The overall Earth System $\mathcal{E}$ consists of two main components, namely the ecosphere $\mathcal{N}$ and the *human factor* $\mathcal{H}$. $\mathcal{N}$ can be quite conventionally "spelled" according to the sub-spheres $\mathfrak{a}$ ("atmosphere"), $\mathfrak{b}$ ("biosphere"), $\mathfrak{c}$ ("cryosphere"), etc. In contrast, the human factor consists of the "physical" sub-component $\mathcal{A}$ (the anthroposphere as the aggregate of all *individual* lives, actions and products) and the "metaphysical" sub-component $\mathcal{S}$ (the Global Subject as a *collective* E & D factor). The latter can, in turn, be decomposed into the triple ($\mathcal{B}$, $\mathcal{V}$, $\mathcal{M}$), where – borrowing from the structure of human beings – $\mathcal{B}$ stands for the "*brain*", $\mathcal{V}$ for the "*value system*" (or even more vaguely expressed, for the "soul") and $\mathcal{M}$ for the "*executive organs*" of the Global Subject.

Note that $\mathcal{S}$ has no *independent* material basis whatsoever in the sense of a "body": its physical elements, including the "organs", are all components of the anthroposphere. The specific combination of the modules of $\mathcal{A}$, which have developed as a result of evolution, establishes the dynamic identity of $\mathcal{S}$ as an immaterial construction, however, which is just as real or unreal as "the life" of an organism composed of billions of molecules or "the music" of a symphony orchestra with complete instrumental casting. We should warn the reader, not to take our little anatomy of the Earth System too literally – it has a primarily allegorical character, but it also proves useful for analytical purposes.

The collective brain $\mathcal{B}$ of the Global Subject is essentially a result of the trans-individual senses and the computer-supported intelligence of the scientific-medial complex described above. In this context, the big, international research programmes for the analysis of the Earth System such as WCRP, IGBP or IHDP play a crucial role (*WCRP*, 1996 [254]; *IGBP*, 1994 [109]; *HDP*, 1996 [102]), as do the activities of the Intergovernmental Panel on Climate Change (IPCC), which represents a gigantic "truth tribunal" of unprecedented character (*IPCC*, 1996 [108]).

The collective ethics $\mathcal{V}$ of $\mathcal{S}$ is created in an extremely complex and less transparent interaction process between groups and individuals, officials and non-governmental organizations, decision makers and those impacted by decisions ("decision takers"), where certain social classes and sectors, mainly of the industrialized nations, dominate on the grounds of their privileged access to the media. The world-wide supply of the masses with ecologically correct elements of attitude by governments and environmental-protection organizations is rapidly taking on professional characteristics in the process and reflects the formation of a generally-accepted, although contradictory canon of moral guiding principles for Global Change. The desiderata on the corresponding list extend from the "preservation of Creation" to "inter-generational equity", from the protection of the whales to setting fair prices for the plantation products of "indigenous cultures".

The collective executive organs $\mathcal{M}$ of the Global Subject (the symbolism is motivated by the Latin word "manus" for hand) are primarily supranational institutions for E & D management, which belong to two distinct categories within the taxonomic system of political science. There are, on the one hand, binding agreements between independent states, together with their reporting, verification and sanction mechanisms. At present, a great deal of hope is placed on international conventions and protocols for the protection of the global environment (climate stabilization, preservation of biological diversity, control of desertification, etc.) (*WBGU*, 1996 [84]), but a certain sobering-up with regard to the effectiveness of these instruments will probably set in before long. On the other hand, concrete institutions and agencies can be named that are either supposed to form the material backbone of the mentioned conventions (such as the office for the Framework Convention on Climate Change that moved to Bonn in 1996, for instance) or that are the appropriate organs of relevant state alliances (e.g. UN or OECD). The international spectrum is extraordinarily heterogeneous and extends from capital-flow regulators (World Bank, GEF) to cultural care agencies with extremely idealistic programmes (UNESCO). The Global Subject materializes through the activities of institutions of these types, but also through the development-aid initiatives of individual countries or the boycott campaigns of non-governmental organizations operating world-wide. As far as that is concerned, the inflatable rafts with which Greenpeace boarded the scrapped oil-drilling platform "Brent Spar" in 1995 are also elements of $\mathcal{M}$ – quite irrespective of the sense or nonsense of this spectacle.

On the basis of its self-consciousness, which is established and further developed in the interplay of the components $\mathcal{B}$, $\mathcal{V}$ and $\mathcal{M}$, the Global Subject $\mathcal{S}$ can semi-autonomously *select and implement global strategies of E & D management* from the available pool of measures that we want to describe through the formal set $\mathfrak{M}$ embracing the elements $\mathbf{M}(t)$, $t \geq 0$. Each $\mathbf{M}(t)$ represents a certain time sequence of management modules that can be activated. With such elements, direct intervention into the biogeophysical metabolism of $\mathcal{N}$ may be involved in those extreme cases that are generally propagated under the heading of "*geo-engineering*": specific injections of propane into the stratosphere for the neutralization of chlorine molecules that endanger the ozone layer, stimulation of the marine "carbon pump" by iron-fattening of the plankton carpets in the South Seas, reforestation of huge areas of savanna and steppe for sequestration of the anthropogenic CO_2 surplus, doping of aeroplane fuel with sulphur to generate a world-wide homogeneous aerosol haze for correction of the planetary radiation balance, massive increase in the continental storage of fresh water with the help of retaining dams to avoid an increase in sea level – this is only a small selection of mostly eccentric proposals for direct technical repair or control of the Earth System.

As a rule, however, $\mathfrak{M}$ stands for strategies that aim primarily at $\mathcal{A}$ and, because of this, indirectly – through avoidance, structuring or adaptation activities – have an effect on the ecosphere. Regulatory-law measures (e.g. the establishment of environmental standards of all types), economic instruments (e.g. tax incentives or the granting of certificates), political campaigns (e.g. public propaganda to improve voluntary family planning), educational and instructional programmes (e.g. advancement of resource-saving individual behaviour), internationally-organized search surveys for the minimization of industrial greenhouse-gas emissions (e.g. joint implementation), specific externally-financed E & D projects with a model character such as technology transfer or capacity building (especially in the developing countries), consumer initiatives (e.g. shopping recommendations to influence the tropical wood or trophy markets) or international agreements on the regulation of trans-boundary problems (e.g. immigration, water consumption or trade treaties) are among the most important management elements of this type. In particular, consistent long-term strategies for the implementation of nation-specific E & D conventions of the AGENDA-21 caliber can be composed out of those elements. For detailed information, we make reference to the extensive recent literature on this topic (see e.g. *Victor*, 1996 [242]; *Simonis*, 1996 [217]; *Sprinz* and *Luterbacher*, 1996 [221]; *Bergesen* and *Parmann*, 1996 [22]; *Efinger* and *Breitmeier*, 1992 [64]; *Breitmeier*, 1992 [31]). In addition, we should emphasize that the intervention options of the Global Subject consist less in massive interference with material processes (like industrial production or agriculture), than in the creation of "intellectual ethers" or collective public moods ("morphogenetic fields") that impress orientation or design instructions for "sustainable" self-organization on the anthroposphere.

Whatever the pool of instruments of $\mathcal{S}$ may look like, our fundamental tenet is that the Global Subject is basically in a position to *control* the coevolution process, and it has already started to do so – although in a groping and still clumsy way. That is why the equation of motion (2) for the "physical" state variables of the Earth System has to be replaced by the following dynamic rule:

$$\begin{aligned} \dot{\mathbf{N}} &= F_2(\mathbf{N}, \mathbf{A}; t; \mathbf{M}(t)) \quad , \\ \dot{\mathbf{A}} &= G_2(\mathbf{N}, \mathbf{A}; \mathbf{M}(t)) \quad , \\ \text{with} \quad & \mathbf{M}(t) \in \mathfrak{M} \quad . \end{aligned} \tag{17}$$

Eq. 17 describes a dynamics *controlled by arbitrary selection of the exogenous strategy* $\mathbf{M}(t)$, whereas Eq. 2 represents the "undisturbed flow" in coevolution space, as it would develop without intervention of the Global Subject. As a matter of fact, the coevolution state can be forced through the activities of $\mathcal{S}$ onto a path deviating from the "natural development".

If we want to again make use of a physical example for illustration of these circumstances, then *the control of a boat in a prescribed flow field* seems to be a most useful allegory (Fig. 12).

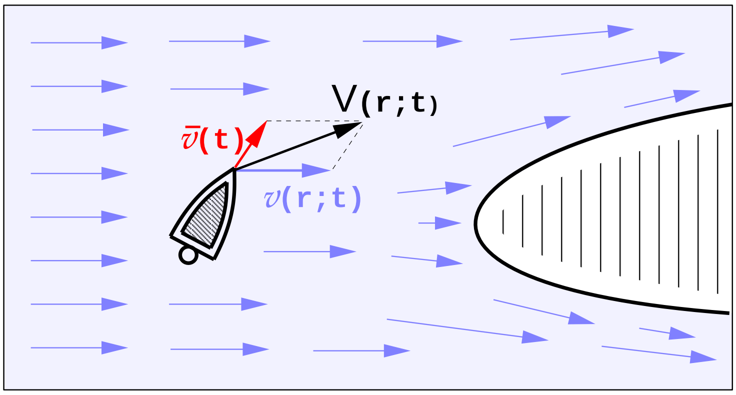


Figure 12. Motion of a propelled vessel on a river. $v(r;t)$ denotes the spatiotemporally varying velocity field of the river relative to a fixed riparian coordinate system. $\overline{v}(t)$ symbolizes the instantaneous boat velocity relative to the supporting fluid as generated by the vessel's driving mechanism, and $V(r;t)$ denotes the resulting absolute velocity of the boat with respect to the river bank.

The movement of the boat can be controlled through a motor, which exerts, for a given steering wheel (and rudder) position, the vector force $m(t)$ on the vehicle at time t. Under certain idealized assumptions – negligible boat mass, scalar effective coefficient of friction γ – the process can be described purely kinetically as defined by the Galilean transformation. The boat velocity in the fixed coordinate system as defined by the shoreline then turns out to be

$$\begin{aligned} V(r;t) &= v(r;t) + \overline{v}(t), \\ \text{with} \quad & \overline{v}(t) = m(t)/\gamma. \end{aligned} \tag{18}$$

The relative velocity $\overline{v}(t)$ is therefore the instantaneous result of the control variable $m(t)$. Note that we have *not* generally assumed stationarity, i.e., $v \equiv v(r)$, for the natural velocity field $v(r;t)$ here: the fluid may, for instance, change its velocity pattern with the seasonal water level.

Despite its extreme simplicity, this mechanical system is indeed suitable to illustrate the essence of the formal dynamic equation (17) for the $\mathcal{N}$-$\mathcal{A}$ complex and to identify the fundamental features of suitable control strategies (see above all Sect. 5). The velocity field $v(r;t)$ represents in this allegory the uncontrolled coevolution as established by Eq. 2. Depending on whether this development is autonomous or not (according to the existence of time-modulated extraterrestrial perturbations), v can be specified as a stationary or as an unsteady flow. The driving force $m(t)$ corresponds to the management strategy of the Global Subject – in spite of the fact that the influence of $\mathbf{M}(t) \in \mathfrak{M}$ on the coevolution will, in general, hardly be representable as an additive quantity in the equation of motion. The resulting absolute velocity $V(r;t)$ finally symbolizes the real development of the coupled metabolisms of the ecosphere and the anthroposphere under the joint effect of micro- and macroscopic forces.

Because of the self-conscious intervention of the Global Subject, we are therefore not dealing with the *one* predestined coevolution path, but instead with the *path bundle* $\{\mathbf{P}(t \mid \mathbf{M}) \mid \mathbf{M} \in \mathfrak{M}\}$ of optional futures of the physical Earth System, which in principle can all emanate from the initial state (Fig. 13).

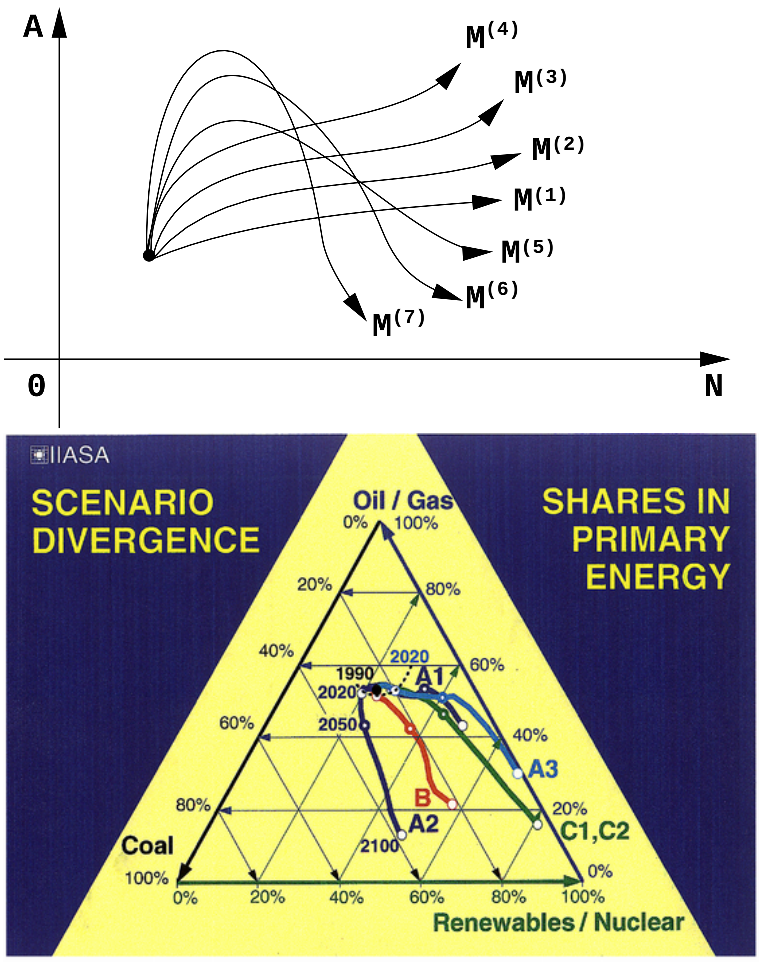


Figure 13. The "fibre bundle" of optional future coevolutions. **(a)** Sketch of several potential coevolution segments in caricature coevolution space. The distinct paths are labelled by their generating management strategies $\mathbf{M}^{(i)}$ as employed by $\mathcal{S}$. **(b)** Bundle of optional energy-mix futures for human civilization, burgeoning out of the historical path. The various evolutions indicated result from a specific set of fundamentally different global policy scenarios (*Grübler* and *McDonald*, 1995 [94]). (Courtesy of N. Nakićenović)

For the sake of clarity and comprehensiveness of the analyses conducted below, it is neccessary to specify and to complete our notation a bit.

Definition 1: Let $\hat{t} \geq 0$ be an arbitrary point in time, $\hat{\mathbf{P}} \in \mathbf{C}$ an arbitrary state in coevolution space, and $\mathbf{M} \in \mathfrak{M}$ a given management sequence. We then denote by $\mathbf{P}(\hat{\mathbf{P}}, \hat{t}; t \mid \mathbf{M})$ the *coevolution path* that develops from the state $\hat{\mathbf{P}}$ at the time $\hat{t}$ under the influence of $\mathbf{M}$ for $t > \hat{t}$.

For each $T > 0$, the corresponding *path segment* $\mathbf{P}(\hat{\mathbf{P}}, \hat{t}; t \mid \mathbf{M}) \mid_{[\hat{t}, \hat{t}+T]}$ will be symbolized by the expression $\mathbf{P}_T(\hat{\mathbf{P}}, \hat{t}; t \mid \mathbf{M})$.

We designate the accompanying *trajectories* in coevolution space with $\boldsymbol{\Pi}(\hat{\mathbf{P}}, \hat{t} \mid \mathbf{M})$ or $\boldsymbol{\Pi}_T(\hat{\mathbf{P}}, \hat{t} \mid \mathbf{M})$, i.e.,

$$\boldsymbol{\Pi}(\hat{\mathbf{P}}, \hat{t} \mid \mathbf{M}) \quad := \quad \{\mathbf{P}(\hat{\mathbf{P}}, \hat{t}; t \mid \mathbf{M}) \mid t \geq \hat{t}\} \quad , \tag{19}$$

$$\begin{aligned} \boldsymbol{\Pi}_T(\hat{\mathbf{P}}, \hat{t} \mid \mathbf{M}) \quad &:= \quad \{\mathbf{P}_T(\hat{\mathbf{P}}, \hat{t}; t \mid \mathbf{M}) \mid t \geq \hat{t}\} \\ &\equiv \quad \{\mathbf{P}(\hat{\mathbf{P}}, \hat{t}; t \mid \mathbf{M}) \mid t \in [\hat{t}, \hat{t} + T]\} \quad . \end{aligned} \tag{20}$$

If $\hat{t} = 0$, we obviously have

$$\mathbf{P}(\hat{\mathbf{P}}, \hat{t}; \hat{t} \mid \mathbf{M}) = \hat{\mathbf{P}} = \mathbf{P}_0 \quad , \tag{21}$$

in agreement with the original notation. ■

We should point out here that we have explicitly exogenized the state of the Global Subject via the decomposition of the Earth System into "physical" and "metaphysical" components according to Eq. 16. As a consequence, we have actually banished the selection act carried out by $\mathcal{S}$ among the available strategies $\mathbf{M}$ into the realm of *a-priori* incalculability, for the time being. This approach does not of necessity imply, however, that the pool $\mathfrak{M}$ of management sequences is an exogenous quantity that does not depend on the development of $\mathcal{N}$ and $\mathcal{A}$ in any way.

Vigorous world-wide economic growth, improved general conditions of international political cooperation or qualitative technological progress could, for instance, significantly expand the global control options. So we are not fundamentally ruling out the possibility of the "coevolution" of $\mathfrak{M}$ with the $\mathcal{N}$-$\mathcal{A}$ complex, but we will not discuss it here in more detail because of the associated mathematical complications. In fact, the dynamism of control is captured in Eq. 17 to a great extent through the observation that a given strategy $\mathbf{M}$ is coupled with the respective states $\mathbf{N}$ and $\mathbf{A}$ through the time-development functions F_2 and G_2, respectively. This accounts for the fact that one and the same management element – e.g. an energy tax of x percent over a time period of τ years - can have different effects in accordance with the factual state of coevolution.

In order to keep the analysis in the following sections reasonably simple, we even assume, as a rule, that the strategy pool $\mathfrak{M}$ is *invariant in time.* This precisely means that from every point in time $\hat{t} \geq 0$ on, the same set of optional management strategies is available:

$$\{\mathbf{M}(t - \hat{t}) \mid_{t \geq \hat{t}} \mid \mathbf{M} \in \mathfrak{M}\} = \{\mathbf{M}(t)\} \equiv \mathfrak{M}. \tag{22}$$

Such an invariance of control possibilities is, for example, evident if measures from a finite list can be chosen and combined in discrete time steps. If we symbolize this list by an alphabet $\{\alpha, \beta, \ldots, \omega\}$, then $\mathfrak{M}$ can be represented as the set of all possible, infinitely long words that can be formed from the given alphabet. The "word" $\alpha\beta\omega\alpha\beta\omega\alpha\beta\omega\ldots$, for instance, then means that at time t_1 the measure α is taken, at time t_2 the measure β, at time t_3 the measure ω, and that this sequence of three basic units periodically repeats. It is clear that the overall strategy pool does not change at all if the first n letters are cut out of all words and the initial point is rescaled.

The simplifying assumption of the time invariance of $\mathfrak{M}$ is justified, above all, for two reasons. On the one hand, we remain with this prerequisite within the structural framework of conventional control theory (see the references in Sect. 5, for example), where the amount of control elements is generally considered to be a fixed, stipulated pool. In our allegory of steering a boat through a velocity field, the optional control activities are completely defined by the technical apparatus; a possibility of free choice only exists with regard to the *order* of the steering measures. On the other hand, management strategies are long-term in character, as a rule. Thus the selection and succession of measures take place at a certain point in time for a usually wide planning horizon, and it is generally not feasible to take the potential development of the control mechanisms themselves into consideration in this planning at this point. Yet mid-way correction or even perpetual readjustment of long-term strategies are by no means ruled out as a result of this, as we will explain in more detail in Sect. 6. A completely new breed of control analysis will then be required, however.

All of the difficulties associated with the potential variability of $\mathfrak{M}$ could possibly be remedied within the framework of a *"super-deterministic approach"*, which makes the Global Subject and, as a consequence, the selection and development of $\mathbf{M}(t)$ *endogenous*. An approach of this type would have to be captured in a formal system of equations with the following structure:

$$\begin{aligned} \dot{\mathbf{N}} &= F_3(\mathbf{N}, \mathbf{A}; t; \mathbf{M}), \\ \dot{\mathbf{A}} &= G_3(\mathbf{N}, \mathbf{A}; \mathbf{M}), \\ \dot{\mathbf{M}} &= H_3(\mathbf{N}, \mathbf{A}; \mathbf{M}), \end{aligned} \tag{23}$$

where H_3 is a suitable time-development function that correctly calculates the variation of the management strategy $\mathbf{M}$ of $\mathcal{S}$ from the extended current coevolution triplet ($\mathbf{N}$, $\mathbf{A}$, $\mathbf{M}$).

However, even if a description of this type appeared to be feasible with regard to content and methodology, one would not thereby escape the trap of *"infinite regression"*. On the basis of the conclusions resulting from the solution of the dynamic equation (23) by the agents of the Global Subject (read: scientists and politicians), $\mathcal{S}$ would presumably try to realize a different strategy $\tilde{\mathbf{M}}(t)$ than the one that is traced out for it – which leads to the problem of "self-avoiding prophecy". This self-referential process might possibly converge towards a strategy that is both stable and acceptable over the long term, but the epistemological complications arising here have at least the same quality as the difficulties obscuring the quantum-mechanical measurement process (see, e.g., *Schrödinger*, 1935 [211]; *Bohm*, 1951 [27]; *d'Espagnat*, 1979 [58]; *Mermin*, 1985 [152]; *Davies*, 1986 [55]; *Griffiths*, 1989 [93]; *Gribbin*, 1991 [92]; *Rosen*, 1996 [199]).

After these observations, we can formulate the main message of this section as follows: E & D policy is not primarily a forecasting problem, but a *control task on the scientific basis of Earth System Analysis*. We may denote this activity of $\mathcal{S}$ as *"geo-cybernetics"* – a process that only has very little in common with the simple technical repair exercises dreamed up by "geo-engineering". Geo-cybernetics is already being pursued on a large scale (via environmental conferences, shareholders' meetings, scientific symposia, media campaigns, grass-root movements and educational programmes), but it is high time to transform this bundle of activities, which has been rather erratic up to now, into systematic international management. It will be the main task of geo-cybernetics to create *now* the prerequisites for a coevolution that is acceptable over the long term within the leeway available in $\mathbf{C}$ in compliance with the natural laws. This requires above all that we *make decisions*, because we can only forecast to a limited extent what we are going to want!

Within the other mechanical allegory made use of several times above – the Earth System as a parametric double pendulum – geo-cybernetics corresponds to the deliberate attempt to control the inherent chaotic dynamics of the construct and, if possible, to put it on the desired track. We will deal with the general *feasibility* of such a project in some depth and detail in Sect. 6.

We now turn to the *key questions* of global E & D management, the answers to which depend heavily on the results of Earth System Analysis (*Clark*, 1989 [43]; *Blackburn*, 1991 [25]):

1. *What kind of world do we have?*
2. *What kind of world do we want?*
3. *What must we do to get there?*

These questions sound naive and presumptuous at the same time; the sheer act of formulating them provokes protest (especially from social scientists), which occasionally increases to hostility. The three key questions nevertheless outline in an adequate way the setting of tasks for the Global Subject, which does not differ *in structure* from the typical everyday management problems of an individual person. The actions of workaday routine are also taken on the basis of uncertain knowledge, and despite the fact that demands and realizability generally gape far apart from each other, nobody is willing to give up the option of attempting, at least, to influence the course of events for the better.

Key Questions 2 and 3 emphasize a fundamental aspect of geo-cybernetics that we have not yet discussed in detail up to now, namely the *targets issue*: Which guiding model or "paradigm" shows the "right" way and by which means can this path best be taken and kept to? Global E & D management is thereby defined as a problem of *optimal control* in the broadest sense.

It is therefore formally necessary to propose or impose deliberately a *paradigm* $\mathcal{P}$. In the simplest case, $\mathcal{P}$ defines a *scalar quality functional* $Q_{\mathcal{P}}[\mathbf{P}(\mathbf{M})]$ for the evaluation of all of the coevolution paths

$\mathbf{P}(\mathbf{M}) \equiv \mathbf{P}(\mathbf{P}_0, 0; t \mid \mathbf{M})$ that can be generated by corresponding management sequences $\mathbf{M} \in \mathfrak{M}$. One may then search for *"best strategies"* $\mathbf{M}^*$, which satisfy the following inequality:

$$Q_{\mathcal{P}}[\mathbf{P}(\mathbf{M}^*)] \quad \geq \quad Q_{\mathcal{P}}[\mathbf{P}(\mathbf{M})] \quad \forall\, \mathbf{M} \in \mathfrak{M} \ . \tag{24}$$

The best strategy is unique under certain circumstances; in general, a larger sub-set of equivalent management sequences from $\mathfrak{M}$ will satisfy Eq. 24. Depending on the design of $\mathcal{P}$, though, it can also be the case that no one-dimensional quality measure for the ranking of possible coevolution paths can be constructed. Then the evaluation of $\mathbf{P}(\mathbf{M})$ – and therefore of the control entity $\mathbf{M}$ – will be achieved through more complex and possibly even qualitative or fuzzy rules (see below). For more than ten years now, a heated debate on the E & D paradigm issue has been dragging on among the "agents" of the Global Subject, whereas very little thought has so far been given to effective procedures or algorithms for determining the best strategies with respect to a given paradigm (with the exception of the rather broad "indicator discussion"; see, e.g., *WB*, 1995 [247]; *FPOB*, 1995 [69]; *UN*, 1996 [238]; *Moldan* and *Billharz*, 1997 [154], and further references in Sect. 4). However, even the scientific analysis of the right models for future coevolution management has remained remarkably vague and is mainly oriented towards the fashionable term "Sustainable Development" (*WCED*, 1989 [255]). This term, which we will abbreviate as SD, has by now been interpreted in hundreds of different ways (Daly's equilibristic definitions standing out here (*Daly*, 1990 [50]), thanks to their intellectual clarity) and has occasionally brought about some peculiar forms of political implementation proposals (such as the plans for "sustainable development" of individual communities or tiny economic segments, testifying a complete failure to appreciate the global interdependencies just complained about).

Despite all of the shortcomings and ideological distortions, the debate about "Sustainable Development" shows the right way for a determination of possible models of geo-cybernetics. We will therefore not avoid this notion, but will rather attempt to put it into concrete terms in the next section. The result will not be a single and binding definition, but instead a collection of *precise optional paradigms of coevolution*, which emphasize different fundamental motives of human action. At the same time, we will attempt to investigate more closely the methods for the selection of the best strategies for realizing the respective ideal.

4. Sustainable Development: One + Four Paradigms

If one tries to analyse the term "Sustainable Development" according to the rules of linguistic logic, one comes to the conclusion that it represents a slightly masked synonym for "*continuable progress*": this interpretation both accounts for the explicitly optional nature of the word "sustainable" and the implicitly positive meaning of the word "development". At the same time, our translation explains, at least in part, the attractiveness of a notion that latently and in technical jargon invokes the naive dream of unlimited improvability of the human conditions of existence. The objection that the realization of such a dream could be shattered already by rigid natural-law restrictions (such as, for example, thermodynamic efficiencies, finite reaction speeds or upper limits for exploitable raw materials supplies) is often casually dismissed with the reference to "qualitative" instead of "quantitative" development.

In general, the term "Sustainable Development" is used, though, with a meaning that mixes the utopia of perpetual progress with fundamental spatiotemporal equity claims. *Clark* (1989) [43] provides a prototypical example, when he quotes the classic formulation of the so-called Brundtland Report (*WCED*, 1989 [255]) as follows: "The WCED, chaired by Prime Minister Brundtland, characterizes Sustainable Development as paths of social, economic and political progress that 'meet the needs of the present without compromising the ability of future generations to meet their own needs.' "

In recent years, a positive definition is generally no longer attempted at all; by way of contrast, certain development trends on all scales of the Earth System are frequently classified as "*non-sustainable*". This tendency may thoroughly reflect a laudable insight into the inadequacy of previous interpretation attempts or even into the fundamental indefinability of "sustainable development". It is also reminiscent, though, of the unfortunate practice of anti-liberal societies to linguistically exclude suspicious or disagreeable activities and movements as "non-christian", "non-German", "non-socialistic", etc. In a similar way, it can happen that the target object with the rating "non-sustainable" will be fundamentally denied "ecological correctness", and therefore the right to objective treatment. Thus by attempting to wangle one's way around a binding clarification of the expression, full license is given for misuse, more than ever! The basically understandable claim for ending the academic debate on "Sustainable Development" by a concrete *operationalizing* of the "concept" can have comparably negative effects: if one wants to take the second (or third) step before the first one in this way, then the danger arises that every player involved in the "sustainability game" will pass off his/her respective recipe (as characterized by individual interests) for local, regional or global E & D management as the exclusive implementation scheme for an exceedingly vague paradigm. Thus the debate would finally deteriorate to the level of a political contest where the strongly promiscuous body of voters is above all won over through the principle of selling (preferably in the media) opportunistic or even unavoidable particular measures as elements of a thoughtful general strategy.

Therefore a *structural analysis* has to precede the operationalizing effort, and this requires in turn a minimum level of formal precision. The rest of this section is devoted to this analysis, which will be restricted to conceptual considerations and nevertheless attempts to create the foundation for a positive definition of the term "Sustainable Development". We will *not* try, however, to review or even to comment on the relevant literature on the topic. We merely make reference to a few important sources within the deluge of more recent contributions (*Pearce* et al., 1989 [177]; *Rees*, 1989 [194]; *Pearce* and *Turner*, 1990 [175]; *Simonis*, 1990 [216]; *Daly*, 1990 [50]; *Brown* et al., 1991 [34]; *Pearce*, 1991 [176]; *Lélé*, 1991 [132]; *Goodland*, 1991 [90]; *Solow*, 1992 [219]; *Buitenkamp* et al., 1992 [37]; *EIAR*, 1992 [65]; *ReVelle* and *ReVelle*, 1992 [195]; *WRI*, 1992 [257]; *Darmstaedter*, 1992 [54]; *Carley*, 1993 [39]; *Pearce*, 1993 [174]; *Daly* and *Townsend*, 1993 [52]; *Lundgren*, 1993 [142]; *Redclift*, 1994 [193]; *McKenzie-Mohr* and *Marien*, 1994 [148]; *WI*, 1994 [259]; *RSU*, 1994 [190]; *Fritsch* et al., 1994 [76]; *Kastenholz* et al., 1996 [117]; *Loske*, 1996 [139]). Otherwise, we will take up certain lines of thought or proposals of other authors if necessary in the course of the analysis.

The pictographic-intuitive approach has proven to be rather successful in the analysis of complex dynamic systems. The following discussion of the potential SD models is therefore mainly based on the illustration of coevolution as a controlled motion in space **C**. We will make a practice of condensing the coevolution space down to *two dimensions* for these illustrative purposes, as has already taken place in Figs. 10 and 13. We may, for instance, interpret the **N** axis as the scale for the *state of the global climate*, and the **A** axis as the scale for the *degree of development of human civilization*. All of the fundamental geo-cybernetic options can be graphically worked out and compactly formalized within the framework of this heavily simplified representation.

The structure of our stylized coevolution space is characterized by the existence of an "*ecological niche*" for the biosphere in general and humanity in particular. On the grounds of favourable astrophysical and geophysical conditions (*Kasting* et al., 1988 [118]), possibly ameliorated and consolidated by "geo-physiological" self-organization processes (*Lovelock*, 1991 [141]; *Krumbein* and *Schellnhuber*, 1990 [126]) our planet offers ideal subsistence conditions to life. For our further illustrative analysis, we will make the simplifying assumption that the (physiogenic or anthropogenic) change of certain planetary master parameters (CO_2 content of the atmosphere, surface albedo, oceanic salinity, etc.) could destabilize the current dynamic equilibrium of the Earth System and – depending on the type of disturbance – might put a "runaway greenhouse process" or a "runaway cooling chamber process" into operation (*Kasting* et al., 1988 [118]). These processes would finally boil down to robust, stationary operating modes again, that are either characteristic for our neighbouring planet Venus, close to the Sun, or for our neighbouring planet Mars, on the far side of the Sun. The ecological niche of life on Earth is thus defined in this context as a window between the Venerian and the Martian regime, i.e. between the basins of attraction of the alternative planetary modes (see Fig. 14).

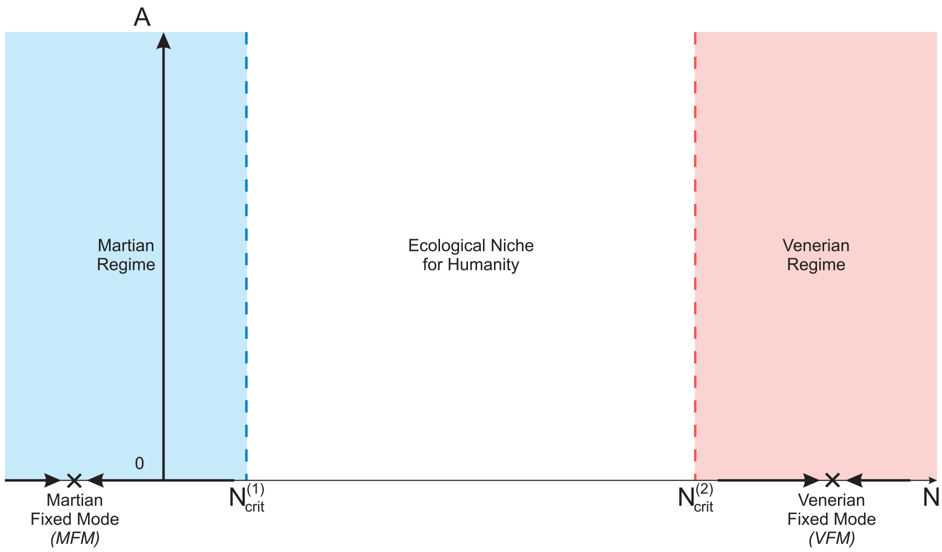


Figure 14. The "habitable zone" in our toy coevolution space is bounded by the vertical lines $\mathbf{N} = \mathbf{N}^{(1)}_{\text{crit}}$ and $\mathbf{N} = \mathbf{N}^{(2)}_{\text{crit}}$, respectively.

The domain characterized by the "terrestrial operating mode" embraces a continuum of conceivable states of the coupled ecosphere-anthroposphere system, but which do not all have to be reachable from the current starting point $\mathbf{P}_0 = (\mathbf{N}_0, \mathbf{A}_0)$. As an example, it is difficult to imagine that humanity could accomplish an extremely high level of civilization in the direct vicinity of the Martian regime. Nevertheless, a multitude of development options, which are determined in turn by the set $\mathfrak{M}$ of strategy options, are available to the Global Subject $\mathcal{S}$ within the "habitable zone". The accessible **N**-**A** states can be described concisely with the help of the following formalization.

Definition 2: Consider an arbitrary initial time $\hat{t}$, an arbitrary successive instant $T \geq \hat{t}$ and an arbitrary initial point $\hat{\mathbf{P}} \in \mathbf{C}$. Then the set of coevolutionary states

$$\mathfrak{U}(\hat{\mathbf{P}}, \hat{t}; T) := \bigcup_{\mathbf{M} \in \mathfrak{M}} \mathbf{P}(\hat{\mathbf{P}}, \hat{t}; t = T \mid \mathbf{M}) \qquad (25)$$

is called a *geo-cybernetic front.*

Similarly, the set

$$\mathfrak{U}_T(\hat{\mathbf{P}},\hat{t}) := \bigcup_{\mathbf{M}\in\mathfrak{M}} \boldsymbol{\Pi}_T(\hat{\mathbf{P}},\hat{t} \mid \mathbf{M}) \tag{26}$$

is called a *geo-cybernetic plume.*

Finally the set

$$\mathfrak{U}(\hat{\mathbf{P}},\hat{t}) := \bigcup_{\mathbf{M}\in\mathfrak{M}} \boldsymbol{\Pi}(\hat{\mathbf{P}},\hat{t} \mid \mathbf{M}) \tag{27}$$

is called the *geo-cybernetic universe* or the *accessible universe* with respect to the initializing pair $(\hat{t},\hat{\mathbf{P}})$. Evidently, we have the inclusion

$$\mathfrak{U}(\hat{\mathbf{P}},\hat{t};T) \subset \mathfrak{U}_T(\hat{\mathbf{P}},\hat{t}) \subset \mathfrak{U}(\hat{\mathbf{P}},\hat{t}) = \lim_{T\to\infty} \mathfrak{U}_T(\hat{\mathbf{P}},\hat{t}) \quad . \tag{28}$$

■

The accessible universe $\mathfrak{U}(\hat{\mathbf{P}},\hat{t})$ is a particularly useful entity here, as it comprises all the states in coevolution space which might be reached sometime from $\hat{\mathbf{P}}$ by implementing some available management strategy $\mathbf{M}$ at time $\hat{t}$.

If we assume, for the sake of simplicity, that neither the management pool $\mathfrak{M}$ nor the Earth-System dynamics itself (see Eq. 17) *explicitly* depend on time, then the geo-cybernetic sets just introduced are only functions of the respective starting point. In particular, we can then easily extend the definition from a single starting point to an entire *starting domain* $\mathfrak{D} \subset \mathbf{C}$. We therefore also consider the quantities

$$\mathfrak{U}(\mathfrak{D};T) \;:=\; \bigcup_{\hat{\mathbf{P}}\in\mathfrak{D}} \bigcup_{\mathbf{M}\in\mathfrak{M}} \mathbf{P}(\hat{\mathbf{P}},0;t=T \mid \mathbf{M}) \quad , \tag{29}$$

$$\mathfrak{U}_T(\mathfrak{D}) \;:=\; \bigcup_{\hat{\mathbf{P}}\in\mathfrak{D}} \bigcup_{\mathbf{M}\in\mathfrak{M}} \boldsymbol{\Pi}_T(\hat{\mathbf{P}},0 \mid \mathbf{M}) \quad , \tag{30}$$

$$\mathfrak{U}(\mathfrak{D}) \;:=\; \bigcup_{\hat{\mathbf{P}}\in\mathfrak{D}} \bigcup_{\mathbf{M}\in\mathfrak{M}} \boldsymbol{\Pi}(\hat{\mathbf{P}},0 \mid \mathbf{M}) \quad , \tag{31}$$

where $T \geq 0$ is an arbitrary stretch of time.

A series of relations between these geo-cybernetic quantities can be derived. Assuming $T_2 \geq T_1 \geq 0$, we find for instance that

$$\mathfrak{U}(\hat{\mathbf{P}};T_2) = \mathfrak{U}(\mathfrak{U}(\hat{\mathbf{P}};T_1);T_2 - T_1) \tag{32}$$

and

$$\mathfrak{U}_{T_2}(\mathfrak{D}) = \mathfrak{U}_{T_1}(\mathfrak{D}) \cup \mathfrak{U}_{T_2-T_1}(\mathfrak{U}(\mathfrak{D};T_1)) \quad , \tag{33}$$

due to the time invariance of $\mathfrak{M}$.

These relations are remotely reminiscent of Huygen's principle of wave mechanics.

The quantity $\mathfrak{U}(\mathbf{P}_0)$, i.e. the universe of coevolutionary states accessible from the current one in the course of time, is certainly of central importance for geo-cybernetics. $\mathfrak{U}(\mathbf{P}_0)$ is the combination of all possible trajectories $\boldsymbol{\Pi}(\mathbf{P}_0, 0 \mid \mathbf{M})$ that can be realized through control – the entire tangle of optional "coevolution spaghetti", so to speak. One should note, though, that two arbitrarily chosen specimens of this tangle may have long segments in common, so they can "stick together" over sections. A conceivable structure of the universe accessible for geo-cybernetics within the framework of our two-dimensional illustration is presented in Fig. 15.

In our example, $\mathfrak{U}(\mathbf{P}_0)$ is not a simply-connected quantity. The specific shape may be interpreted as follows: in order to achieve a higher level of civilizatory development (among other things, industrialization of the "Third World"), humanity has to accept either a warming of the Earth's climate (through unabated

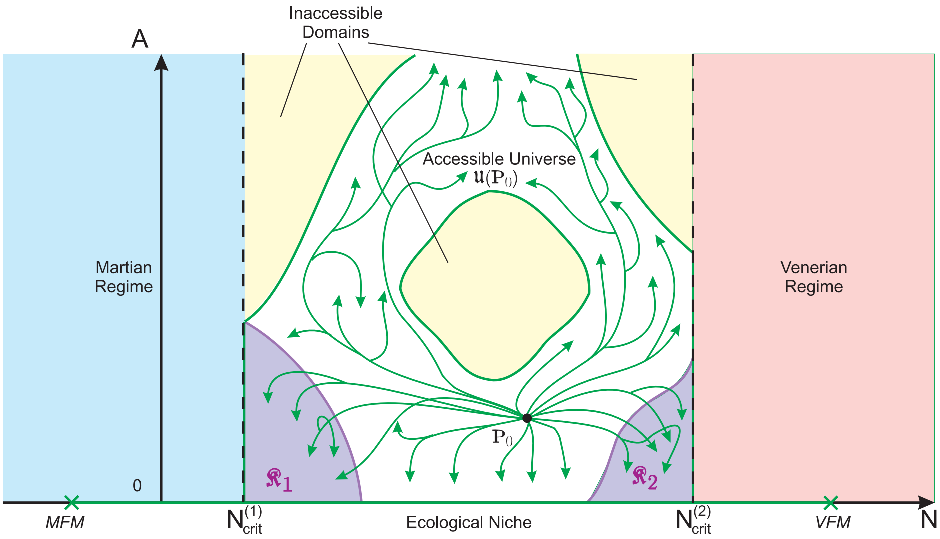


Figure 15. Set of all coevolution states which can be reached from $\mathbf{P}_0$ by appropriate management (*green contour*). The *violet* sub-sets $\mathfrak{K}_1$, $\mathfrak{K}_2$ of $\mathfrak{U}(\mathbf{P}_0)$ are "catastrophe domains" (see explanation in the text below).

consumption of fossil fuels) or a cooling of it (because of an increase of the planetary albedo accompanying massive land use changes, for instance) *over the medium term*. The attainment of the higher development stage permits, however, a subsequent throttling down of the "ecological overload" (for instance within the framework of a complete transition to some form of regenerative energy economy or with the help of the "New Green Revolution" (*FAO*, 1996 [73]). A climate-preserving upwards movement is, in contrast, no more possible in our model world than a vertical backwards drop from a high level of civilization – that is why we observe a "hole" in our accessible universe. The other non-accessible domains result from the plausible assumption that an extremely high level of civilization can only be realized in proximity to the optimal climate.

In Fig. 15, we have also indicated specific sub-sets $\mathfrak{K}_1$ and $\mathfrak{K}_2$ of $\mathfrak{U}(\mathbf{P}_0)$. These represent exemplary *catastrophe domains*, which should be avoided at all costs in the geo-cybernetic process! For the precise definition of such domains it is necessary to introduce an "*environmental-economic Lagrange function*" $L(\mathbf{P})$, which assesses the overall quality of the coevolution state $\mathbf{P} = (\mathbf{N}, \mathbf{A})$. L can also be interpreted as an integrated utility function and will typically have the following structure:

$$L(\mathbf{N}, \mathbf{A}) = l(w(\mathbf{N}), q(\mathbf{A})) \quad , \tag{34}$$

with

$$w(\mathbf{N}) = \omega\left(w_A(\mathbf{N}), w_S(\mathbf{N}), w_N(\mathbf{N})\right) \quad . \tag{35}$$

Here, w_A represents the immediate *value of the global natural resources* for humanity, w_S assesses *the systems quality of* $\mathbf{N}$ as defined by ecological theory (stability, resilience, complexity, capacity for development, etc.) and w_N takes into consideration *the "eigenvalue" of nature* according to some determination scheme. q, on the other hand, is a compound indicator for the quality of the socioeconomic and cultural dimensions associated with $\mathbf{A}$. For possible concrete definitions of the functions l, w, and q we refer the reader to the relevant "indicator literature" (e.g., *Nordhaus* and *Tobin*, 1972 [166]; *Zolotas*, 1981 [264]; *Cobb* and *Cobb*, 1994 [47]; *Daly* and *Cobb*, 1994 [51]; *WB*, 1995 [247] and to the recent article of *Costanza* et al., 1997 [48]). We point out here that the "Lagrange function" L can certainly also depend on the time derivatives of $\mathbf{N}$ or $\mathbf{A}$ and, in addition, explicitly on t, i.e.

$$L \equiv L(\mathbf{N}, \dot{\mathbf{N}}; \mathbf{A}, \dot{\mathbf{A}}; t) \tag{36}$$

or even

$$L \equiv L(\mathbf{N}, \dot{\mathbf{N}}, \ddot{\mathbf{N}}, \ldots; \mathbf{A}, \dot{\mathbf{A}}, \ddot{\mathbf{A}}, \ldots; t) \quad . \tag{37}$$

In these cases, it would be useful to switch from the representation of coevolution in "configuration space" $\mathbf{C}$ to *phase-space representation* (*Goldstein*, 1982 [89]; *Desloge*, 1982 [57]). A complication of this type is not necessary, however, for the main part of our exploration of fundamental SD paradigms as carried out in this section. Unless stated otherwise, we will also assume in our illustrative analysis that the $\mathcal{N}$-$\mathcal{A}$ dynamics is autonomous in the sense that it is controlled by $\mathcal{S}$ but not influenced by varying external forces.

As a rule, a given coevolution state $\mathbf{P} = (\mathbf{N}, \mathbf{A})$ will be acceptable – or at least tolerable – if its overall quality $L(\mathbf{N}, \mathbf{A})$ has reached a certain *minimum level* L_{min}. We can now exactly describe what we mean by catastrophe domains.

Definition 3: A non-void sub-set $\mathfrak{K}$ of $\mathbf{C}$ is called a *catastrophe domain*, if the following conditions are met.

(i) $\mathfrak{K}$ is *accessible*, i.e., $\mathfrak{K} \subset \mathfrak{U}(\mathbf{P}_0)$.
(ii) All states in $\mathfrak{K}$ are *intolerable*, i.e., $L(\mathbf{P}) < L_{min}$ for all $\mathbf{P} \in \mathfrak{K}$.
(iii) $\mathfrak{K}$ is *inescapable*, i.e., $\mathfrak{U}(\mathfrak{K}, T) \subset \mathfrak{K}$ for all $T \geq 0$, therefore $\mathfrak{U}(\mathfrak{K}) = \mathfrak{K}$.

■

Expressed in less technical terms, we are considering here irreversible coevolutionary collapses brought about by mismanagement! One should note that the Martian and Venerian regimes are not catastrophe domains taken as a whole, because they represent largely inaccessible areas. The abscissa sections between $N_{crit}^{(1)}$ and MFM resp. $N_{crit}^{(2)}$ and VFM in the example of Fig. 15 belong to $\mathfrak{K}_1$ or $\mathfrak{K}_2$, though. One can, for instance, imagine here that all these catastrophe domain states will be attracted, in the long run and independently of the management sequence $\mathbf{M}$ applied, by the Mars mode or the Venus mode, i.e.,

$$\lim_{T\to\infty} \mathfrak{U}(\mathfrak{K}_1; T) \equiv \mathfrak{U}(\mathfrak{K}_1; \infty) = MFM \quad , \tag{38}$$

$$\lim_{T\to\infty} \mathfrak{U}(\mathfrak{K}_2; T) \equiv \mathfrak{U}(\mathfrak{K}_2; \infty) = VFM \quad . \tag{39}$$

Within the picture of the boat allegory (Fig. 12) for managed coevolution, the asymptotic states MFM or VFM consequently represent pointlike maelstroms that cannot be escaped from once one has dared to get too close to them.

Here we may, of course, ask ourselves where the coevolution would move to if the Global Subject $\mathcal{S}$ entirely refrained from geo-cybernetic activities. We identify this "non-strategy" with the element zero in $\mathfrak{M}$, i.e. $\mathbf{M} = 0$. The resulting coevolution path will be denoted as the "business-as-usual scenario" (BAU), symbolized by $\mathbf{P}^{(0)}(t)$:

$$\mathbf{P}^{(0)}(t) := \mathbf{P}(\mathbf{P}_0, 0; t \mid 0) \quad . \tag{40}$$

$\mathbf{P}^{(0)}(t)$ is consequently the properly initialized solution of Eq. 2, which has to turn into the corresponding solution of Eq. 17 for $\mathbf{M} = 0$. In our exemplary model world, we can make the assumption that this BAU path will enter the catastrophe domain $\mathfrak{K}_2$ in a finite time and, thus, terminate in VFM (Fig. 16).

We have now created the formal and substantial prerequisites for the identification and description of the fundamental (or "pure") SD paradigms in the further course of this section. These paradigms can be assigned to elementary control principles, which in turn correspond to archetypical *human ideals* (positive interpretation) or, likewise archetypical, *human vices* (negative interpretation), respectively. The resulting little taxonomy (Tab. 1) concludes our preliminary remarks.

4.1 Standardization

We begin our survey with a geo-cybernetic paradigm, which is not rooted in some deeper theoretical systems principle, and that therefore only represents a *pseudo-paradigm*. What we mean by this is the direct prescription of norm values, development corridors, target domains, etc. for controlled coevolution – the *establishment of absolute E&D standards*, in brief. The coevolution criteria involved here are not stringently derived – or even derivable – from the internal dynamics of the system under consideration, but from external normative settings of the Global Subject instead. The actual systems dynamics only comes into play via the question concerning the attainability in principle of the standards that have been set.

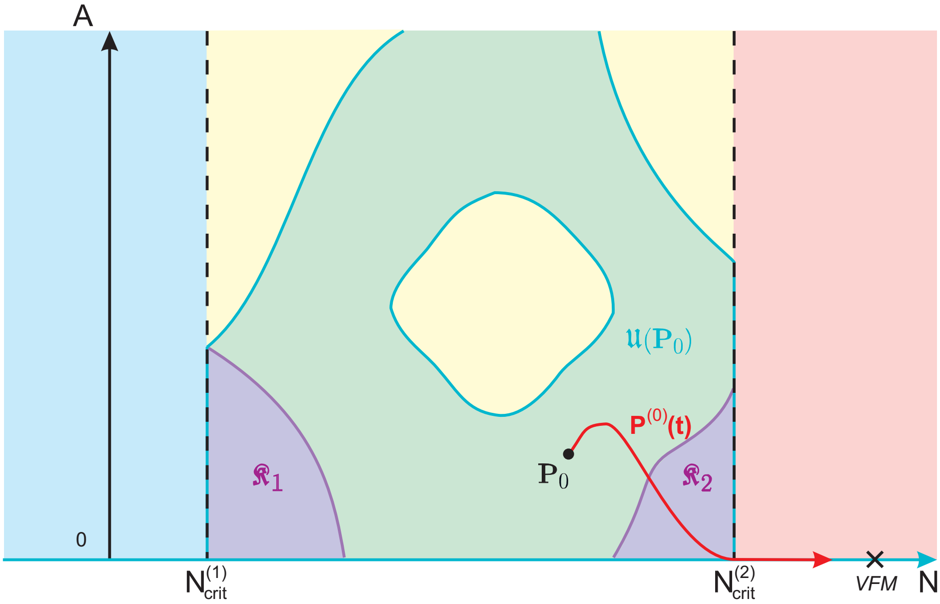


Figure 16. The disastrous coevolution path as generated by global "Business As Usual".

We label this paradigm, which seems to be trivial at first glance, with the symbol $\mathcal{P}_0$ and call it "*Standardization*" (see Tab. 1). The underlying philosophy has, on the one hand, much to do with the naive arbitrariness of the Stalinist five-years plans, but on the other hand also with the sense of responsibility of eco-toxicologists who attempt to establish adequate critical loads for hazardous environmental pollutants.

The real public life in the industrialized countries is already more strongly influenced by the Standardization principle than one would assume: norms, quota, criteria – from exhaust gas control through "affirmative action" to the Maastricht conditions for EU country membership, everything and everyone is regulated through standards that are often quite difficult to justify!

Illuminating examples relevant for geo-cybernetics are Germany's self-imposed obligation to reduce its CO_2 emissions by at least 25% by 2005 with respect to the base year 1990, and, of course, the international reduction quota for the output of all sorts of greenhouse gases that could be stipulated at the end of 1997 in Japan through the "Kyoto Protocol" to the Framework Convention on Climate Change.

The Standardization paradigm $\mathcal{P}_0$ offers a seductively simple and concrete possibility for operationalizing the sustainable-development idea: certain environmental quantities or entire aggregated functions are declared *sustainability indicators*, and the coevolution in question is considered to be correct if the indicator

Table 1.
Classification of the pure SD paradigms which will be explained in detail below.

Symbol	Name of Paradigm	Positive Goal	Negative Motive
$\mathcal{P}_0$	***Standardization***	***Order***	***Despotism***
$\mathcal{P}_1$	***Optimization***	***Prosperity***	***Greed***
$\mathcal{P}_2$	***Pessimization***	***Security***	***Cowardice***
$\mathcal{P}_3$	***Equitization***	***Fairness***	***Jaundice***
$\mathcal{P}_4$	***Stabilization***	***Reliability***	***Indolence***

values keep on varying within a "*green range*" that is likewise to be defined. Explicit proposals for the definition of such a green range are, for example, provided by the model study "Sustainable Germany" (*Loske*, 1996 [139]; *Loske* and *Sachs*, 1997 [140]), which constitutes a rather impressive analysis of standardization concepts like the ecocapacity principle (*Opschoor* et al., 1991 [168]; *Weterings* and *Opschoor*, 1992 [249]; *Opschoor* and *v. d. Straaten*, 1993 [169]; *Buitenkamp* et al., 1994 [37]) or the so-called MIPS approach (*Schmidt-Bleek*, 1994 [209]).

In principle, the SD strategy $\mathcal{P}_0$ is characterized by the hope that complex environmental systems can be put on the right course through some sort of "technical instructions" in the sense of German regulatory law. This hope is generally justified, in turn, by the assumption that the *non-sustainable* value ranges of the key indicators are evident to a certain extent. In other words, the respective system is supposed to be steerable, more or less "by sight", i.e. via the largely statistical, perpetual evaluation of spatiotemporal close-range information. Fig. 17 illustrates this fundamental strategy and, at the same time, sketches some of the problems associated with it.

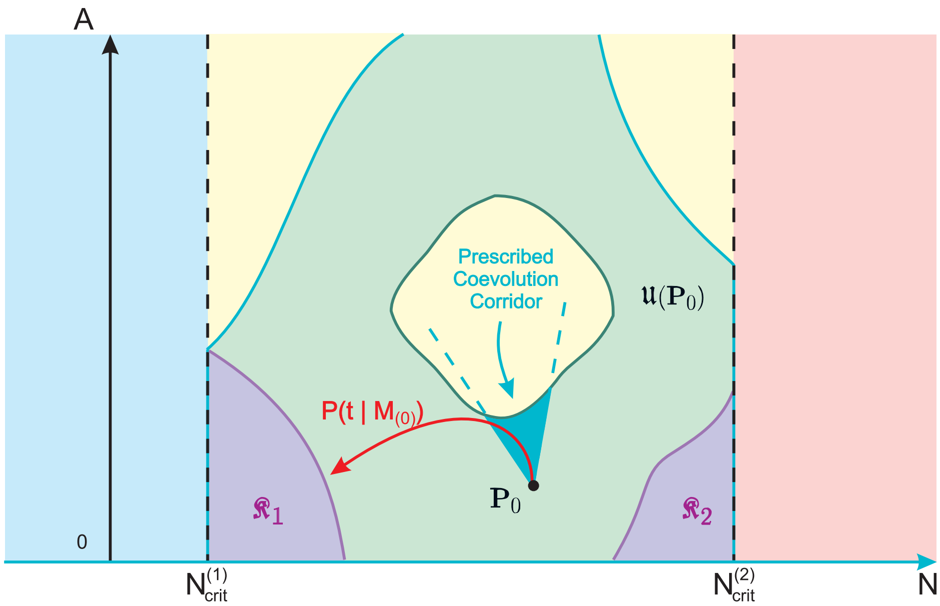


Figure 17. Exemplary realization of the Standardization paradigm in our toy world. The SD corridor (indicated in *green*) is defined according to certain standards, which do not take into account the general accessibility conditions. A coevolution path is shown, which is generated by the management sequence $\mathbf{M}_{(0)}$ complying with the normative principle $\mathcal{P}_0$. Note that $\mathbf{P}(t \mid \mathbf{M}_{(0)})$ has to leave the prescribed corridor and ultimately even risks entering the catastrophe domain $\mathfrak{K}_2$.

The fundamental arbitrariness in the stipulation of coevolution norms for the Standardization paradigm involves the great danger that essential interactions, repercussions and side-effects in the non-linear system to be controlled are not taken into consideration. In the most favourable case, the standards that are to be set are at least intuitively or proto-analytically derived from one of the "*teleological*" paradigms still to be described, i.e., on the basis of a systems analysis that is at least rudimentary. Under the latter circumstances, a revision of the selected standards is possible if those norms should prove to be untenable on the grounds of new findings and insights.

In the worst case, however, the geo-cybernetic standards are the result of a policy-dominated search and definition process. The Standardization then tends to favour key indicators that are as catchy (= simple) as possible and hastens to comply with the public acceptance of the corresponding norms. Standards generated that way can, in general, only be revised with much difficulty – even if the revision seems compelling in view of new scientific insights or pioneering ethical discourses. Under such conditions, the control strategy $\mathcal{P}_0$ may take on a "*teleocratic*" character, i.e., degenerate to the ritual fulfillment of rigidly defined standards. Then a general shift in thinking could only be brought about by the real systems dynamics exposing the standards as an illusion.

We will try to express the Standardization paradigm for SD in a more formal way in the following and to put it in concrete terms with the aid of a few examples. The basic elements of the strategy $\mathcal{P}_0$ are certain E & D quantities X_l; $l = 1, 2 \ldots L$ (state variables, compound indicators, functions, etc.), which have to satisfy the *inequalities*

$$X_l^{min} \leq X_l \leq X_l^{max} \quad ; l = 1, 2 \ldots L \quad , \tag{41}$$

with fixed *limit values* X_l^{min} and X_l^{max}. Frequently the boundaries $X_l^{min} = 0$ or $X_l^{max} = \infty$ are employed. In the most restricted case, Eq. 41 degenerates to an exact target-value instruction through the demand $X_l^{min} = X_l^{max}$ for certain l.

All coevolution paths

$$\mathbf{P}(t \mid \mathbf{M}) \equiv (N_1(t \mid \mathbf{M}), N_2(t \mid \mathbf{M}), \ldots ; A_1(t \mid \mathbf{M}), A_2(t \mid \mathbf{M}), \ldots) \tag{42}$$

are to be controlled in such a way that the rule (41) is not violated at any point in time, i.e.

$$X_l^{min} \leq X_l(\mathbf{P}(t \mid \mathbf{M})) \leq X_l^{max} \quad \text{for all} \quad t \geq 0 \quad \text{and all} \quad l \quad . \tag{43}$$

Example 1 ("Eco-Centrism"):

In this case, the E & D rules exclusively focus on the *"natural components"* of the Earth System; the socio-economic standards are completely ignored. The requirement is, for example, quite simply that

$$N_l^{min} \leq N_l \leq N_l^{max} \quad ; l = 1, 2 \ldots L \quad . \tag{44}$$

A somewhat more subtle, normative strategy would prescribe, e.g.,

$$w_{min} \leq w(\mathbf{N}) \quad , \tag{45}$$

where $w(\mathbf{N})$ is the quality index for the ecosphere introduced through Eq. 35.

Example 2 ("Tolerable E & D Window"):

Here a fixed admissible range in coevolution space is declared within which each possible development is permitted. In contrast to the eco-centric version of $\mathcal{P}_0$, the *human dimensions* are explicitly taken into account by requiring:

$$N_i^{min} \leq N_i \leq N_i^{max} \; ; i = 1, 2 \ldots I \; , \tag{46}$$

$$\text{and} \quad A_j^{min} \leq A_j \leq A_j^{max} \; ; j = 1, 2 \ldots J \; , \tag{47}$$

where $\{N_1, \ldots, N_I; A_1, \ldots, A_J\}$ represents a carefully-selected sub-set of the total ensemble of state variables.

Example 3 ("Living Standard Maintenance"):

By way of contrast to the previous examples, where detailed *separate* standards were set for the individual components of the Earth System, the tactical variant of $\mathcal{P}_0$ considered now refers to a *highly-aggregated coevolution indicator*. An obvious choice for the latter would be the "Lagrange function" $L(\mathbf{P})$ defined in Eq. 34. Then the management sequence $\mathbf{M} \in \mathfrak{M}$ has to be selected in such a way that the so-created coevolution path $\mathbf{P}(t \mid \mathbf{M})$ fulfills the inequality

$$L_{min} \leq L(\mathbf{P}(t \mid \mathbf{M})) \tag{48}$$

for all times $t \geq 0$. The establishment of the minimum standard L_{min} is, of course, a complex and highly political matter!

The corresponding SD paradigm may be refined through additional rules, which will *guarantee the geographic homogeneity* of the coevolution quality measured by L, or *limit the time variation* of $L(t) \equiv L(\mathbf{P}(t \mid \mathbf{M}))$ for example. The "variation" of a scalar function is a non-trivial mathematical entity, though; we refer the reader to the relevant monographies on functional analysis for its precise definition (see e.g. *Kreyszig*, 1978 [124]).

We wish to point out that the concrete realization of $\mathcal{P}_0$ sketched in this example explicitly permits trade-offs between natural and civilizatory qualities, i.e., between "ecology" and "economy". A coevolution path can therefore be classified as "sustainable" if a transient degradation of environmental standards is *overcompensated* through massive socio-economic advantages. A corresponding development philosophy laid the foundations for the "Green Revolution" of the 1960s and 1970s (see *Barrow*, 1995 [15] and the references therein), which was more or less fixated on food-production rates.

Example 4 ("Continuous Progress"):

We emphasized at the beginning of this section that the term "Sustainable Development" is so attractive because it suggests the fundamental possibility of "continuable progress" in a slightly cryptic way. The following operationalization of $\mathcal{P}_0$ comes closest to this extreme interpretation.

The Standardization paradigm is based here on *dynamic quality functionals*

$$Q_{\mathcal{P}_0}[\mathbf{P}(t \mid \mathbf{M})] \equiv Q_0(t \mid \mathbf{M}) \quad , \tag{49}$$

which continuously assess the "progress" associated with the controlled coevolution $\mathbf{P}(t \mid \mathbf{M})$ (see also Sect. 3). A simple choice for such a functional is, for example,

$$Q_0(t \mid \mathbf{M}) := \frac{d}{dt} \left\{ L(\mathbf{P}(\mathbf{P}_0, 0; t \mid \mathbf{M})) \right\} \quad , \tag{50}$$

i.e. Q_0 represents the *time variation of the generalized utility function.* According to this prescription, a sequence $\mathbf{M}$ would then warrant permanent progress if, and only if,

$$0 < Q_{min} \leq Q_0(t \mid \mathbf{M}) \quad \text{for all} \quad t \geq 0 \quad . \tag{51}$$

More complex progress measures are also conceivable, however, for instance

$$Q_0(t \mid \mathbf{M}) := \frac{1}{T} \left\{ L(\mathbf{P}(\mathbf{P}_0, 0; t + T \mid \mathbf{M})) - L(\mathbf{P}(\mathbf{P}_0, 0; t \mid \mathbf{M})) \right\} \quad , \tag{52}$$

with suitable averaging time $T \in (0, \infty)$.

This measure defines, in conjunction with condition (51), the requirement of perpetual *mean* coevolutionary progress.

For the general construction of Q_0 the "quality factors" $w(\mathbf{N})$ and $q(\mathbf{A})$ (see Eq. 34) should be combined in a reasonable (maybe non-linear) way and the resulting aggregate should be then subject to appropriate mathematical operations (possibly including higher time derivatives). The concrete form merely depends on society's preferences that are to be reflected in the notion "progress". For the state of Malaysia, for example (*WN* (1996) [248]), coevolutionary progress is synonymous with "sustained and self-supporting economic growth", while preserving the stock of natural resources of the country. The Standardization paradigm obviously determines the government's structural policy here: Malaysia is to be "a fully developed industrialized nation" by the year 2020, but in the course of this development, "only three of the total of 19 million hectares of forest area will be released for human use", for instance.

* * *

The basic question remains as to whether the fundamental strategy reflected in the Standardization paradigm can be successful *over the long term.* In particular, we have to ask: Is the "continuous progress" as defined through a largely arbitrary indicator Q_0 also "*continuable*" – as required by the SD ideal? Does the observance of certain norms for short-term E & D management furnish any guarantee at all for the fulfillment of the requirement? We will try to shed some light on the structure of this dilemma through an examplary, yet formal discussion.

The Standardization strategy will, in reality, focus on a limited time period $[0, T]$, $T > 0$, which we want to designate as the "*planning horizon*". The scope of the planning horizon is determined on the one hand by the reliable findings of the natural and social sciences regarding the state and dynamics of the environmental system under consideration (e.g. the entire Earth System), and on the other hand by the distribution of power and further political circumstances that the E & D managers have to observe. Assuming democratic conditions, standards like the duration of legislative periods, re-electability, statutes of limitation on legal affairs (e.g. environmental liability), etc. must be considered. Under authoritarian conditions (in the "most favourable" case, an "eco-dictatorship"), the planning horizon tends to be set much longer; it is, however, directly linked with the stability of the ruling regime, which is practically incalculable (see for instance the still unpredictable ecological consequences of the economically-caused collapse of the Eastern-European E & D management à la Russe).

Let us now consider a given progress measure $Q_0(t \mid \mathbf{M})$, a *minimum standard* $Q_{min} > 0$ and a planning horizon T for some environmental systems to be controlled. We further assume that the progress measure is not determined by the management *future*, but exclusively by the respective coevolution *history*. A well-defined measure of that type is obtainable, for example, if we declare

$$Q_0(t \mid \mathbf{M}) := \frac{1}{\Delta}\left\{L(\mathbf{P}(t \mid \mathbf{M})) - L(\mathbf{P}(t-\Delta \mid \mathbf{M}))\right\}, \quad \Delta > 0 \quad , \tag{53}$$

and postulate certain regularity properties of the quantities involved. We generally assume, anyway, that the coevolution path $\mathbf{P}(t \mid \mathbf{M})$ is a *continuous function of time* for every admissable management sequence $\mathbf{M}(t) \in \mathfrak{M}$. If L is not constructed in an irregular way, this property is conveyed to $Q_0(t \mid \mathbf{M})$, the initial value $Q_0(0)$ of which is unambiguously determined as a consequence of the causality principle.

For the further discussion, we will also introduce the notion of a *management episode*. Let T_1, T_2 be two arbitrary points in time, with $0 \le T_1 \le T_2$, and $\mathbf{M} \in \mathfrak{M}$ an arbitrary management sequence. The accompanying management episode is then defined as

$$\mathbf{M}_{[T_1,T_2]} := \mathbf{M}(t)\big|_{[T_1,T_2]} \quad . \tag{54}$$

The symbol $\mathfrak{M}_{[T_1,T_2]}$ then denotes the entire set of all of the management episodes that can be selected in the time period $[T_1, T_2]$, i.e.,

$$\mathfrak{M}_{[T_1,T_2]} := \left\{\mathbf{M}(t)\mid_{[T_1,T_2]} \Big| \mathbf{M} \in \mathfrak{M}\right\} \quad . \tag{55}$$

In the special case $T_1 = 0$, we can replace T_2 by the symbol T and use the simplified notations

$$\mathbf{M}_T \;:=\; \mathbf{M}(t)\big|_{[0,T]} \quad , \tag{56}$$

$$\mathfrak{M}_T \;:=\; \left\{\mathbf{M}(t)\mid_{[0,T]} \Big| \mathbf{M} \in \mathfrak{M}\right\} \quad . \tag{57}$$

If we assume time invariance of the management pool $\mathfrak{M}$ (see Eq. 22), then the following identity holds:

$$\mathfrak{M}_{[T_1,T_2]} = \left\{\mathbf{M}_{T_2-T_1}(t+T_1) \Big| \mathbf{M} \in \mathfrak{M}\right\} \quad . \tag{58}$$

We are now in a position to analyse more closely the planning problems that typically arise with the paradigm $\mathcal{P}_0$, as outlined in Fig. 18.

This picture is particularly supposed to make clear that some management strategy which satisfies all desired standards over the short term can lead nevertheless to an irreversible development which destroys all of the long-term demands of the paradigm. In such a case, the initial progress is *not continuable* or, in other words, the development is not sustainable. There is, however, no systematic procedure for avoiding erroneous developments of this type within the framework of the pseudo-paradigm $\mathcal{P}_0$. The environmental system under consideration can have "*lines of no return*" that are not recorded by the local/instantaneous available indicators and are only detectable by a *teleological analysis*. The most important element of such an analysis is the careful exploration of the potential limitations of future options induced by the selection of a specific management episode.

The considerations necessary for this can be better structured through a precise concept formation. We begin by defining the set $\mathfrak{M}(\hat{\mathbf{M}}_T)$ of all possible management sequences *which can be generated from the episode* $\hat{\mathbf{M}}_T \in \mathfrak{M}_T$, i.e.,

$$\mathfrak{M}(\hat{\mathbf{M}}_T) := \left\{\mathbf{M} \in \mathfrak{M} \Big| \mathbf{M}(t) = \hat{\mathbf{M}}_T(t) \quad \forall \quad t \in [0,T]\right\} \quad . \tag{59}$$

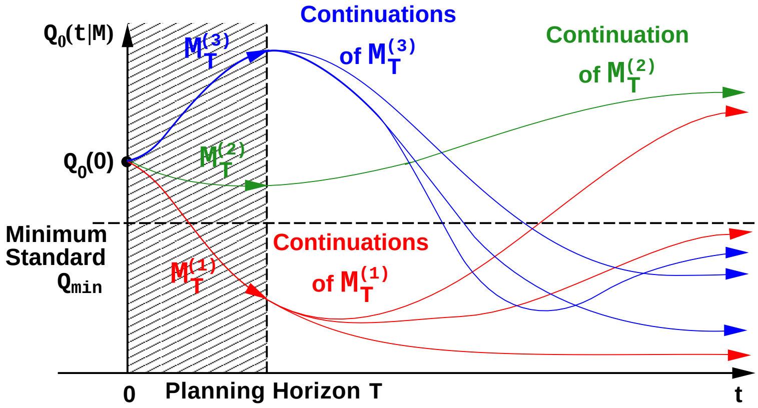


Figure 18. Time development of coevolution progress measure $Q_0(t \mid \mathbf{M})$ for a number of possible management sequences. According to the Standardization paradigm the coevolution segments generated by the management episodes $\mathbf{M}_T^{(2)}$ and $\mathbf{M}_T^{(3)}$, respectively, are admissible – at least with respect to the controllable initial time window. However, note that all available continuations of $\mathbf{M}_T^{(3)}$ ultimately violate the standard, so this management episode leads directly into a dead-end street. The episode $\mathbf{M}_T^{(2)}$, on the other hand, possesses at least one admissible continuation and therefore generates a "sustainable" coevolution segment.

Evidently, we have

$$\mathfrak{M}(\hat{\mathbf{M}}_T) \subset \mathfrak{M} \tag{60}$$

and – again applying the time invariance of $\mathfrak{M}$ -

$$\mathfrak{M}(\hat{\mathbf{M}}_T) = \left\{ \mathbf{M} \in \mathfrak{M} \middle| \mathbf{M}(t) = \left\{ \begin{array}{lll} \hat{\mathbf{M}}_T(t), & 0 & \leq t \leq T \\ \tilde{\mathbf{M}}(t-T), & T & < t, \text{with arbitrary } \tilde{\mathbf{M}} \in \mathfrak{M} \end{array} \right\} \right. . \tag{61}$$

In addition, we introduce the entity $\mathfrak{M}_T^*$ of all *management episodes compatible with* $\mathcal{P}_0$, i.e.,

$$\mathfrak{M}_T^* := \left\{ \mathbf{M}_T \in \mathfrak{M}_T \middle| Q_{min} \leq Q_0[\mathbf{P}(t \mid \mathbf{M}_T)] \quad \forall \quad t \in [0,T] \right\} \quad , \tag{62}$$

and the set $\mathfrak{M}^*$ of all (infinite) *management sequences compatible with* $\mathcal{P}_0$, i.e.,

$$\mathfrak{M}^* := \left\{ \mathbf{M} \in \mathfrak{M} \middle| Q_{min} \leq Q_0[\mathbf{P}(t \mid \mathbf{M})] \quad \forall \quad t \geq 0 \right\} \quad . \tag{63}$$

Then the following obvious observation can be made:

$$\mathfrak{M}^* \subset \bigcup_{\mathbf{M}_T^* \in \mathfrak{M}_T^*} \mathfrak{M}(\mathbf{M}_T^*) \quad . \tag{64}$$

If we finally define the set $\mathfrak{M}^*(\mathbf{M}_T^*)$ of *admissible continuations of management episodes complying with* $\mathcal{P}_0$, i.e.,

$$\mathfrak{M}^*(\mathbf{M}_T^*) := \left\{ \mathbf{M} \in \mathfrak{M}(\mathbf{M}_T^*) \middle| Q_{min} \leq Q_0[\mathbf{P}(t \mid \mathbf{M})] \quad \forall \quad t > T \right\} \quad , \tag{65}$$

then we even have the identity

$$\mathfrak{M}^* = \bigcup_{\mathbf{M}_T^* \in \mathfrak{M}_T^*} \mathfrak{M}^*(\mathbf{M}_T^*) \quad . \tag{66}$$

The last relation reflects the evident fact that admissible (infinite) management sequences can only be generated from admissible management episodes.

We are now ready to formulate precisely the term "sustainability" in the sense of a Standardization paradigm. In doing so, we make a fundamental distinction between a "sustainable path segment" and a "sustained path".

Definition 4: A coevolution path segment $\mathbf{P}_T(t \mid \hat{\mathbf{M}}) \equiv \mathbf{P}_T(\mathbf{P}_0, 0; t \mid \hat{\mathbf{M}})$ is called *sustainable* if it is

(i) generated from an admissible management episode, i.e.,

$$\hat{\mathbf{M}}_T \equiv \hat{\mathbf{M}}\big|_{[0,T]} \in \mathfrak{M}_T^* \quad , \tag{67}$$

and

(ii) continuable in an admissible way, i. e.,

$$\mathfrak{M}^*(\hat{\mathbf{M}}_T) \neq \emptyset \quad . \tag{68}$$

A coevolution path $\mathbf{P}(t \mid \hat{\mathbf{M}}) \equiv \mathbf{P}(\mathbf{P}_0, 0; t \mid \hat{\mathbf{M}})$ is called *sustained* if it is generated from an admissible management sequence, i.e.,

$$\hat{\mathbf{M}} \in \mathfrak{M}^* \quad . \tag{69}$$

■

When scrutinizing an environmental system to be controlled, it will generally be relatively simple to identify the elements of $\mathfrak{M}_T^*$, i.e., the management episodes admissable over the short or the medium term. The task becomes significantly more difficult, as a rule, for the admissable continuations, and $\mathfrak{M}^*(\mathbf{M}_T^*)$ will probably be void for most of the episodes $\mathbf{M}_T^* \in \mathfrak{M}_T^*$! Only a brute-force long-term analysis can supply really dependable information here, but this requires that the dynamic equations (17) are integrated for all possible continuations of the management episodes from $\mathfrak{M}_T^*$. This is only possible, though, if the "teleological horizon" is extented, based on valid simulation models of coevolution (see Sect. 5), substantially beyond the actual planning horizon.

Definition 5: The path segment $\mathbf{P}_T(t \mid \mathbf{M}_T^*)$ generated by $\mathbf{M}_T^* \in \mathfrak{M}_T^*$ is called *sustainable to degree x*, where $x \in (0, 1]$, if a fraction x of all possible continuations is admissible, i.e., the sub-set $\mathfrak{M}^*(\mathbf{M}_T^*) \subset \mathfrak{M}(\mathbf{M}_T^*)$ has the relative weight x.

$\mathbf{P}_T(t \mid \mathbf{M}_T^*)$ is called *absolutely sustainable* if all possible continuations are admissible, i.e., $\mathfrak{M}^*(\mathbf{M}_T^*) = \mathfrak{M}(\mathbf{M}_T^*)$.

Evidently, an absolutely sustainable path segment is sustainable to degree 1. ■

As a matter of fact the expression "sustainable to degree x" may have a great deal of practical significance, because the management episodes selected by future generations cannot be predicted with certainty.

There is, by the way, a trivial option to guarantee "sustainable coevolution" in the sense of the Standardization paradigm. In order to achieve this one "only" has to push the planning horizon arbitrarily far ahead, i.e., $T \to \infty$, and prescribe an explicit, complete management sequence $\mathbf{M}^*(t)$, which ensures the compliance with the desired standards for all times! *Per constructionem*, each segment of the associated coevolution path is then sustainable.

This extreme version of $\mathcal{P}_0$ may already be qualified as the "*Desideration paradigm*", because it is by no means clear for a complex environmental system – and certainly even less so for the Earth System – whether a suitable $\mathbf{M}^*$ exists or how it is to be determined. However, even if the latter problems could be solved, such a "10,000-years plan" would fundamentally contradict all our ideas of freedom and personal responsibility. The "true" SD paradigms to be introduced in the next subsections undoubtedly also have a greater "ethical value".

4.2 Optimization

The SD paradigm to be discussed in this section represents the classic example of a *fundamental teleological strategy*, which fully accounts for the internal systems dynamics. After all, the seemingly perfect physical world view of the 19th century was founded almost exclusively on the axiom that "nature" indeed singles out motions of the type *that optimize certain functionals over the long term.* The differential equations for the dynamics of the respective mechanical system to be described result in a straightforward manner from this "Hamiltonian Variational Principle" (see, *Goldstein*, 1982 [89]).

In the same spirit, the "*Optimization paradigm*" $\mathcal{P}_1$ requires from controlled coevolution "simply" the *maximization of generalized utility* over the prescribed time periods. The "utility" or "benefit" is hereby defined in a *normative* way from social preferences via innumerable acts and interactions of individual volition. The notion itself, as well as the possibilities for operationalizing it, play an important role in the scientific developments of the modern age – ranging from the philosophically-based "Utilitarianism" of J. Bentham and J. S. Mill to "Game Theory" (*von Neumann*, 1944 [244]) and the modern political-economic theory of "Rational Choice" (see, e.g., *Kirsch*, 1993 [122], and references therein). However, however the generalized utility may be determined, the paradigm $\mathcal{P}_1$ reflects a fundamental constant of human motivation, namely "*wanting the best*".

With respect to our geo-cybernetic task, this means that we have to select *optimal management sequences* $\mathbf{M}^* \in \mathfrak{M}$. They have to maximize some total coevolutionary utility that may be defined via the already familiar "environmental-economic Lagrange function" $L(\mathbf{P})$ (see Eq. 34). Let us begin with a few examples for potential concrete maximization rules:

Example 1 ("Canonical Optimization"):

For an arbitrarily-chosen planning horizon $T > 0$, the management episode $\mathbf{M}_T^*(t)$ is to be selected in order to maximize the *functional*

$$I\left[\mathbf{P}(\mathbf{M}_T)\right] := \int_0^T L(\mathbf{P}(t \mid \mathbf{M}))dt \quad , \tag{70}$$

i.e.,

$$I\left[\mathbf{P}(\mathbf{M}_T)\right] \leq I\left[\mathbf{P}(\mathbf{M}_T^*)\right] \quad \text{for all} \quad \mathbf{M} \in \mathfrak{M}_T \quad . \tag{71}$$

Under certain conditions (see below), this variational task has a unique solution for each T; the limit $T \to \infty$ then generates the optimal management sequence $\mathbf{M}^*(t) \in \mathfrak{M}$, which incorporates all episodes.

We point out that such a canonical optimization, which represents the most simple realization of the general SD paradigm $\mathcal{P}_1$, plays a major role in the current debate confronting environment and economics. This applies above all to the various *integrated assessment* studies on the global climate problem (*Kaya* et al., 1993 [120]; *Nakićenović* et al., 1994 [160] *Nakićenović* et al., 1996 [161]). As an example, *Nordhaus*'s [165] DICE model is based on Ramsay's theory of optimal economic growth (see, e.g., *Intriligator*, 1971 [110]).

Example 2 ("Optimal Outcome"):

As an alternative to the maximization of the integral (= mean) utility over a longer planning period, an optimization of the environmental-economic quality *at the end of this period* might be considered. Temporary drawbacks are accepted within the framework of such a *"per aspera ad astra"* strategy, if only the target utility can be increased.

This is formally achieved by selecting for a given planning horizon $T \gg 0$ a $\mathbf{M}_T^* \in \mathfrak{M}_T$ in such a way that

$$L\left(\mathbf{P}(T \mid \mathbf{M}_T)\right) \leq L\left(\mathbf{P}(T \mid \mathbf{M}_T^*)\right) \quad \text{for all} \quad \mathbf{M}_T \in \mathfrak{M}_T \quad . \tag{72}$$

A geo-cybernetic strategy that is optimal in this sense would, for example, do without economic growth rates that are maximal due to the exploitation of non-renewable natural resources in the first decades of the next century, in order to obtain, in return, a coevolution level that is all the higher in the year 2100, say. The opinion prevails among most economists, though, that canonical optimization also ensures the optimal outcome *at all times*. For the justification of this opinion, the so-called "discount rate" (see, for instance, *Samuelson* and *Nordhaus* (1995) [204]) plays a role that is almost as mysterious as the part of Einstein's "cosmological constant" in the physical theory of the development of the Universe ...

Example 3 ("Qualified Optimization"):

The rigorous optimization goals pursued in the above examples can be moderated through a number of *boundary conditions*, that will bring to bear especially the ecological or social aspects involved. We may, for instance, consider the following type of auxiliary conditions:

(i)

$$L_{min} \leq L\left(\mathbf{P}(t \mid \mathbf{M})\right) \quad \text{for all} \quad t \geq 0; \tag{73}$$

(ii)

$$N_{min} \leq N_i(t \mid \mathbf{M}), \quad A_{min} \leq A_j(t \mid \mathbf{M}) \quad \text{for all } t \geq 0 \ , \tag{74}$$

where the indices i and j designate specific variables of the ecosphere and the anthroposphere, respectively.

Because of the introduction of such "constraints", the Optimization paradigm is enriched with Standardization elements. We will discuss the *blending* of fundamental SD strategies, which turns out to be most significant in practice, rather broadly in the concluding Sect. 4.6.

* * *

There exists a highly-developed mathematical theory for the solution of *dynamic optimization tasks* of the type just considered, i.e., for the determination of the "best" management sequences $\mathbf{M}^*(t)$. This theory is associated above all with the names of Lagrange, Bolza, Mayer, Pontryagin and Bellman, and it provides necessary and sufficient conditions, respectively, for the existence and uniqueness of the optimal control functions. The corresponding bulk of wisdom primarily applies to *deterministic* problems only, however, – the theory of *stochastic* optimization has certainly made a lot of progress in recent decades, but is still restricted to the supply of efficient search algorithms, in the best case (see, e.g., *Fleming* and *Rishel*, 1975 [72]; *Papageorgiou*, 1991 [171]). Furthermore, the quantities involved have to satisfy *regularity requirements* that are relatively demanding: continuity, differentiability, convexity, etc. We will briefly compile in the following the *necessary* conditions for the solution of a dynamic optimization task that

(a) fulfills the mathematical requirements just mentioned and
(b) fits the spirit of the geo-cybernetic paradigm $\mathcal{P}_1$, within the framework of our illustrative formalization.

Our description will borrow from *Cesari*'s [41] excellent monography.

Mathematical Excursion - the necessary conditions for Mayer problems of optimal control: Let t_1, t_2 be successive points in time, i.e., $t_1 < t_2$. Let $x(t) = \left(x^1(t), \ldots, x^n(t)\right)$ be the systems (vector) variable in question and $u(t) = \left(u^1(t), \ldots, u^m(t)\right)$ the control (vector) variable, which can be chosen from a set $U(t)$. x and u have to satisfy the set of *differential equations*

$$\frac{dx^i}{dt} = f_i\left(x(t), u(t), t\right), \quad i = 1, \ldots, n \ , \tag{75}$$

and certain boundary conditions. An *optimal pair* $(x_*(t), u_*(t))$ is searched for which *minimizes the Mayer functional*

$$I[x, u] = g\left(t_1, x(t_1), t_2, x(t_2)\right) \ , \tag{76}$$

where g is an appropriate real-valued function.

In other words,

$$I[x_*, u_*] \leq I[x, u] \tag{77}$$

for all admissible pairs (x, u). (Note that minimization is equivalent to maximization here as g may be replaced by $-g$ without loss of generality.)

Let $\lambda(t) = \left(\lambda^1(t), \ldots, \lambda^n(t)\right)$ be an auxiliary vector (of "*Lagrange multipliers*") and

$$H(x, u, \lambda, t) := \sum_{i=1}^{n} \lambda^i f_i(x, u, t) \tag{78}$$

an auxiliary real-valued function ("*Hamiltonian*").

Finally let R be the *infimum of* H if the latter is considered as a function of u only, i.e.,

$$R(x, \lambda, t) := \inf_{u \in U} H(x, u, \lambda, t) \quad . \tag{79}$$

Then the optimal pair (x_*, u_*) necessarily has the following properties:

1.
$$\frac{d\lambda^i}{dt} = -\frac{\partial H}{\partial x_*^i} \left(x_*(t), u_*(t), \lambda(t), t\right) \quad . \tag{80}$$

   Note that we evidently also have

$$\frac{dx_*^i}{dt} = \frac{\partial H}{\partial \lambda^i} \quad . \tag{81}$$

   The combined set of differential relations form the so-called "*canonical equations*" of the optimization problem.

2.
$$R(x_*, \lambda, t) = H(x_*(t), u_*(t), \lambda(t), t) \quad \text{for all} \quad t \in [t_1, t_2] \quad . \tag{82}$$

3.
$$\frac{dR}{dt}(x_*(t), \lambda(t), t) = \frac{\partial H}{\partial t} \left(x_*(t), u_*(t), \lambda(t), t\right) \quad . \tag{83}$$

4. A "*transversality condition*" is satisfied, i.e.,

$$\lambda^0 \, dg + \left[R(t) \, dt - \sum_{i=1}^{n} \lambda^i(t) \, dx_*^i \right]_1^2 = 0 \quad , \tag{84}$$

   where $\lambda^0 \geq 0$ is some constant and the variations of t and x_* at the "end events" have to comply with the boundary conditions. ■

In addition to this important result, *sufficient* conditions for the existence and uniqueness of optimal solutions can be formulated in many cases. We refer here to the relevant literature, particularly to the outstanding Russian school of control theory.

Fig. 19 sketches the *ideal situation* for the geo-cybernetic paradigm $\mathcal{P}_1$, namely a situation where the optimal management sequence $\mathbf{M}^*_{(1)}(t)$ – and thus the optimal coevolution path $\mathbf{P}(t \mid \mathbf{M}^*_{(1)})$ – can be determined for all times ahead in an unambiguous way.

At a first glance, the Optimization paradigm appears to be an absolutely convincing fundamental strategy for Sustainable Development; however, we have only touched upon some basic difficulties relating to both *contents and methodology* yet. With respect to this the following comments apply:

(i) Generally speaking, it should be analytically difficult and politically almost impossible to define or impose *scalar* target values for optimization. This point is supported, for example, by the hot debate that developed during the production of the recent IPCC Report (*IPCC*, 1996 [108]) about the monetization of climate impacts: is it possible (or acceptable) to trade off, say, human lives against consumer goods – and if so, to monetize at geographically varying "exchange rates" (*Fankhauser*, 1995 [67])? Geo-cybernetics will therefore not be able to rest on a "simple" environmental-economic Lagrange function; it will have to face within the framework of the paradigm $\mathcal{P}_1$ the complex problem of "*multi-objective optimization*" (see, e.g., *Bell* et al., 1977 [17]). We will look more closely at some of the main aspects of this problem in Sect. 4.6.

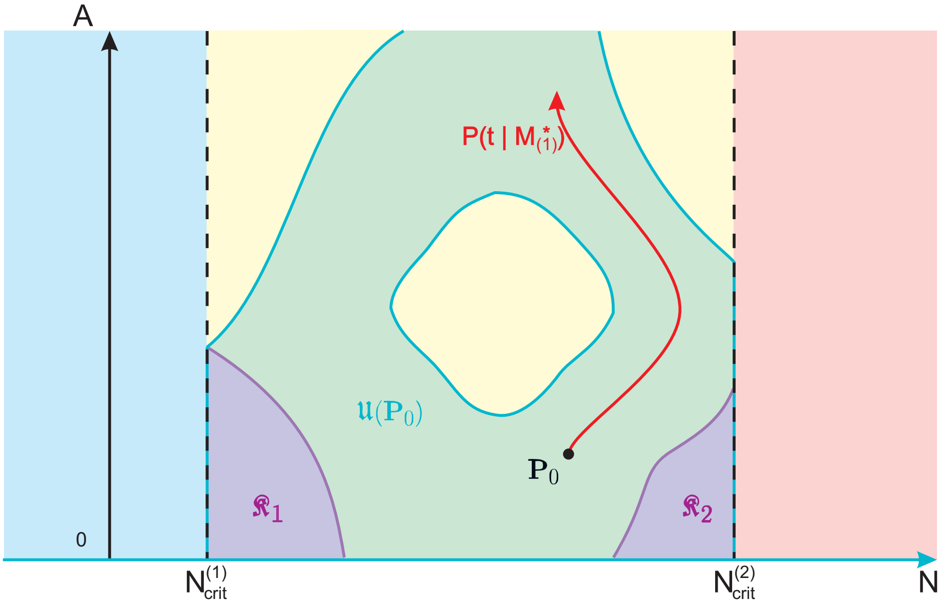


Figure 19. Unique optimal coevolution path $\mathbf{P}(t \mid \mathbf{M}^*_{(1)})$ according to one possible realization of the SD paradigm $\mathcal{P}_1$ within our caricatural Earth System.

(ii) If we nonetheless succeed in defining and providing all the necessary mathematical quantities, then the particular features of the optimization problem under consideration may permit the derivation of *local*, i.e., differential conditional equations for the desired solution (see Mathematical Excursion above). Actually finding the solution can then become an extremely labour-intensive and slow business, however. Even if this most favourable case should apply, there is no guarantee that the solutions determined from local equations are also *globally* optimal. Here particular attention has to be paid to the sufficient conditions for existence and uniqueness. Otherwise one runs the risk that short-term optimal management episodes are automatically seen as initial segments of the desired management episode for a considerably wider planning horizon. However, for $T_2 > T_1$, the following may apply:

$$\mathbf{M}^*_{T_2}(t) \mid_{[0,T_1]} \not\equiv \mathbf{M}^*_{T_1}(t) \quad . \tag{85}$$

In other words, it may happen that for an optimal coevolution with respect to a large time window, a *completely different* control option should be chosen than for the short-term maximization of utility (in this connection, see also the discussion in the previous section).

We illustrate this problem by an extremely simple *mechanical example*:
Let us consider a charged particle of mass m, which is moving in one dimension under the combined influence of a local electrostatic force f and a spatially homogeneous but time-dependent control force u. If $x \equiv x(t)$ denotes the instantaneous position of the particle, then its dynamics is governed by the differential equation

$$m\ddot{x} = f(x) + u(t) \quad . \tag{86}$$

We assume that the control force u is restricted to a finite interval, namely

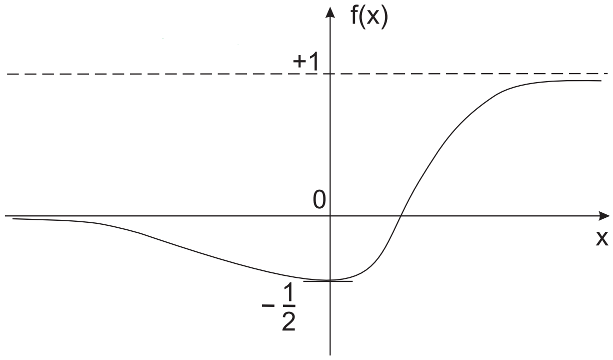
$$u \in [-1, 1] \quad . \tag{87}$$

The optimization task is to maximize the kinetic energy,

$$E = \frac{m}{2}\dot{x}^2 \quad , \tag{88}$$

for a given planning horizon $T > 0$ under the restrictions (initial conditions)

$$x(0) = \dot{x}(0) = 0 \quad . \tag{89}$$



Suppose now that $f(x)$ has the following (approximate) shape:
It is then clear, without any explicit calculation, what the optimal control force $u(t)$ has to look like: For small planning horizon $T = T_1$ we will have to choose

$$u(t) = -1 \quad \text{for all} \quad t \in [0, T_1] \ , \tag{90}$$

while for large $T = T_2 \gg T_1$ we must pick

$$u(t) = +1 \quad \text{for all} \quad t \in [0, T_2] \ . \tag{91}$$

Note that the short-term strategy is obviously not compatible with the long-term one, so at a certain time horizon, $T = T_{crit}$, the optimal control *history* will have to change abruptly!

(iii) Even in the ideal situation sketched in Fig. 19, where the globally optimal coevolution path can be uniquely determined for all times, the fundamental strategy $\mathcal{P}_1$ may not be without problems: an optimal result is namely utterly dependent on perfect control, which means within our geo-cybernetic context above all the long-term *self-control* of the Global Subject $\mathcal{S}$. But what happens in the case of episodic excursions from the ideal control scheme? How far will the Earth System then deviate from the optimal course, which may lead terrifyingly close to inhospitable regions or even catastrophe domains? This problem is one of the main motivations for an alternative paradigm to "Optimization", as described in the next section.

4.3 Pessimization

The Optimization paradigm for Sustainable Development is supported by a fundamentally *optimistic* attitude that assumes that the best possible coevolution can be actually realized under all circumstances. This requires a more or less *perfect base of knowledge* and a *"secular"* discipline, so to speak, of the Global Subject in the form of a coherent, collective volition process extending over many communicating generations. Everybody who tends to be more *pessimistic* will have strong doubts about the realization of such ideal requirements and, in contrast, will lean towards a fundamental strategy that practically represents the opposite position to the Optimization paradigm. The core of this fundamental SD strategy $\mathcal{P}_2$, which we want to call the *Pessimization paradigm*, is the elementary precautionary principle of "*preventing the worst*". Thus, if one wants to guarantee the smallest possible amount of damage instead of the greatest possible benefit, then the "optimal" coevolution path $\mathbf{P}(t \mid \mathbf{M}^*_{(1)})$ in Fig. 19, for example, is taboo: it runs much too close along the catastrophe domain $\mathfrak{K}_2$, and the mismanagement of intermediate generations could lead directly to disaster ...

The pessimization paradigm $\mathcal{P}_2$, in comparison, strives for the greatest possible safety vis-à-vis human failure and whims of nature in every form. In view of Murphy's (semi-humorous) Law "Everything that can go wrong, will go wrong!", $\mathcal{P}_2$ may be qualified as the *"Anti-Murphy Strategy of SD"*. This strategy will attempt under all circumstances to avoid *disastrous coevolution paths*, i.e., paths that lead directly into catastrophe domains. But it will, moreover, shy away from *potentially disastrous coevolution paths*: these are developments that do not themselves terminate in catastrophe domains, yet support sufficiently many *disastrous by-paths* as generated by slight modifications of the management sequence. We will discuss, in the following, several ways of operationalizing $\mathcal{P}_2$ which differ considerably in sophistication.

Example 1 ("Minimax Strategy"):

The main prerequisite here is the existence of a *damage functional* $D[\mathbf{P}(\mathbf{M})]$. The latter calculates the "maximum damage" for each and every $\mathbf{M} \in \mathfrak{M}$, and the associated coevolution path $\mathbf{P}(\mathbf{M})$ generated through this. The computation may involve, for example, the *lowest value of the environmental-economic Lagrange function L* as realized by $\mathbf{P}(\mathbf{M})$ or the *duration of violating the stipulated standards* for certain ecosphere and/or anthroposphere variables. The "pessimal" management sequence $\mathbf{M}^*_{(2)}(t)$ is then defined to be that element of $\mathfrak{M}$ which *minimizes the maximum damage*, i.e.,

$$D[\mathbf{P}(\mathbf{M}^*_{(2)})] \leq D[\mathbf{P}(\mathbf{M})] \quad \text{for all} \quad \mathbf{M} \in \mathfrak{M} \quad . \tag{92}$$

This is a well-known strategy from game or decision theory (see, e.g., (*Kreyszig*, 1991 [125]; *Binmore*, 1990 [24]). In the form described here, the scheme is less a "true" variant of the Pessimization paradigm, than rather an optimization strategy in disguise: disastrous paths are, in fact, ruled out with certainty, but not *potentially* disastrous ones. Thus the target damage has been minimized but not the *risk* !

Example 2 ("Strong Anti-Murphy Strategy"):

In the case of the "genuine" Anti-Murphy strategy for risk confinement, a "game" is played against the inability or disinformation of the coming generations. In the most favourable case, a coevolution course can be taken such that *even foolish management will have no chance of wreaking havoc at a later point in time* ... We are explicitly assuming here a perfectly foreseeable and therefore particularly deterministic Earth System, which is only subject to the voluntative uncertainty associated with the will of the Global Subject (see also Sect. 6).

For the illustrative description of the pertinent management principle, we will focus on one specific catastrophe domain $\mathfrak{K} \subset \mathfrak{U}(\mathbf{P}_0)$, e.g., on $\mathfrak{K}_2$ in Fig. 15. We introduce the set $\mathfrak{U}^{-1}(\mathfrak{K})$, the *basin of access to* $\mathfrak{K}$, which will serve as the counterpart to the accessible universe $\mathfrak{U}(\mathfrak{K})$ associated with the set $\mathfrak{K}$:

$$\mathfrak{U}^{-1}(\mathfrak{K}) := \{\mathbf{P} \in \mathfrak{U}(\mathbf{P}_0) \mid \mathfrak{U}(\mathbf{P}) \cap \mathfrak{K} \neq \emptyset \} \quad , \tag{93}$$

i.e., $\mathfrak{U}^{-1}(\mathfrak{K})$, is the set of all points $\mathbf{P}$ in the geo-cybernetic universe $\mathfrak{U}(\mathbf{P}_0)$ from which the catastrophe domain $\mathfrak{K}$ can be actually reached through (mis-)management.

Evidently, we have

$$\mathbf{P}_0 \in \mathfrak{U}^{-1}(\mathfrak{K}) \quad , \tag{94}$$

due to the assumption $\mathfrak{K} \subset \mathfrak{U}(\mathbf{P}_0)$.

This does *not* necessarily mean, though, that $\mathfrak{U}(\mathbf{P}_0)$ is identical with $\mathfrak{U}^{-1}(\mathfrak{K})$. For the sake of feasibility of our strong Anti-Murphy strategy, we will, in fact, presume that

$$\mathfrak{U}^{-1}(\mathfrak{K}) \neq \mathfrak{U}(\mathbf{P}_0) \quad , \tag{95}$$

i.e., $\mathfrak{U}^{-1}(\mathfrak{K})$ is a *true sub-set* of $\mathfrak{U}(\mathbf{P}_0)$.

This is certainly only possible if the geo-cybernetic dynamics ("physical" Earth System dynamics + management) *is not perfectly reversible.* Otherwise, one could return from every point $\hat{\mathbf{P}}$ in $\mathfrak{U}(\mathbf{P}_0)$ to $\mathbf{P}_0$ and subsequently reach $\mathfrak{K}$. Fig. 20 gives a non-trivial example for such a situation within the framework of our hydrographic illustration of geo-cybernetics (see Fig. 12).

Under the conditions just specified, an efficient Anti-Murphy strategy might be designed as follows:

(i) *Determine* by brute-force scanning of $\mathfrak{U}^{-1}(\mathbf{P}_0)$ and $\mathfrak{M}$, through inverse integration of the dynamics (an example in a different context is given by *Kappertz* et al., hjs:Kappertz.1994 [**?**], via careful inspection of the reversibility conditions, or by alternative techniques the *basin of access* to $\mathfrak{K}, \mathfrak{U}^{-1}(\mathfrak{K})$. Special attention has to be directed to the identification of the boundaries of $\mathfrak{U}^{-1}(\mathfrak{K})$: beyond these lines even the silliest or most irresponsible management episodes cannot give rise to disaster any more!

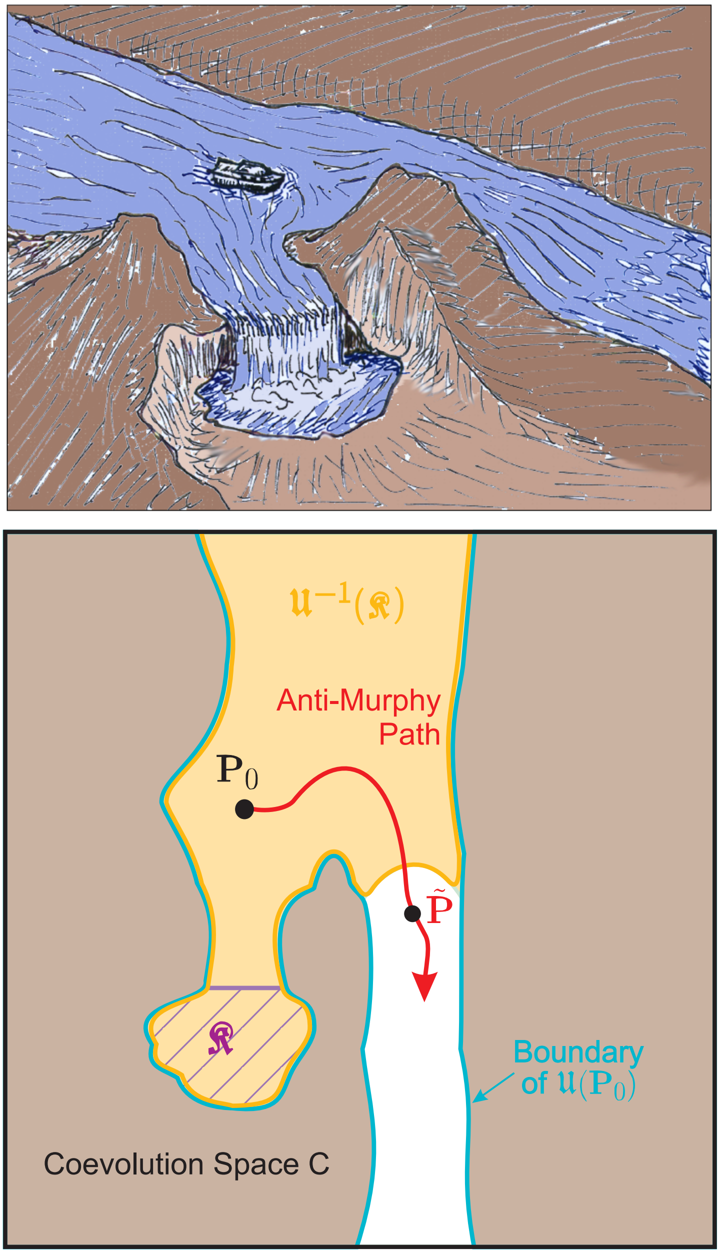


Figure 20. Allegoric representation of a geocybernetic situation where the strong Anti-Murphy strategy works. **(a)** Boat situated upstream of a river bifurcation. Depending on the actual steering, the vessel will either enter the disastrous path towards the waterfall, or the tolerable path through the rapids. The propulsion of the boat is assumed to be too weak to cross the rapids against the current. **(b)** Translation of the real constellation into the abstract two-dimensional coevolution space. Note that $\mathfrak{U}^{-1}(\mathfrak{K})$ is a true sub-set of $\mathfrak{U}(\mathbf{P}_0)$, so there are management sequences which will steer the stystem in question forever away from the basin of access to $\mathfrak{K}$ (towards the point $\tilde{\mathbf{P}}$, for instance).

(ii) *Determine* the set $\mathfrak{M}_{(2)}$ of all management sequences $\mathbf{M}_{(2)}(t) \in \mathfrak{M}$, which will bring the coevolution state ultimately out of the basin of access to $\mathfrak{K}$. Each coevolution path $\mathbf{P}(t \mid \mathbf{M}_{(2)}) \equiv \mathbf{P}(\mathbf{P}_0, 0; t \mid \mathbf{M}_{(2)})$ generated by such a management sequence will be called an *Anti-Murphy path* and is acceptable from the point of view of the Pessimization paradigm.

(iii) As a more sophisticated option, *determine* those $\mathbf{M}^*_{(2)} \in \mathfrak{M}_{(2)}$ which minimize the time for reaching the boundary of $\mathfrak{U}^{-1}(\mathfrak{K})$ from the starting point $\mathbf{P}_0$. $\mathbf{M}^*_{(2)}$ may be unique under certain conditions and will then be called the *best Anti-Murphy management*. The associated entity $\mathbf{P}(t \mid \mathbf{M}^*_{(2)})$ will be referred to as the *best Anti-Murphy path* or the "pessimal coevolution path".

Example 3 ("Weak Anti-Murphy Strategy"):

The strong Anti-Murphy strategy sketched above tries to nullify the coevolutionary risk of running into a catastrophe domain. Such a perfect risk avoidance may not be feasible under the conditions to be taken into account. For example, it may turn out that

$$\mathfrak{U}^{-1}(\mathfrak{K}) = \mathfrak{U}(\mathbf{P}_0) \tag{96}$$

or, at least,

$$\bigcup_j \mathfrak{U}^{-1}(\mathfrak{K}_j) = \mathfrak{U}(\mathbf{P}_0) \quad , \tag{97}$$

where the index j counts all the catastrophe domains actually involved. Under circumstances of that type, a short-term "pessimal" management for establishing *long-term absolute* security against disastrous life conditions *cannot* be realized.

Furthermore, even if the available "safety belt" is non-void but *very small*, i.e.,

$$\mathfrak{U}(\mathbf{P}_0) \setminus \mathfrak{U}^{-1}(\mathfrak{K}) \quad \approx \quad \emptyset \quad , \tag{98}$$

$$\text{resp.} \quad \mathfrak{U}(\mathbf{P}_0) \setminus \bigcup_j \mathfrak{U}^{-1}(\mathfrak{K}_j) \quad \approx \quad \emptyset \quad , \tag{99}$$

then the hope for a more or less riskless shaping of the future may remain an illusion: the *precision control* of coevolution, necessary under these conditions, may not be realizable in practice.

In adverse situations of the types just described, geo-cybernetic actions within the Pessimization paradigm must aim at steering the coevolution as long as possible or necessary through those subdomains of $\mathfrak{U}(\mathbf{P}_0)$ from which disaster ranges might be approached by rather *drastic mismanagement* only. Thus, this kind of *weak or relative Anti-Murphy Strategy* is trying to minimize the *unavoidable* residual risk. Evidently, the underlying principle also applies to the initial component of any strong Anti-Murphy strategy in the sense of a tactical element, especially when the road from the starting point $\mathbf{P}_0$ to the security zone is very long or tortuous.

For the precise description of the weak Anti-Murphy strategy some further formal elements are required.

Definition 6: Let $x \in [0,1]$ and assume that systems dynamics and the management pool do not depend explicitly on time. The *x-risk environment* of $\mathfrak{K}$, symbolized by $\mathfrak{R}_x(\mathfrak{K})$, is defined as follows:

$$\mathfrak{R}_x(\mathfrak{K}) := \{\mathbf{P} \in \mathfrak{U}(\mathbf{P}_0) \mid \text{A fraction } y \geq x \text{ of all possible management sequences } \mathbf{M} \text{ connects } \mathbf{P} \text{ with } \mathfrak{K}\}. \tag{100}$$

The *complement* of $\mathfrak{R}_x(\mathfrak{K})$ in $\mathfrak{U}(\mathbf{P}_0)$ will be called the *x-safety zone with respect to* $\mathfrak{K}$ and symbolized by $\mathfrak{S}_x(\mathfrak{K})$. Thus

$$\mathfrak{S}_x(\mathfrak{K}) := \mathfrak{U}(\mathbf{P}_0) \setminus \mathfrak{R}_x(\mathfrak{K}) \quad . \tag{101}$$

Each point in $\mathfrak{S}_x(\mathfrak{K})$ therefore has the property that only a fraction z of all possible management sequences $\mathbf{M} \in \mathfrak{M}$ connects this point to $\mathfrak{K}$, and z is *smaller* than x. ■

Several *technical remarks* concerning these definitions seem to be in order:

(i) The expression "fraction of all possible management sequences" will only have a precise meaning if a *measure* μ regarding the set $\mathfrak{M}$ has been declared (see for instance the classical treatise by *Halmos* (1974) [97]). Such a measure assigns a non-negative real number $\mu(\Omega)$ to each sub-set $\Omega \subset \mathfrak{M}$. Let $\mathfrak{M}(\tilde{\mathbf{P}} \mid \mathfrak{K})$ denote the sub-set of all management sequences which connect an arbitrary point $\tilde{\mathbf{P}} \in \mathfrak{U}(\mathbf{P}_0)$ to the catastrophe domain $\mathfrak{K}$, i.e., for each $\mathbf{M} \in \mathfrak{M}(\tilde{\mathbf{P}} \mid \mathfrak{K})$ there is a time $t(\mathbf{M}) < \infty$ such that

$$\mathbf{P}(\tilde{\mathbf{P}}, 0; t \mid \mathbf{M}) \in \mathfrak{K} \quad \text{for all} \quad t \geq t(\mathbf{M}) \quad . \tag{102}$$

Then the *fraction* of all possible management sequences contained in $\mathfrak{M}(\tilde{\mathbf{P}} \mid \mathfrak{K})$ is simply defined as

$$Fr(\tilde{\mathbf{P}} \mid \mathfrak{K}) := \frac{\mu(\mathfrak{M}(\tilde{\mathbf{P}} \mid \mathfrak{K}))}{\mu(\mathfrak{M})} \quad , \tag{103}$$

where we assume that $\mu(\mathfrak{M}) < \infty$.

Note that a naive computation of such a fraction by forming an aleatoric sequence $\mathbf{M}^{(1)}, \mathbf{M}^{(2)}, \mathbf{M}^{(3)}, \ldots$ of elements in $\mathfrak{M}$ and calculating the number of hits (= connection of $\tilde{\mathbf{P}}$ to $\mathfrak{K}$ actually achieved) divided by the number of trials is quite dubious here:

Generally $\mathfrak{M}$ is a *non-denumerable* set, so our aleatoric sequence may be absolutely irrepresentative! Therefore we have to resort to more sophisticated techniques like the functional integration methods employed in Feynman's formulation of quantum mechanics (*Feynman* and *Hibbs*, 1965 [71]). This topic, however, cannot be scrutinized in any depth within the scope of this essay.

(ii) In a sense, $Fr(\tilde{\mathbf{P}} \mid \mathfrak{K})$ measures how easily $\mathfrak{K}$ can be approached from $\tilde{\mathbf{P}}$ by (in-)appropriate management. As the latter exclusively depends on the will of the Global Subject $\mathcal{S}$, we may call $Fr(\tilde{\mathbf{P}} \mid \mathfrak{K})$ the strength of the *voluntative connectivity* between $\tilde{\mathbf{P}}$ and $\mathfrak{K}$. An overall topological structure of the coevolution space $\mathbf{C}$ can be induced along these lines by extending the notion of "voluntative connectivity" to arbitrary pairs $(\mathbf{P}_1, \mathbf{P}_2)$ of points in $\mathbf{C}$. Again, we refrain from investigating this intricate issue here.

(iii) Note that the definition of $\mathfrak{R}_x(\mathfrak{K})$ and $\mathfrak{S}_x(\mathfrak{K})$, respectively, directly implies

$$\mathfrak{R}_0(\mathfrak{K}) = \mathfrak{U}(\mathbf{P}_0) \tag{104}$$

$$\text{and} \quad \mathfrak{S}_0(\mathfrak{K}) = \mathfrak{U}(\mathbf{P}_0) \setminus \mathfrak{U}(\mathbf{P}_0) = \emptyset \quad . \tag{105}$$

For $x' > x$ we further have

$$\mathfrak{R}_x(\mathfrak{K}) \supset \mathfrak{R}_{x'}(\mathfrak{K}) \tag{106}$$

$$\text{and} \quad \mathfrak{S}_x(\mathfrak{K}) \subset \mathfrak{S}_{x'}(\mathfrak{K}) \ . \tag{107}$$

If we define

$$\mathfrak{r}_x(\mathfrak{K}) := \{\mathbf{P} \in \mathfrak{U}(\mathbf{P}_0) \mid \text{A fraction } x \text{ of all possible management sequences } \mathbf{M} \text{ connects } \mathbf{P} \text{ to } \mathfrak{K}\} \quad , \tag{108}$$

then the following relations obviously hold:

$$\mathfrak{R}_x(\mathfrak{K}) = \bigcup_{x \le z \le 1} \mathfrak{r}_z(\mathfrak{K}), \tag{109}$$

$$\mathfrak{r}_x(\mathfrak{K}) = \bigcap_{x < z \le 1} \mathfrak{R}_x(\mathfrak{K}) \setminus \mathfrak{R}_z(\mathfrak{K}) = \mathfrak{R}_x(\mathfrak{K}) \setminus \bigcup_{x < z \le 1} \mathfrak{R}_z(\mathfrak{K}). \tag{110}$$

We may say that a risk of degree x is associated with the "marginal set" $\mathfrak{r}_x(\mathfrak{K})$, while the risk associated with the set $\mathfrak{R}_x(\mathfrak{K})$ is *at least* of degree x!
Using the complementary definition just introduced, we further observe:

$$\mathfrak{U}(\mathbf{P}_0) \setminus \mathfrak{U}^{-1}(\mathfrak{K}) \subset \mathfrak{r}_0(\mathfrak{K}) \quad , \tag{111}$$

because no management whatsoever connects the "zone of absolute safety" (which may be void, however) to the catastrophe domain. However, note that (111) is not necessarily an equality, for $\mathfrak{r}_0(\mathfrak{K})$ may embrace additional sub-sets of $\mathfrak{U}(\mathbf{P}_0)$ which are connected to $\mathfrak{K}$ by management sets of measure zero.
We also have

$$\mathfrak{R}_1(\mathfrak{K}) = \mathfrak{r}_1(\mathfrak{K}) \tag{112}$$

$$\text{and} \quad \mathfrak{K} \subset \mathfrak{r}_1(\mathfrak{K}). \tag{113}$$

Here we emphasize that

$$\mathfrak{S}_1(\mathfrak{K}) \equiv \mathfrak{U}(\mathbf{P}_0) \setminus \mathfrak{R}_1(\mathfrak{K}) \tag{114}$$

is the sub-set of $\mathfrak{U}(\mathbf{P}_0)$, where the probability of picking at random a disastrous management sequence is at least less than unity!

The weak Anti-Murphy strategy can now be formulated as follows:

On the basis of societal demand analyses a $\hat{x} \in [0, 1]$ is selected, which defines the *maximum tolerable disaster risk.* The associated sub-set $\mathfrak{R}_{\hat{x}}(\mathfrak{K})$ of $\mathfrak{U}(\mathbf{P}_0)$ includes all points of the accessible universe that have a "*voluntative distance*" to $\mathfrak{K}$ of $1 - \hat{x}$ or smaller — at least a fraction $\hat{x}$ of all volitions select management sequences which drive the coevolution into $\mathfrak{K}$. $\mathfrak{S}_{\hat{x}}(\mathfrak{K})$ therefore represents the zone of relative security, i.e. the set of all points in $\mathfrak{U}(\mathbf{P}_0)$ from which management of arbitrary incompetence leads to disaster in an "acceptable" fraction of cases only. We assume now that

$$\mathbf{P}_0 \in \mathfrak{S}_{\hat{x}}(\mathfrak{K}) \ . \tag{115}$$

Then the strategic instruction – i.e., the operationalization of $\mathcal{P}_2$ – simply reads: Determine and employ an $\mathbf{M}_{(2|\hat{x})} \in \mathfrak{M}$ such that $\mathbf{P}(t \mid \mathbf{M}_{(2|\hat{x})})$ *develops entirely within the $\hat{x}$-safety zone* $\mathfrak{S}_{\hat{x}}(\mathfrak{K})$. This fundamental strategy provides, after all, a relatively reliable protection against human failure, i.e., against dramatically wrong decisions of future decision makers. The set of all weak Anti-Murphy managements will be symbolized by $\mathfrak{M}_{(2|\hat{x})}$, i.e.,

$$\mathfrak{M}_{(2|\hat{x})} := \left\{ \mathbf{M}_{(2|\hat{x})} \in \mathfrak{M} \mid \boldsymbol{\Pi}(\mathbf{P}_0, 0 \mid \mathbf{M}_{(2|\hat{x})}) \subset \mathfrak{S}_{\hat{x}}(\mathfrak{K}) \right\} \ . \tag{116}$$

The *feasibility* of this variant of the Pessimization paradigm is guaranteed by the following result.

Theorem: *The set $\mathfrak{M}_{(2|\hat{x})}$ of weak Anti-Murphy managements is not void if certain (mild) conditions are satisfied.*

The proof of this theorem will be presented elsewhere, since a number of technical considerations have to be worked out in detail. But let us sketch at least the basic lines of argumentation:

Let $\hat{\mathbf{P}} \in \mathfrak{S}_{\hat{x}}(\mathfrak{K})$, for instance $\hat{\mathbf{P}} = \mathbf{P}_0$, as presumed above. Choose an arbitrary time step $T > 0$ and consider the geo-cybernetic front $\mathfrak{U}(\hat{\mathbf{P}}; T)$, which is generated from the coevolution centre $\hat{\mathbf{P}}$ through the application of $\mathfrak{M}$. By definition (see Eqs. 25 and 29) we have

$$\tilde{\mathbf{P}} \in \mathfrak{U}(\hat{\mathbf{P}}; T) \ \Leftrightarrow \tilde{\mathbf{P}} = \mathbf{P}(\hat{\mathbf{P}}, 0; T \mid \tilde{\mathbf{M}}) \quad \text{for some} \ \ \tilde{\mathbf{M}} \in \mathfrak{M} \ . \tag{117}$$

Each point $\tilde{\mathbf{P}}$, in turn, is the origin of a bundle

$$\mathfrak{B}(\tilde{\mathbf{P}}; T) := \Big\{ \mathbf{P}(\tilde{\mathbf{P}}, T; t \mid \mathbf{M}) \mid \mathbf{M} \in \mathfrak{M} \Big\} \tag{118}$$

of continuations of the corresponding initial coevolution segment(s).

This means that the total set of all possible continuations of coevolution after time T is given by the collection

$$\bigcup_{\tilde{\mathbf{P}} \in \mathfrak{U}(\hat{\mathbf{P}}; T)} \mathfrak{B}(\tilde{\mathbf{P}}; T) \ . \tag{119}$$

Now let $x(\tilde{\mathbf{P}})$ denote the fraction of (management sequences that generate) paths in $\mathfrak{B}(\tilde{\mathbf{P}}; T)$ which will ultimately enter $\mathfrak{K}$. Assume that

$$x(\tilde{\mathbf{P}}) \geq \hat{x} \quad \text{for all} \quad \tilde{\mathbf{P}} \in \mathfrak{U}(\tilde{\mathbf{P}}; T). \tag{120}$$

This assumption obviously implies that an overall fraction $\tilde{x} \geq \hat{x}$ of *all* possible coevolution paths emanating from $\hat{\mathbf{P}}$ at time 0 – and passing through $\mathfrak{U}(\hat{\mathbf{P}}; T)$ at time T – will end in the catastrophe domain $\mathfrak{K}$. However, this is clearly *in contradiction* to the initial presumption that $\hat{\mathbf{P}}$ is an element of $\mathfrak{S}_{\hat{x}}(\mathfrak{K})$!

Hence there must exist at least one point $\hat{\hat{\mathbf{P}}} \in \mathfrak{U}(\hat{\mathbf{P}}; T)$ with $x(\hat{\hat{\mathbf{P}}}) < \hat{x}$, i.e., the fraction of disastrous coevolution paths (continuations) emerging from $\hat{\hat{\mathbf{P}}}$ is less than $\hat{x}$. So $\hat{\hat{\mathbf{P}}} \in \mathfrak{S}_{\hat{x}}(\mathfrak{K})$ by definition. Therefore, we can make the general statement that *each* coevolution front originating from *any* point in $\mathfrak{S}_{\hat{x}}(\mathfrak{K})$ contains at least one point in the $\hat{x}$-safety zone:

$$\mathfrak{U}(\hat{\mathbf{P}};T) \cap \mathfrak{S}_{\hat{x}}(\mathfrak{K}) \neq \emptyset\,, \quad \text{if} \quad \hat{\mathbf{P}} \in \mathfrak{S}_{\hat{x}}(\mathfrak{K})\ . \tag{121}$$

As the time step $T > 0$ can be chosen arbitrarily (small), we conclude that a complete coevolution path within $\mathfrak{S}_{\hat{x}}(\mathfrak{K})$ can be generated from the starting point $\hat{\mathbf{P}} \in \mathfrak{S}_{\hat{x}}(\mathfrak{K})$ by appropriate management. ■

If $\mathbf{P}_0 \notin \mathfrak{S}_{\hat{x}}(\mathfrak{K})$ then there are two possibilities to rescue the weak Anti-Murphy strategy:

(i) Reduce the safety standard, i.e., increase $\hat{x}$ until $\mathbf{P}_0$ lies within the corresponding safety zone.

(ii) Find and apply the management episode which establishes the minimum risk passage from $\mathbf{P}_0$ to $\mathfrak{S}_{\hat{x}}(\mathfrak{K})$. The "risk" associated with a given passage may be defined, for example, as the (properly normalized) time integral over $x(\mathbf{P}(t))$.

We have thus shown that the weak (or relative) Anti-Murphy strategy can be realized under the specified preconditions and restrictions. As mentioned above, this particular operationalization of $\mathcal{P}_2$ does usually not provide a unique management sequence and a corresponding unambiguous $\hat{x}$-safe coevolution path. Actually all management sequences in $\mathfrak{M}_{(2|\hat{x})}$ are allowed, and they generate the bundle of trajectories

$$\mathfrak{f}_{\hat{x}}(\mathfrak{K}) := \left\{ \boldsymbol{\Pi}(\mathbf{P}_0, 0 \mid \mathbf{M}_{(2|\hat{x})}) \mid \mathbf{M}_{(2|\hat{x})} \in \mathfrak{M}_{(2|\hat{x})} \right\} \quad . \tag{122}$$

We refer to $\mathfrak{f}_{\hat{x}}(\mathfrak{K})$ as *the $\hat{x}$-safely explorable universe with respect to* $\mathfrak{K}$, since this sub-set of $\mathfrak{U}(\mathbf{P}_0)$ embraces all those coevolution states which can be (or have to be) visited from $\mathbf{P}_0$ in consideration of the stipulated relative security standards.

We emphasize that

$$\mathfrak{f}_{\hat{x}}(\mathfrak{K}) \subset \mathfrak{S}_{\hat{x}}(\mathfrak{K}) \quad , \tag{123}$$

but the equality would generally not be true. It is easy to construct explicit examples of geo-cybernetic settings where some point in $\mathfrak{f}_{\hat{x}}(\mathfrak{K})$ cannot be reached from $\mathbf{P}_0$ by any managerial efforts – even if $\mathbf{P}_0 \in \mathfrak{S}_{\hat{x}}(\mathfrak{K})$.

The characteristics of the weak Anti-Murphy strategy are sketched in Fig. 21.

We should point once again to the fact that the statements made in this section so far are valid in the specified form only if the "eigen-dynamics" of the Earth System as well as the management pool $\mathfrak{M}$ are *not* explicitly time-dependent. Yet even if these preconditions are not satisfied, an analysis of the Pessimization paradigm is possible along the lines pursued above. The price to be paid, however, will be a significant complication of both the formalism and the deductive process.

We should also point out here that especially the weak Anti-Murphy variant of $\mathcal{P}_2$ evokes the risk of "*infinite regression*" (see e.g., *Popper*, 1992 [187], and Sect. 3): for to what degree of relative security can you actually realize a relatively secure path? With respect to the problem structure, we are here in the same situation as someone who has to cross an abyss on a slippery plank and who tries to keep as far as possible to the centre of the plank: how well can this person actually maintain a safe distance from the edges of that miserable bridge?

Therefore, the set $\mathfrak{M}_{(2|\hat{x})}$ of relative Anti-Murphy managements might, in turn, be subject to a relative Anti-Murphy analysis and one could, e.g., select those sequences which may be readjusted rather easily in case of voluntative deviations. However, to what degree can we then be secure that these corrections will be actually be implemented, and so on... As a matter of fact, this is just a theoretical and not really a practical problem: in the individual case, one simply has to decide how many steps in the security hierarchy one wants to take into account. Error tolerability with respect to mismanagement will, as a rule, rapidly grow with the regression level (see for this issue also Sect. 6).

Example 4 ("Probabilistic Pessimization"):

The general setting for the potential operationalizations of the Pessimization paradigm discussed so far involves considerably idealized assumptions regarding determinism, predictability and autonomy of the environmental system to be controlled. If we add some elements of realism to our analysis, then those assumptions have to be modified in at least two respects:

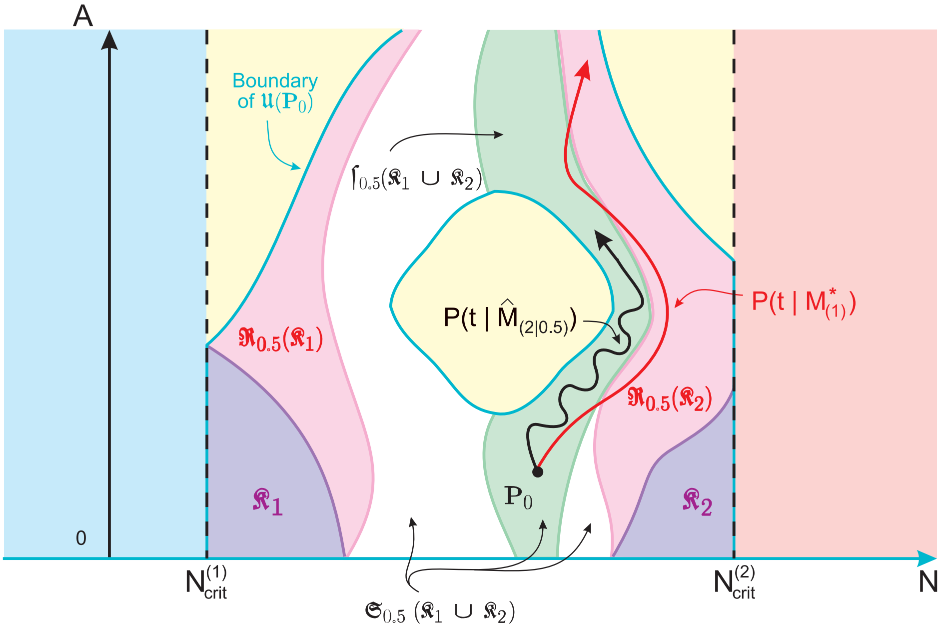


Figure 21. Cartoon of weak Anti-Murphy strategy as one possible variant of the SD paradigm $\mathcal{P}_2$. $\hat{x} = 0.5$ here; the 0.5-safety zone and the 0.5-safely explorable universe, respectively, refer to the union of catastrophe domains $\mathfrak{K}_1 \cup \mathfrak{K}_2$. In this example $\mathfrak{f}_{0.5}$ is a true sub-set of $\mathfrak{S}_{0.5}$. Note that the "optimal" coevolution path according to $\mathcal{P}_1$ from Fig. 19, $\mathbf{P}(t \mid \mathbf{M}^*_{(1)})$, trespasses into the 0.5-risk environment at least twice and is therefore forbidden by the Pessimization paradigm. By way of contrast, the management $\hat{\mathbf{M}}_{(2|0.5)}$ steers the "Earth System" as safely as required through coevolution space. The progress associated with $\mathbf{P}(t \mid \hat{\mathbf{M}}_{(2|0.5)})$ may be rather slow, however.

(i) A considerable *cognitive uncertainty* with respect to the system's components, processes and boundary conditions has to be taken into account.
(ii) The strongly inhomogeneous probability distribution for the realization of the various voluntative options associated with the elements in $\mathfrak{M}$ has to be considered.

When both these aspects are integrated into the paradigm $\mathcal{P}_2$ then Pessimization becomes, in essence, "a game against our descendants and against nature". Within the framework of this interpretation, the fundamental guiding principle may be operationalized, for instance, by assigning to each point $\hat{\mathbf{P}} \in \mathfrak{U}(\mathbf{P}_0)$ a probabilistic distance to the pertinent catastrophe domain, i.e. a quantity $d(\hat{\mathbf{P}} \mid \mathfrak{K})$. This distance accounts for the total ensemble $\mathfrak{M}(\hat{\mathbf{P}} \mid \mathfrak{K})$ of eligible managements connecting $\hat{\mathbf{P}}$ to $\mathfrak{K}$, the probabilistic weights of these disastrous control options as derived from a "psychogram" of the Global Subject $\mathcal{S}$, and the uncertainties associated with the dynamics of the "physiologic" components $\mathcal{N}$ and $\mathcal{A}$ of the whole Earth System $\mathcal{E}$ (see Eq. 16). Thus $d(\hat{\mathbf{P}} \mid \mathfrak{K})$ may be qualified as an *integrated risk measure*.

Based on this measure, a *sophisticated minimax strategy* (see above) may be employed. Define for each $\mathbf{M} \in \mathfrak{M}$

$$d_{min}(\mathbf{M} \mid \mathfrak{K}) := \min_{\hat{\mathbf{P}} \in \mathbf{P}(t|\mathbf{M})} d(\hat{\mathbf{P}} \mid \mathfrak{K}) \quad , \tag{124}$$

i.e., $d_{min}(\mathbf{M} \mid \mathfrak{K})$ quantifies the integrated probabilistic proximity to $\mathfrak{K}$ for the coevolution path $\mathbf{P}(t \mid \mathbf{M})$ generated by the management sequence $\mathbf{M}$.

The "pessimal" management $\mathbf{M}^*_{(2)}$ therefore has to satisfy

$$\begin{aligned} d_{min}(\mathbf{M}^*_{(2)} \mid \mathfrak{K}) &= \max_{\mathbf{M} \in \mathfrak{M}} d_{min}(\mathbf{M} \mid \mathfrak{K}) \\ &= \max_{\mathbf{M} \in \mathfrak{M}} \left[\min_{\hat{\mathbf{P}} \in \mathbf{P}(t|\mathbf{M})} d(\hat{\mathbf{P}} \mid \mathfrak{K}) \right] \quad . \end{aligned} \tag{125}$$

This means that $\mathbf{M}^*_{(2)}$ provides the *best worst case scenario* with respect to disastrous coevolution. Note, however, that $\mathbf{M}^*_{(2)}$ does not have to be unique.

The variant of $\mathcal{P}_2$ just discussed may be further refined, of course. One might, for example, include the evaluation of the respective times that are spent by the system in a probabilistic distance from $\mathfrak{K}$ through appropriate integrals along the coevolution path considered. For the sake of brevity, we will not further explore here this rather promising approach to operationalizing the Pessimization paradigm.

* * *

Let us conclude this section devoted to $\mathcal{P}_2$ with two general remarks:

First, we must re-emphasize that this SD paradigm does not primarily determine *the* pessimal management sequence, but rather *excludes non-tolerable control options*. As a consequence, a fairly large manoeuvring space for geo-cybernetic activities usually remains. The precision control within that "decision leeway" may be pinned down to a unique sequence of steering elements by employing auxiliary SD paradigms according to a "nested strategy" (see Sect. 4.6).

Second, it has to be realized and accepted that the Pessimization paradigm heavily depends on normative elements through the identification of catastrophe domains. From this perspective, $\mathcal{P}_2$ might be perceived as a "qualified Standardization paradigm". The latter approach is advocated by the German Global Change Advisory Board within the context of their "Guardrail Philosophy" (*WBGU*, 1996 [84]): Sustainable Development is interpreted there as a coevolution that, first and foremost, keeps away from the "lethal syndromes" of Global Change. The syndromes themselves are defined as the dominant functional patterns of environmental degradation as a consequence of the global transformation process accelerating since the end of World War II.

4.4 Equitization

The recent E & D debate with its preliminary climax in Rio, 1992, revolves around notions like "fairness", "justice", and "equity". It is therefore structurally characterized by the problems of *comparative endowment* of individuals, groups, classes or nation states with natural resources, development chances, environmental security, agreeable ambiances, etc. As the 20th century draws to a close, this debate actually resumes – on an international (in fact geostrategic) stage – a fundamental conflict, which has generated, under purely political-economic signs, the rise and fall of the great ideologies of that century. This *spatial* extension of the traditional complex of problems towards a genuinely global challenge is complemented, however, by a qualitatively novel aspect: the issue of *inter-generational equity*, i.e., the quest for just allocation of options *in time*.

The yearning for fair spatiotemporal endowment of all the actors involved in the game of life, which is obviously deeply rooted in the human cosmos of values, constitutes the ethical background for a further fundamental SD strategy. We will call it the *Equitization paradigm* and register it as the fundamental strategy $\mathcal{P}_3$. $\mathcal{P}_3$ forms, in a manner that similarly applies to $\mathcal{P}_1$ and $\mathcal{P}_2$, a logical pair together with the Standardization paradigm $\mathcal{P}_0$: the crucial feature exhibited by both paradigms is namely the act of *comparison*. In the case of Standardization, though, it is a matter of comparing the coevolutionary quality with *absolute* standards ("E & D standard metres", so to speak), which are imposed from outside upon the environmental system to be controlled through normative acts of long-term effect. By way of contrast, Equitization aims at the *relative* balancing of the respective interests of the actors in a permanent process, fully taking the intrinsic systems dynamics into consideration.

The distinct consequences of absolute and relative comparison may be well illustrated through the example of the definition of poverty: In the first case, this definition is customarily based on fixed or very slowly changing assessment standards such as canonical market baskets, quality thresholds for social housing development schemes, reimbursement regulations of the public health insurance funds, etc. In the second case, "poverty" is defined on a purely comparative basis – through the 50%-margin of the average available per capita income of a community, for instance. This can lead to the bizarre conclusion that the municipality of, say, Palm Springs accommodates a considerable number of "poor" dollar millionaires.

Now, how can we operationalize the just spatiotemporal allocation of options within the framework of a fundamental SD strategy? The basic prerequisite for this is a handy and robust concept that remains perceptible, communicable and conveyable across the real competition of political interests. In searching for such a concept for the Equitization paradigm, one should try to avoid sophisticated interpretations of the notion of "equity" (see, *Rawls*, 1971 [191]; *Cline*, 1992 [46]; *Rayner*, 1997 [192]; *Tòth*, 1997b [232]), and to factor out the familiar aspects of economic-geographic fair allocation (for this, see Sect. 5). Only then will it be possible to focus on the specific quality of the task, which is entirely due to the evolutionary aspect.

We therefore identify here "equity" essentially with "*equality of E&D options for successive global generations*". By doing so, we are especially capable of providing a solid operational basis for the legendary but evasive Brundtland definition of Sustainable Development – meet the needs of the present generation without compromising the *ability* of future generations to meet their own needs.

We have repeatedly placed strong emphasis on the words "options" and "ability", which are supposed to highlight the importance of self-determination and self-responsibility of each generation within the framework of paradigm $\mathcal{P}_3$. If the latter values are disregarded, then a "teleocratic" prescription for coevolution in the spirit of the fundamental strategy $\mathcal{P}_0$ can readily be formulated. As an example, one might demand that an appropriate geo-cybernetic management $\mathbf{M}^*_{(3)}$ satisfied the requirement

$$\int_{\substack{\text{time span of}\\ \text{generation } n+1}} L(\mathbf{P}(t \mid \mathbf{M}^*_{(3)}))dt = \int_{\substack{\text{time span of}\\ \text{generation } n}} L(\mathbf{P}(t \mid \mathbf{M}^*_{(3)}))dt \quad , \tag{126}$$

where the index n counts all future generations. Even the dynamic change of needs and the resources available for their satisfaction could possibly be taken into account here through the quality function L; thus $\mathbf{M}^*_{(3)}$ would have to warrant, for instance, a steady *ratio* between these factors over the long term.

Our objectives, however, require more subtle approaches for the operationalization of the Equitization paradigm. In the following discussion of such approaches we will again tacitly assume – if not explicitly specified otherwise – that the geo-cybernetic dynamics is not directly dependent on time.

Example 1 ("Miraculous Equitization"):
We start by considering *radical interpretations of the Brundtland definition* of Sustainable Development, mainly in order to expose the fundamental problems associated with a formula that has become almost ritual. Two examples for coevolutions that leave all of the dynamic options open are outlined in Figs. 22 and 23. For descriptive purposes, the coevolution space **C** is collapsed to one dimension only here, and the coevolution paths are properly represented as functions of time.

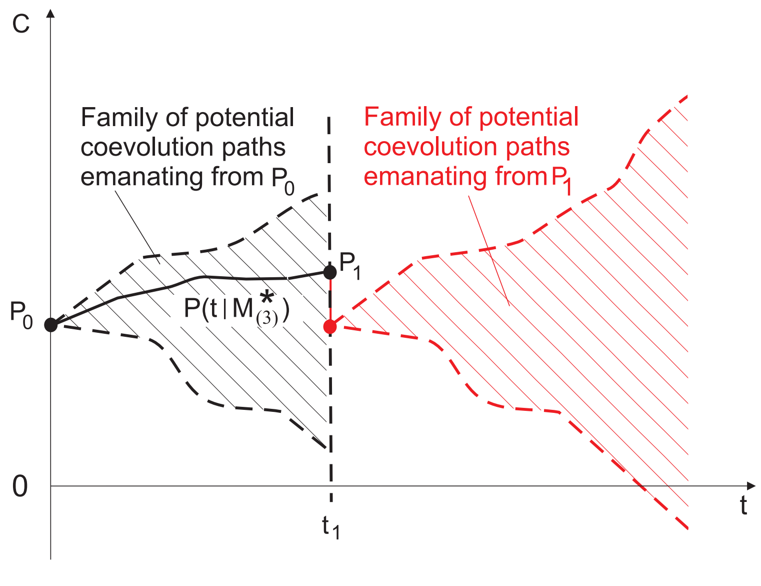


Figure 22. Miraculous Equitization, Variant 1. $\mathbf{M}^*_{(3)}$ generates a coevolution path with the property that at an arbitrary point in time $t_1 > 0$, the same bundle of potential coevolutions as at time 0 is disposable (almost) instantaneously.

Both versions of "miraculous Equitization" presented here formalize the naive ideal that one may decide for certain development possibilities without inducing the loss of options at some later point in time. The

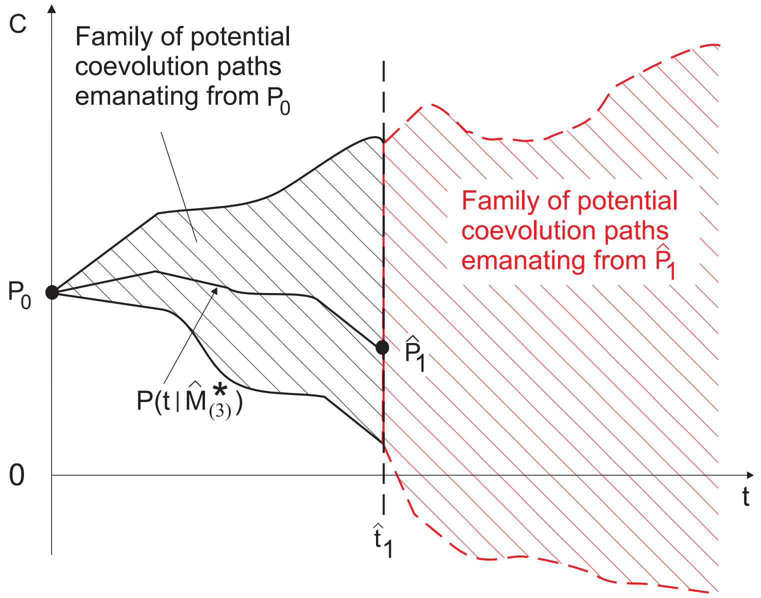


Figure 23. Miraculous Equitization, Variant 2. $\hat{\mathbf{M}}^*_{(3)}$ generates a coevolution path with the property that the bundle of potential coevolutions at some later time $\hat{t}_1 > 0$ is the union of all continuation bundles of all possible path segments in $[0, \hat{t}_1]$.

two variables are structurally different, though: in the first case (Fig. 22), a management sequence $\mathbf{M}^*_{(3)}(t)$ is being searched for *that allows itself to be "undone" quasi-instantaneously at any time*. In the second case (Fig. 23), it is exactly the other way around: by judicious choice of $\hat{\mathbf{M}}^*_{(3)}(t) \in \mathfrak{M}$, the optional management episodes not realized instead of segments of the latter sequence should be *endowed with the capacity of being "done" quasi-instantaneously at any time*. This idea is not altogether absurd if we think of quantum reality, where all potential time developments of a system run virtually in parallel if certain mild conditions are met (see the literature on Schrödinger's fabulous cat, e.g., *Schrödinger*, 1935 [211]; *Bohm*, 1951 [27]; *Davies*, 1986 [55]; *Gribbin*, 1991 [92]). We emphasize, though, that both of the outlined radical versions of the Equitization paradigm fully earn the adjective "miraculous" in the context of geo-cybernetics – they violate, among other things, the requirement for coevolutionary continuity and therefore merely have hermeneutic value with respect to the Brundtland formula.

Under certain circumstances there is, however, a trivial possibility for the realization of Variant 1: if the system is successfully "parked" in the state $\mathbf{P}_0$ through suitable management (see also Sect. 4.5), then the development options will seemingly be identically preserved. In fact, though, this is a matter of "freezing" these options, as one rules out their use by the very fact that one wants to keep them open for all times! This situation is precisely described through the parable of the horse (or the classical dilemma of Buridan's donkey) that starves to death between two piles of hay, because it can't make a decision on either one of the two. The SD debate frequently seems to be characterized by such a horse mentality ...

In the light of the considerations just made, the goal of the Equitization paradigm can be formulated more sharply: *Maximal preservation of E&D options under minimal obstruction of the current coevolution.* If one disregards miracles, this goal will not be achievable. We will outline in the following, however, several approximations to this "Brundtland Ideal" that can be realized in principle.

Example 2 ("Weak Brundtland Strategy"):
The weakest form of inter-generational equity, which is, in return, the version most likely to be operationalized, is the "*preservation of the overall coevolutionary future*". This seemingly paradoxical expression epitomizes a variant of $\mathcal{P}_3$ that conserves the accessible universe, i.e. all *asymptotic E&D options for* $t \to \infty$. The formal recipe for this weak Brundtland strategy is as follows:

Determine $\mathbf{M}^*_{(3)}(t) \in \mathfrak{M}$ in such a way that for arbitrary $\hat{t} \geq 0$ the relation

$$\mathfrak{U}(\mathbf{P}(\hat{t} \mid \mathbf{M}^*_{(3)})) = \mathfrak{U}(\mathbf{P}_0) \tag{127}$$

is satisfied. We emphasize here that, due to *causality*, we have

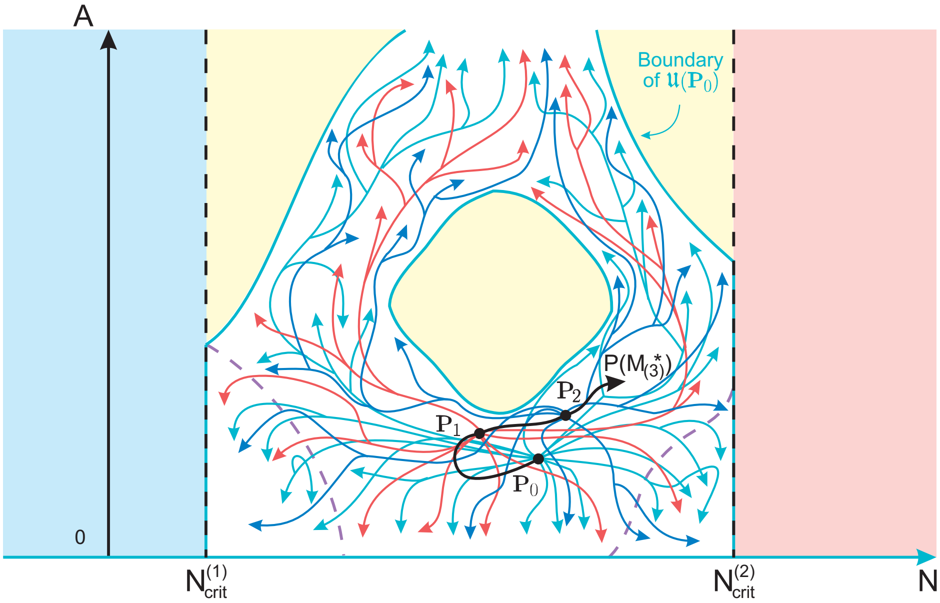


Figure 24. Sketch of weak Brundtland management in our two-dimensional geo-cybernetic toy system. $\mathbf{M}^*_{(3)}$ generates a coevolution path $\mathbf{P}(\hat{t} \mid \mathbf{M}^*_{(3)})$, which preserves all *asymptotic* E & D options. For example, all states in $\mathfrak{U}(\mathbf{P}_0)$ can ultimately be reached from $\mathbf{P}_1 \equiv \mathbf{P}(\hat{t}_1 \mid \mathbf{M}^*_{(3)})$ and $\mathbf{P}_2 \equiv \mathbf{P}(\hat{t}_2 \mid \mathbf{M}^*_{(3)})$, respectively, by appropriate management. However, note that passage type and time may vary considerably with the starting point on $\mathbf{P}(\hat{t} \mid \mathbf{M}^*_{(3)})$.

$$\mathfrak{U}(\mathbf{P}(\hat{t} \mid \mathbf{M})) \subset \mathfrak{U}(\mathbf{P}_0) \tag{128}$$

for arbitrary $\hat{t} \geq 0$ and $\mathbf{M} \in \mathfrak{M}$.

The strategy $\mathbf{M}^*_{(3)}$ stands out for guaranteeing even strict equality of all accessible universes strung along the corresponding coevolution path. This situation is illustrated in Fig. 24.

If a weak Brundtland strategy $\mathbf{M}^*_{(3)}$ exists, then it is generally not the unique solution of this specific version of the SD problem. Note that $\mathbf{M}^*_{(3)}$ satisfies the requirements made if, and only if,

$$\boldsymbol{\Pi}(\mathbf{M}^*_{(3)}) \equiv \boldsymbol{\Pi}(\mathbf{P}_0, 0 \mid \mathbf{M}^*_{(3)}) \subset \mathfrak{U}^{-1}(\mathbf{P}_0) \quad . \tag{129}$$

Proof:

(i) Select an arbitrary time $\hat{t} \geq 0$ and assume that Eq. 129 applies. From this assumption it follows that

$$\mathbf{P}(\hat{t} \mid \mathbf{M}^*_{(3)}) \in \boldsymbol{\Pi}(\mathbf{M}^*_{(3)}) \subset \mathfrak{U}^{-1}(\mathbf{P}_0) \quad , \tag{130}$$

i.e., the coevolution state considered is in the basin of access to $\mathbf{P}_0$. Therefore, $\mathbf{P}_0$ can be reached from $\mathbf{P}(\hat{t} \mid \mathbf{M}^*_{(3)})$ by appropriate management, and subsequently the entire universe $\mathfrak{U}(\mathbf{P}_0)$ may be explored.

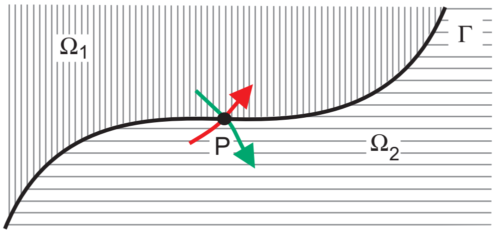
(ii) Assume that Eq. 129 is not satisfied, so there is a time $\tilde{t} > 0$ with

$$\mathbf{P}(\tilde{t} \mid \mathbf{M}^*_{(3)}) \notin \mathfrak{U}^{-1}(\mathbf{P}_0) \quad . \tag{131}$$

Then the state $\mathbf{P}_0$, which is definitely an element of $\mathfrak{U}(\mathbf{P}_0)$, cannot be reached from $\mathbf{P}(\tilde{t} \mid \mathbf{M}^*_{(3)})$ by definition. Thus, $\mathbf{M}^*_{(3)}$ is not eligible for weak Brundtland management. ■

As a consequence, the weak Brundtland strategy boils down to *keeping the coevolution within the basin of access to* $\mathbf{P}_0$. This implies that there remains, as a rule, considerable freedom in picking a management sequence which may meet complementary objectives.

However, how can it be ensured that the coevolution does not leave $\mathfrak{U}^{-1}(\mathbf{P}_0)$? In order to answer this question, the irreversibilities in systems control as defined by *critical manifolds*, must be investigated.



Definition 7: Consider a manifold Γ which separates two adjacent domains Ω_1, Ω_2 of coevolution space **C**. Γ is called *critical* if for each point $\mathbf{P} \in \Gamma$ we find that the managed coevolution may pass through **P** from Ω_1 to Ω_2, but *not* vice versa. ■

Remarks:

(i) The above definition is made without loss of generality as the labels of the respective domains can be chosen at will.

(ii) The boundary between the domains does not have to be as smooth as the above sketch and the mathematical expression "manifold" suggest. Modern dynamic systems theory tells us that such separating sets may be rather "strange" or "fractal" (*Mandelbrot*, 1991 [145]), even in low-dimensional systems.

(iii) Our definition of "critical" is fairly wide in so far as it identifies this notion with *irreversible* coevolutionary moves, which do not have to be *intolerable* or *discontinuous* as well. Therefore, the boundary of any catastrophe domain is certainly critical, but critical manifolds may also hedge in absolute security zones (see Sect. 4.3).

Existence, form and position of critical manifolds in coevolution space depend on the intrinsic systems dynamics as well as on the peculiarities and limits of the available geo-cybernetic options. In our hydrographic illustration of an Anti-Murphy strategy as depicted in Fig. 20b, for instance, two critical lines were already identified: one of them, the edge of the waterfall as a boundary of the catastrophe domain $\mathfrak{K}$, is quasi-independent of all potential manoeuvres. The borderline which delimits the basin of access to $\mathfrak{K}$ upstream of the rapids, however, is largely determined by the propulsive endowment and the hydrodynamic properties of the boat.

We have to emphasize that the coevolutionary irreversibility defined by a critical manifold has only *local* relevance, if this manifold does not completely isolate an "interior domain" from the rest of the accessible universe $\mathfrak{U}(\mathbf{P}_0)$ within **C**. Consider, for example, the metaphoric hydrographic situation sketched in Fig. 25.

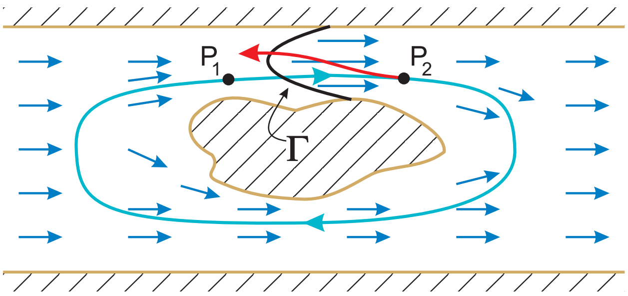


Figure 25. The critical line Γ is determined here by a limit stream velocity which is only exceeded in the upper river arm. The move from $\mathbf{P}_1$ to $\mathbf{P}_2$ is locally irreversible, yet *globally reversible* due to the fact that Γ does not form a *closed loop*.

The answer to the question of whether a given critical manifold Γ nevertheless admits *global* reversibility is generally a difficult task. One major prerequisite is a thorough investigation of the manifold's topology with respect to the embedding sets $\mathfrak{U}^{-1}(\mathbf{P}_0)$ and **C**. Such a situation is well known from non-linear Hamiltonian dynamics, where impermeable barriers in phase space (the so-called Kolmogorov-Arnold-Moser tori) do not forbid global intrinsic mobility. This phenomenon, which requires sufficiently high dimensionality of the system in question, goes by the name of "Arnold diffusion" (*Arnold*, 1964 [6]) and is responsible for the long-term instability of most arrangements of celestial bodies in the universe (see Sect. 6).

Note that our critical manifolds behave rather like "semi-permeable membranes" with respect to geo-cybernetic action. Let us now assume that the highly non-trivial survey of distributions and properties of these membranes in coevolution space can be performed in a satisfactory way. Let us also assume that this analysis results in some kind of *"navigational chart"* that clearly indicates the set $\{\Gamma(\mathbf{P}_0)\}$ of critical manifolds which delimit $\mathfrak{U}^{-1}(\mathbf{P}_0)$ in the sense of *global irreversibility*. Then weak Brundtland management sequences $\mathbf{M}^*_{(3)}$ characterized by Eq. (129) are implicitly generated by the following operational rule:

Avoid crossing any of the manifolds in the collection $\{\Gamma(\mathbf{P}_0)\}$, i.e., implement only those geo-cybernetic actions which keep the system away from a given $\Gamma(\mathbf{P}_0)$ or make it move tangentially to that critical boundary.

Several *comments* on this innocent-looking instruction have to be made:

(i) As mentioned before, the operational scheme generally does not determine a unique weak Brundtland strategy but leaves the Global Subject with considerable freedom for maneuvring according to complementary E & D criteria. Whether this freedom is sufficiently large – or small – to guarantee the possible satisfaction of all the individual generations to come is by no means evident. We will return to this point below.

(ii) The observance of the boundaries $\{\Gamma(\mathbf{P}_0)\}$ is both a necessary and a sufficient condition for preserving all asymptotic coevolutionary options. A less efficient operational principle, yet safer and easier to implement, would be the following one:
Just refrain from traversing any *locally* critical manifold $\Gamma_{\text{loc}}(\mathbf{P}_0)$, i.e., any "semi-permeable membrane" for geo-cybernetic motion departing from $\mathbf{P}_0$ (see the general definition of critical manifolds above).
Note that a locally critical manifold with respect to $\mathbf{P}_0$ does not have to be globally critical as well: Fig. 25 features such a situation within our hydrographic allegory. The same allegory also gives us a hint how the entity $\Gamma_{\text{loc}}(\mathbf{P}_0)$ might be identified and avoided in an on-line-fashion, that is, by direct inspection of short-term coevolution dynamics. The steersman "simply" has to perpetually monitor the local velocity of the supporting medium, and to change course if this velocity approaches a maximum value defined by the propulsive equipment.
Note that the "primitive" operational scheme formulated here is clearly *sufficient* in the weak Brundtland sense, as

$$\{\Gamma(\mathbf{P}_0)\} \subset \{\Gamma_{\text{loc}}(\mathbf{P}_0)\} \quad . \tag{132}$$

(iii) Whether a weak Brundtland strategy can be implemented at all – by any operational principle – crucially depends on the topological properties of the family of critical manifolds in coevolution space. These manifolds might, e.g., embrace the starting point $\mathbf{P}_0$ like a dense set of onion skins. In such a case there remains no open domain for geo-cybernetic manoeuvring.

(iv) Things become even more complicated *if the geo-cybernetics depends explicitly on time.* Under such circumstances, the (local and global) critical manifolds may not be stationary, for instance

$$\{\Gamma(\mathbf{P}_0)\} \equiv \{\Gamma(t \mid \mathbf{P}_0)\} \quad . \tag{133}$$

As a consequence, local manoeuvring becomes rather risky and cannot warrant global reversibility of coevolutionary motion any more (just think of steering a vessel through a river delta influenced by strong tidal forces). The formal analysis of this genuinely dynamic control problem requires a fully "teleological" approach and is beyond the scope of this essay.

Example 3 ("Qualified Brundtland Strategies"):
Up to now we have discussed only extreme variants of the Equitization paradigm, which are supposed to secure either the instantaneous or the asymptotic availability of E & D options in the coevolution process. Clearly, the first strategy is not a realistic one, while the second strategy may be intolerable for certain generations along the coevolution line: weak Brundtland management, after all, only guarantees the access

to specific pockets of $\mathbf{C}$ in the long run – but not necessarily within the time span relevant to the generations in question.

So we have to ask ourselves whether *intermediate* variants of $\mathcal{P}_3$ can be devised that warrant "intergenerational equity" in its proper sense. An obvious approach would be to consider time windows of reasonable length ($T = 20$ or 50 years) and the corresponding *geo-cybernetic plumes*. Then the Equitization recipe might be formulated in the following way:

Find a management sequence $\mathbf{M}^*_{(3)}$ with the property that

$$\mathfrak{U}_T(\mathbf{P}(\hat{t} \mid \mathbf{M}^*_{(3)})) = \mathfrak{U}_T(\mathbf{P}_0) \quad \text{for all} \quad \hat{t} \geq 0 \ . \tag{134}$$

Most probably, there is no such element in the management pool $\mathfrak{M}$ which is capable of strictly satisfying the above condition. There may be, however, various ways of relaxing the rigorous requirement without spoiling its essence. We might, for instance, consider two plumes $\mathfrak{U}_T(\mathbf{P}_1)$ and $\mathfrak{U}_T(\mathbf{P}_2)$ to be "nearly equal" if the following statement holds:

Let $d > 0$ be a given (small) distance in the *normed* coevolution space $\mathbf{C}$ (see also Sect. 4.5). Then the d-neighbourhood of any point $\bar{\mathbf{P}}_1 \in \mathfrak{U}_T(\mathbf{P}_1)$ contains at least one point $\bar{\mathbf{P}}_2 \in \mathfrak{U}_T(\mathbf{P}_2)$ and vice versa.

However, note that even such an approximate equality of geo-cybernetic plumes accessible to the generations interlinked through a specific coevolution path might not be attainable. As a consequence, we ultimately may have to resort, within the framework of paradigm $\mathcal{P}_3$, to *qualified* Brundtland strategies which at least preserve the *equivalence* of the co-variant medium-term option space. Let us emphasize that we thereby will introduce, inevitably, patronizing (at best) or gratuitous (at worst) elements into the geo-cybernetic process, so there is a high price to be paid for feasibility.

One operational scheme for generating qualified Brundtland strategies is the *"principle of self-referential positive discrimination"*. We will make no attempt to formalize this principle here, yet we sketch the underlying rationale:

Imagine that the first generation, departing from state $\mathbf{P}_0$, chooses a management episode $\mathbf{M}^*_T$ which produces the path segment $\mathbf{P}_T(\mathbf{P}_0, 0; t \mid \mathbf{M}^*_T)$. This coevolution segment may traverse a number of critical manifolds that will constitute impermeable barriers for the coming generations. The choice of the first generation may nevertheless be accepted as "equitable" *if* these manifolds either

- delimit *miserable* or *dangerous* pockets in coevolution space (like the basins of access to catastrophe domains), or
- encompass optional realms in $\mathbf{C}$ that all future generations supposedly will not wish to reenter *due to the trend-setting initial choice* (like the status quo ante of wetlands transformed into bucolic landscapes or flourishing cities in the Netherlands),

and *if* the manifolds are crossed in the "right" direction, of course.
Then the second generation (or couple of generations) will make their choice, and so on. This interactive process hopefully keeps the optional quality of the respective geo-cybernetic plumes at least at a constant level, although (or because) the future generations are progressively deprived of their "license" to commit fatal mistakes ...

We have to point out, however, that the SD recipe just described only involves "eternal" critical thresholds, so it might be even used for "improving" the weak Brundtland strategy. If we *seriously* want to compare the optional T-plumes available to distinct generations down the coevolution line, we have to deal with a most intricate additional problem: migration along any coevolution path generally rules out certain options for future generations – simply because the Earth System has moved away from initially accessible states in $\mathbf{C}$ and cannot be driven back there within the limited time span T. On the other hand, new opportunities will emerge, as a rule, due to this drift in coevolution space. Now the difficult task is to *compare* the options lost to the options gained by number and character in order to determine *whether the overall opportunistic quality of the T-plume will be preserved.*

To fulfill such a task, a fully-fledged teleological analysis of all geo-cybernetic paths emanating from $\mathbf{P}_0$ is needed, not to mention the projective value-judgements to be made. As a consequence, a robust and practical implementation scheme for genuinely qualified Brundtland strategies may not exist – a fact that would drastically diminish their political relevance. However, all this is at present scientific "terra incognita" and remains a major research challenge for the future. Fig. 26 tries to give an impression of what the analysis will have to be all about.

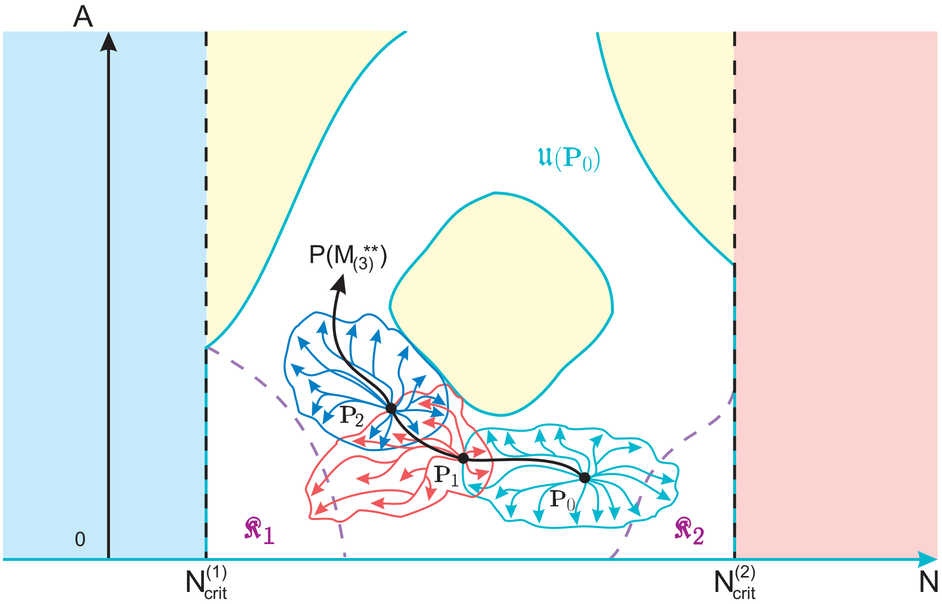


Figure 26. Cartoon of a qualified Brundtland coevolution inducing "equivalent" successive T-plumes in the sense of optional equity. The underlying management sequence is $\mathbf{M}_{(3)}^{**}$, and $\mathbf{P}_1 \equiv \mathbf{P}(T \mid \mathbf{M}_{(3)}^{**})$, $\mathbf{P}_2 \equiv \mathbf{P}(2T \mid \mathbf{M}_{(3)}^{**})$, etc., are the generational stepping stones down the E & D flow. However, note that we may run here again into a tantalizing inherent problem of paradigm $\mathcal{P}_3$, which we already mentioned earlier: in order to preserve (qualified medium-term) options, almost all of them have to be dismissed!

4.5 Stabilization

We now come to a principal geo-cybernetic model – the "*Stabilization paradigm*" $\mathcal{P}_4$ – which seems to fit best the popular notions of "Sustainable Development" and which can be expected to yield to operationalization most easily. On closer examination, however, this paradigm proves to be quite problematic in its essence as well as structure.

The entire E & D debate is still – predominantly in the advanced industrialized countries – characterized by *massive fears* of losing the doggedly elaborated level regarding consumption options, mobility, security, educational and recreational offers, etc. The "Limits-to-Growth" philosophy of the Club of Rome continues to resound in these fears, although the public concerns about the future of this planet have recently focused more on the natural "sinks" for the metabolic secretions of the anthroposphere "Beyond the Limits" (*Meadows* et al., 1992 [149]). As a consequence, society and its decision-makers exhibit a strong desire for safety, stability, even *stagnation* in the relationship between global civilization and nature. Strictly speaking, this is a desire for the *"end of all environmental history"*.

This longing for stable equilibria is expressed in a relatively vague way in various recent publications such as Al Gore's bestseller "Earth in the Balance" (*Gore*, 1992 [91]), but also quite concretely and socio-economically effectively in the stability goals or stabilization mechanisms, respectively, of global environmental treaties such as the "Framework Convention on Climate Change" and the "Montreal Protocol" for protecting the stratospheric ozone layer (*WBGU*, 1996 [84]).

In its most simplified version, the Stabilization paradigm boils down to the deliberate steering towards a selected state $\mathbf{P}^*$ in coevolution space, *where the Earth System can be safely "detained" through suitable geo-cybernetic management.* $\mathcal{P}_4$ is therefore in diametric opposition to the Equitization paradigm $\mathcal{P}_3$, which moves the evolutionary capacity and flexibility of the environmental system under consideration into the limelight. Thus the Stabilization paradigm may be seen as a radical, yet systemic materialization of the quite sweeping

Standardization paradigm $\mathcal{P}_0$. On the one hand, $\mathcal{P}_4$ rules out any net long-term coevolutionary progress and therefore replaces the subtle desideratum "Sustainable Development" by the rather blunt objective of "*Sustainability*". On the other hand, the Stabilization paradigm does *not* simply *prescribe* coevolution states or paths, but searches systematically for balancing management options in accordance with the intrinsic dynamics of the Earth System and with the available pool of steering instruments. So we can interpret $\mathcal{P}_4$ as the "true" logical counterpart to paradigm $\mathcal{P}_3$.

One may dream of blending those two SD models. This could be accomplished, in particular, if a coevolution state $\mathbf{P}^{**} \in \mathbf{C}$ were found which united maximum stability and evolutionary capacity – thus constituting a simultaneously optimal defense and attack position, in military jargon. The actual existence of a state of this type, or at least the availability of a corresponding set of states (see below), is a speculative matter that we do not want to pursue further here.

We rather wish to attempt in the following to formulate the Stabilization paradigm more precisely, to discuss its main aspects and to analyse the prerequisites for its operationalization. Let us initially disregard the systemic questions concerning the availability or accessibility of "equilibrium states $\mathbf{P}^{*}$" and assume that a choice has to be made among many states of this type. We are thus confronted with the second of our fundamental questions formulated above, namely *"What kind of world do we want?"* Or, expressed in more specific terms: Which environmental qualities are to be strived for and to be stabilized without thereby ignoring the pertinent socio-economic dimensions?

The corresponding public and academic debate is generally not characterized by oversized imagination. With very few exceptions the following guiding principles on the road to equilibrium are encountered over and over again:

(i) Preservation.
This strategy aims at practically *freezing the current coevolution state* along with all its natural and civilizatory aspects. This in no way means that the status quo is viewed as being the best possible state of affairs. It possesses, however, the dignity of an unplanned historical product, just like the biological species that it includes. The preservationist attitude certainly lacks sophistication, but it is precisely this shortcoming that makes it a directly convincing and extremely impressive conviction. Everyone who has, for example, argued with governmental curators of historic monuments about the development (or reconstruction) of urban ensembles can tell you a thing or two about that.

(ii) Restoration.
A frequently advanced radical eco-centric alternative to preservation is the *re-establishment of the status quo ante*, i.e. of a "virgin" nature unspoilt by anthropogenic deformations and perturbations. However, what does this primeval reference state look like for a specific biotope to be restored – or for the Earth System as a whole? How many decades or centuries do we have to go back in the flow of time to be able to catch sight of the "pure" state? These questions are especially difficult to answer if anthropomorphic landscapes are to be "renaturalized" – a process that may induce significant losses in biological diversity, ecological performance and aesthetic attractions. Apart from these problems, restoration is illusory as a *comprehensive*, large scale strategy, as it will always be restricted to specific areas within narrow bounds (such as river meadows, for example).

(iii) Segregation.
By way of constrast, an environmental policy that aims at a stepwise *disentanglement of nature and civilization* may be comparatively "successful". The final product of such a strategy would have be a global ensemble of protected areas (ranging from national parks to miniscule wetlands set aside by municipalities) that were largely decoupled from coevolution and left to their own self-organized development. The Federal Environmental Agency of Germany (UBA), e.g., actually defines as the reference state of a "valuable" biogeotope the asymptotic conditions that would form without further human intervention (*Irmer*, 1997 [111]).

Such a "ghettoization strategy" for nature certainly enjoys a relatively high degree of public acceptance or even approval at present, but it is problematic in several respects: what environmental quality standards should apply to the immense rest of the "civilized" areas; what opportunities for experiencing nature would remain for human beings; and, above all, how could the areas to be protected be screened off from large-scale anthropogenic influences (e.g., through the atmosphere)? On closer inspection, a long-term, stable segregation of the ecosphere and the anthroposphere appears to be neither a desirable nor a realizable venture . . .

Our brief outline of the various popular, but ill-defined alternatives for the establishment of a coevolutionary target state should already have made it clear that, in addition to the question of social preference, the aspects of *"attainability"* and "*sustainability*" must not be neglected. Thus it is imperative that systems analysis complements the normative considerations. A series of more recent and more subtle approaches to the definition of global or regional environmental-quality goals already meet this demand to a certain extent; i.e. these approaches formulate action principles ("ecological imperatives") that characterize the respective "target state" as an explicit or implicit equilibrium. Let us illustrate this with a few examples:

A number of topical studies on the sustainability of large geographic units like countries or continents (see, e.g., *Buitenkamp* et al., 1992 [37]; *FEE*, 1995 [75]; *Spangenberg*, 1995 [220]; *Loske*, 1996 [139]) rely on the *"environmental space"* concept (*Opschoor*, 1992 [167])) also relevant to the Standardization paradigm (see Sect. 4.1)). That concept is derived from an ecological theory considering the limited "carrying capacity" of the planetary ecosystem to be shared among a growing number of human beings – not to speak of other species. The overall approach therefore envisages not a target coevolution state but rather a *minimum-standard equilibrium* enforced by the laws of nature.

A counterpart of this is provided by the vision of *"Park Earth"*, which evokes the picture of a biosphere that is largely preserved yet optimally designed according to cultural preferences and needs. Within the framework of ecosystems theory, the corresponding equilibrium is rather a *"climax state"* as determined by humanity's abilities as a "gardener" (see, e.g., *Clark* and *Munn*, 1986 [44]). The resulting global environmental patchwork is supposed to guarantee both the maximum mutual permeability and stabilization of nature and civilization, as striven for – at the landscape level – by UNESCO's "Man and the Biosphere Programme" (*UNESCO*, 1988 [237]; *USNC*, 1995 [241]).

Explicit *operational rules* for constructing a coevolutionary *fixed state* are given by the Daly school of environmental economists (*Barbier*, 1989 [14]; *Daly*, 1990 [50]; *Pearce* and *Turner*, 1990 [175]):

(i) The consumption rate of any renewable natural resource must not exceed its regeneration rate.
(ii) The reduction rate of any non-renewable resource must not exceed the rate of substituting it by a fully equivalent renewable resource.
(iii) The emission rate of any anthropogenic substance must not exceed the pertinent absorption and transformation rates by natural sinks.

At first sight, these rules seem to reflect a dull and static concept which simply aims at preserving the very status quo. At second sight, we notice, however, that those rules (in particular, (ii)) refer to *compound variables* which allow for some freedom regarding the values of the individual constituents. As a matter of fact, there are many more subtleties involved here. We have to take into account particularly the fact that the above-mentioned regeneration, absorption or transformation rates of natural systems may be elastic quantities heavily depending on the harvesting or immission intensities. Standard chemical reactions theory certainly supports such a point of view. The "Daly Equilibrium" is therefore a *dynamic* (or homeorhetic) entity in disguise and, as a consequence, is both less illusive and more problematic than it initially appears. An exemplary discussion further below will feature some of the highlights and deficiencies of this concept.

* * *

These first thoughts on the Stabilization paradigm already make clear that the concept of "equilibrium" has to be defined in the SD context much more broadly than usual. It is probably completely futile to strive for a fixed coevolution state with a detailed specification of all micro-variables, even if a social agreement concerning such a desideratum could be reached. Rather, it will be useful, if not necessary, to consider entire *sets of coevolution states* as complex stabilization targets. These sets define *generalized dynamic equilibria* with respect to temporal averaging or compositional aggregation.

So the question "What kind of world do we want?" will have no simple answer, but this is by no means the whole story. Even if a satisfactory *generalized coevolutionary equilibrium* were identified, the question *"How do we get there?"* would still have to be pondered. The answer to the latter question will be complex as well: both the overall *accessibility* of the target equilibrium and the comparative *costs* (in the broadest sense of the word) of the eligible stabilizing avenues have to be investigated in full depth. All these aspects will be dealt with in the rest of this section.

4.5.1 Generalized Equilibria

A. Dynamic Stabilization.

First of all we have to state in precise terms what type of managed coevolution can be classified as a "stable" one.

Definition 8:

(i) As indicated above, let us assume that the coevolution space $\mathbf{C}$ is endowed with a norm $\| \ \|$ that allows us, in particular, to measure the *distance* between any pair of coevolution states. Now let $\varepsilon > 0$ and $\bar{\mathbf{P}}$ be some arbitrary point in $\mathbf{C}$. Then the (open) ε-neighbourhood of $\bar{\mathbf{P}}$ in coevolution space, $\mathfrak{V}_\varepsilon(\bar{\mathbf{P}})$, is defined as follows:

$$\mathfrak{V}_\varepsilon(\bar{\mathbf{P}}) := \{\mathbf{P}' \in \mathbf{C} \mid \|\mathbf{P}' - \bar{\mathbf{P}}\| < \varepsilon\} \quad . \tag{135}$$

(ii) Consider an arbitrary coevolution path $\mathbf{P}(\hat{\mathbf{P}}, \hat{t}; t \mid \mathbf{M})$, as generated by the management sequence $\mathbf{M} \in \mathfrak{M}$, and the associated coevolution trajectory $\boldsymbol{\Pi}(\hat{\mathbf{P}}, \hat{t}; \mathbf{M})$ with starting point $\hat{\mathbf{P}}$. For given $\varepsilon > 0$ and coevolution state $\mathbf{P}(\bar{t}) \equiv \mathbf{P}(\hat{\mathbf{P}}, \hat{t}; \bar{t} \mid \mathbf{M})$ the recurrence time $T_\varepsilon(\mathbf{P}(\bar{t}))$ is defined as the minimum time needed by the coevolution to revisit the ε-neighbourhood of $\mathbf{P}(\bar{t})$. So

$$\mathbf{P}(\bar{t} + T_\varepsilon(\mathbf{P}(\bar{t}))) \quad \in \quad \mathfrak{V}_\varepsilon(\mathbf{P}(\bar{t})) \quad , \tag{136}$$

$$\text{i.e.} \quad \|\mathbf{P}(\bar{t} + T_\varepsilon(\mathbf{P}(\bar{t}))) \quad - \quad \mathbf{P}(\bar{t})\| < \varepsilon \quad . \tag{137}$$

Note that, in general, $T_\varepsilon(\mathbf{P}(\bar{t}))$ does not have to be finite, i.e. $\mathfrak{V}_\varepsilon(\mathbf{P}(\bar{t}))$ might not be revisited at all.

(iii) A *stable coevolution path* $\mathbf{P}(t) \equiv \mathbf{P}(\hat{\mathbf{P}}, \hat{t}; t \mid \mathbf{M}^*_{(4)})$ satisfies the following condition:

$$\sup_{t \geq \hat{t}} T_\varepsilon(\mathbf{P}(t)) < \infty \quad \text{for any} \quad \varepsilon > 0 \quad . \tag{138}$$

The generating management sequence $\mathbf{M}^*_{(4)}$ is then referred to as a *stabilizing management.* ■

Remark:

The stability condition formulated above guarantees that the corresponding coevolution reapproaches any of its states as closely as desired after a finite waiting time. This implies, in particular, that each point on the trajectory $\boldsymbol{\Pi}(\hat{\mathbf{P}}, \hat{t} \mid \mathbf{M}^*_{(4)})$ is an "accumulation point" of the coevolutionary sequence of states. It does *not* imply, however, that all the distinct points on $\boldsymbol{\Pi}(\hat{\mathbf{P}}, \hat{t} \mid \mathbf{M}^*_{(4)})$ are covered within a finite period.

Examples of Stable Coevolutions.

Let us first emphasize that a stable coevolution path is established by the right choice of the triple $(\hat{\mathbf{P}}, \hat{t}, \mathbf{M}^*_{(4)})$ of control variables, i.e. by appropriate selection of initial state, starting time and management sequence. The triple reduces to the control couple $(\hat{\mathbf{P}}, \mathbf{M}^*_{(4)})$ if the geo-cybernetic process does not explicitly depend on time.

We further note that our stability concept does not directly refer to robustness or resilience properties in the usual sense of stability theory, but primarily to the *recurrent* character of the coevolution path in the sense of *stationarity.* Thus, our definition of stable coevolution accommodates a wide range of dynamic patterns in coevolution space, which will be perceived as generalized equilibria. In the following we present a few illustrating examples.

(i) *Fixed Points:*

$$\mathbf{P}(\hat{\mathbf{P}}, \hat{t}; t \mid \mathbf{M}^{fix}_{(4)}) = \hat{\mathbf{P}} = const. \quad , \tag{139}$$

i.e. the management sequence $\mathbf{M}_{(4)}^{fix} \in \mathfrak{M}$ exactly preserves the initial coevolution state in spite of the intrinsic Earth System dynamics as described by Eq. 2. This is, of course, the trivial case of a generalized equilibrium which coincides with the familiar *static* concept.
$\hat{\mathbf{P}} \equiv (\hat{\mathbf{N}}, \hat{\mathbf{A}})$ is a *fixed coevolution state* from the time $\hat{t}$ on if and only if the following conditions are fulfilled (see Eq. 17):

$$\begin{aligned} \dot{\mathbf{N}} = \quad & F_2(\hat{\mathbf{N}}, \hat{\mathbf{A}}; t; \mathbf{M}_{(4)}^{fix}) \quad = 0 \ , \\ \dot{\mathbf{A}} = \quad & G_2(\hat{\mathbf{N}}, \hat{\mathbf{A}}; \mathbf{M}_{(4)}^{fix}) \quad = 0 \ , \\ & \text{for all} \quad t \geq \hat{t} \ . \end{aligned} \tag{140}$$

If the system is "autonomous", implying that t does not appear in the first line of Eq. 140, then stationary management

$$\mathbf{M}_{(4)}^{fix}(t) \equiv \hat{\mathbf{M}}_{(4)}^{fix} = const. \tag{141}$$

will suffice to do the job. However, note that even under autonomous conditions there might not exist such a management element for any real starting point $\mathbf{P}_0$ of the coevolution. It seems, for instance, impossible to stabilize the present climate by any reduction scenario for the global greenhouse gas emissions because of the inertia of the planetary geophysical circulation system. On the other hand, it cannot be completely ruled out that a judicious addition of certain "geo-engineering ingredients" like afforestation or aerosol injection could meet the preservation goal in spite of that inertia.

(ii) *Periodic Orbits:*

$$\mathbf{P}(\hat{\mathbf{P}}, \hat{t}; t + \hat{T} \mid \mathbf{M}_{(4)}^{per}) = \mathbf{P}(\hat{\mathbf{P}}, \hat{t}; t \mid \mathbf{M}_{(4)}^{per}) \tag{142}$$

for all $t \geq \hat{t}$ and some *finite period* $\hat{T} > 0$.
The coevolution trajectory $\boldsymbol{\Pi}(\hat{\mathbf{P}}, \hat{t} \mid \mathbf{M}_{(4)}^{per})$ is then a *closed loop* in coevolution space $\mathbf{C}$.

(iii) *Quasiperiodic Orbits:*
Here $\mathbf{P}(\hat{\mathbf{P}}, \hat{t}; t \mid \mathbf{M}_{(4)}^{qp})$ can be expressed as a function (*Bergé* et al., 1984 [21])

$$f(\omega_1 t, \omega_2 t, \ldots, \omega_L t) \ , L \geq 2 \ , \tag{143}$$

for all $t \geq \hat{t}$.
Quasiperiodicity of such a coevolution is established by the fact that the map $f : \mathbb{R}^L \to \mathbf{C}$ is 1-periodic in each of its arguments, i.e.,

$$f(x_1, \ldots, x_l + 1, \ldots, x_L) = f(x_1, \ldots, x_L) \quad \text{for any} \quad l \in \{1, \ldots, L\} \ , \tag{144}$$

and the "fundamental frequencies" $\omega_1, \ldots, \omega_L$ are *incommensurate.* The latter simply means that the equation

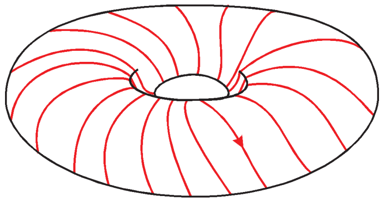
$$\sum_{l=1}^{L} n_l \omega_l = 0 \tag{145}$$

cannot be satisfied by a non-trivial L-tuple $(n_1, \ldots, n_L)$ of integers.
We obviously have

$$f(\omega_1 \hat{t}, \ldots, \omega_L \hat{t}) = \hat{\mathbf{P}} \ , \tag{146}$$

and the coevolution trajectory $\boldsymbol{\Pi}(\hat{\mathbf{P}}, \hat{t} \mid \mathbf{M}_{(4)}^{qp})$ densely covers a *torus* in $\mathbf{C}$, as sketched below for the simplest case $L = 2$ (*Stewart*, 1989 [223]).

The quasiperiodic functions constitute a specific sub-set of the so-called *almost periodic* functions: as a matter of fact, all of the latter entities may represent stable coevolution patterns according to our definition.



(iv) *Strange Attractors:*
Our qualification of stable coevolutions as recurrent ones also allows for very complicated "equilibrium" motion in **C**, which may produce wild trajectories similar to the pattern shown in Fig. 27.

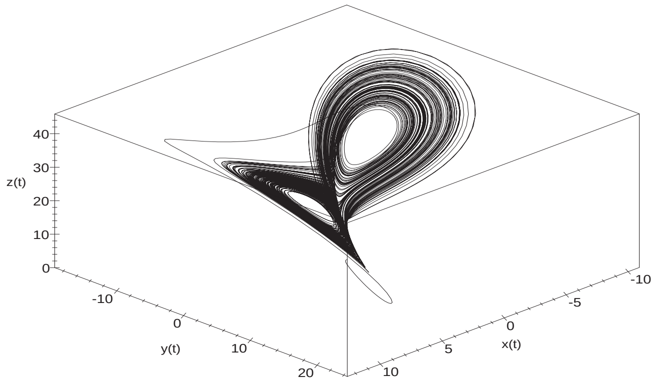


Figure 27. The famous *Lorenz Attractor*, which governs the dynamic behaviour of the solutions of a non-linear reduced-form model for the atmospheric circulation (*Lorenz*, 1963 [138]).

The pattern depicted above is the first example ever recognized by scientists of a so-called "strange attractor" – a complicated invariant set encountered in dissipative dynamic systems that stands out for its *Cantor structure* (see e.g., *Falconer*, 1990 [66]).
It is by no means improbable that certain management sequences $\mathbf{M}_{(4)}^{str}$ are capable of keeping the coevolution, if not in a fixed state, then at least on such bizarrely confined tracks. But contrary to the examples presented in (i) through (iii), we are here not able to describe the explicit form of $\mathbf{P}(\hat{\mathbf{P}}, \hat{t}; t \mid \mathbf{M}_{(4)}^{str})$ in simple mathematical terms.

* * *

All our examples of generalized equilibria in the sense of recurrent motion are taken from the theory of dissipative or symplectic dynamic systems that emerged in the last three decades. This theory is equipped with yet many more patterns according to which a stable coevolution may unfold – like those tenuous fractal objects named "Julia Sets" (*Julia*, 1918 [112]).

However, note that we deal within the geo-cybernetic setting with non-linear dynamic systems which are subject to external control as an additional complication. Thus a thorough analysis might reveal novel and even more complex structures accommodating stable coevolutions.

B. Compound Stabilization.

Due to the extension of the equilibrium concept to recurrent motion, as discussed above, the possibilities for realizing the Stabilization paradigm of Sustainable Development are considerably enhanced. The remaining requirements on geo-cybernetic management are nonetheless high, as virtually *all* sub-variables representing the coevolution state **P** have to be stabilized (dynamically).

As an alternative, the concept of equilibrium may be generalized and thus relaxed to a certain degree, if only *partial aspects* or *aggregated quantities* of the coevolution were considered, stipulating true constancy in time, however. Especially the second option, whose goal is the stabilization of the compound variables, i.e. of the *macro-features* of the environmental system considered, turns out to be quite relevant.

The formal aspects of this fundamental strategy are readily sketched.

Let A, B, C, ... denote pertinent macro-variables which can be derived from the micro-variables $x_1, x_2, \ldots, x_N$ representing the full information on the system in question (for the sake of simplicity, we assume the set of micro-variables to be finite). Thus

$$A \equiv A(x_1, \ldots, x_N)\ ,\ B \equiv B(x_1, \ldots, x_N)\ \ , \text{ etc.} \tag{147}$$

Compound equilibrium then simply means that, e.g.,

$$\dot{A} = 0\ . \tag{148}$$

The necessary condition for this to be satisfied clearly is

$$\sum_{n=1}^{N} \frac{\partial A}{\partial x_n} \dot{x}_n = 0 \quad , \tag{149}$$

but *not* the detailed-balance requirement

$$\dot{x}_1 = \dot{x}_2 = \ldots = \dot{x}_N = 0 \quad . \tag{150}$$

Eq. 149 leaves us with a considerable amount of managerial freedom.

This freedom can well be illustrated by a concrete example that is eminently important for geo-cybernetics. If we select as the pertinent compound variable the mean surface temperature T_{global} of the Earth, then this quantity is mainly a function of the spatial distribution of all greenhouse gas and aerosol particles. The equilibrium condition

$$\dot{T}_{global} = 0 \tag{151}$$

can, in principle, be satisfied by most different regional patterns of compensatory simultaneous enrichment of the Earth's atmosphere with climate-effective substances, the distinct residence times of which have to be taken into account meticulously. The *robustness*, however, of such an artificially-balanced geophysical equilibrium state with respect to natural and anthropogenic disturbances is a different cup of tea – humanity is probably just about to manoeuvre itself unintentionally into a rather risky and fragile situation (*Schult* et al., 1997 [212]; *Feichter* et al., 1997 [70]).

Daly's SD rules (see above) certainly rely on the concept of compound equilibrium as they explicitly allow for *substitution* between "equivalent" resources and do not enforce a detailed-balance ecological accounting. However, which are the aggregate entities to be preserved, and what substitutes are rated equivalent? The answers to these questions are not trivial and the implications of the operational rules may be rather undesirable, as will be demonstrated now for the *energy issue*.

Let us assume that the energy resources that will be accessible to civilization in the medium-term future are restricted to three main components, namely fossil fuels F, renewable biomass energy B, and photovoltaic energy S harvested directly from the sun. Now a naive application of Daly's second rule would call for the preservation of the compound entity

$$E := F + B + S \quad , \tag{152}$$

i.e. the sum of energy bulks stored in some form somewhere on this planet.

However, note that it appears unfeasible to accumulate amounts of energy from photovoltaic collection which are in any way comparable to the huge quantities tucked away in the prospected layers of coal or other fossil fuels. As a matter of fact, there is no point in doing so because the crucial entity for civilization is not the overall amount of existing energy but its daily or annual allowance of energy *consumption*. In other words, the quantity to be preserved is the *sum total of available power*

$$L_E = L_F + L_B + L_S \quad , \tag{153}$$

where L_F denotes the energy per unit time provided by fossil fuels, and so on. The preservation rule

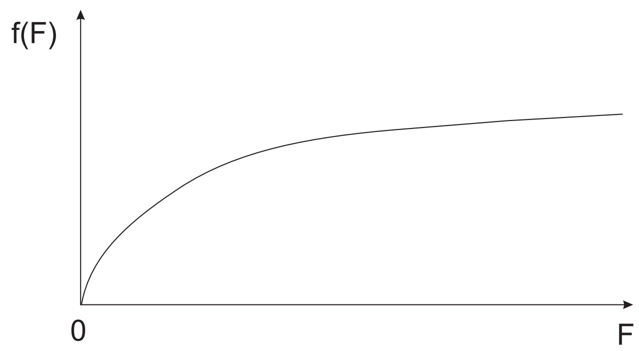
$$\dot{L}_E = 0 \tag{154}$$

guarantees that the *energy-consumption option* for humanity is – at least quantitatively – held constant in the course of time. We emphasize that this approach to SD does not take into account explicitly the economic costs involved.

It seems plausible to represent the instantaneous power supply in the following form:

$$L_E = w_F f(F) + w_B g(B) + w_S A \quad . \tag{155}$$

Here w_F, w_B, w_S are *efficiency functions* that depend mainly on technological and logistic developments and therefore explicitly on time t. $f(F)$ and $g(B)$ are *availability functions* for fossil fuels and biomass, respectively, which depend particularly on the distribution and accessibility of these energy forms, while A simply measures the overall area of installed solar-cell panels. Our assumption that the geographic patterns of fossil fuels deposits and biomass-production sites are basically fixed implies that the functions f and g should – to a first approximation – not depend on t. These functions may deviate, however, markedly from the linear shape. The possible form of $f(F)$ is sketched below:



Here the specific feature $f'(0) \gg 1$ is due to the fact that the least accessible deposits will be the last ones to be exploited. Evidently, we have $f(0) = 0$ (as well as $g(0) = 0$).

Let us now scrutinize the stability condition (154), which is equivalent to the equation

$$\dot{w}_F f(F) + w_F f'(F)\dot{F} + \dot{w}_B g(B) + w_B g'(B)\dot{B} + \dot{w}_S A + w_S \dot{A} = 0 \quad , \tag{156}$$

or the even simpler requirement

$$f'(F)\dot{F} + g'(B)\dot{B} + \dot{A} = 0 \quad , \tag{157}$$

if we assume the efficiency functions to have almost constant values close to unity in time.

However,

$$\dot{F} \;=\; -\varphi(t) \quad , \tag{158}$$

$$\dot{B} \;=\; b(B) - \beta(t) \quad , \tag{159}$$

where $\varphi(t)$ is the current consumption rate of fossil fuels, $b(B)$ is the generation rate of biomass, and $\beta(t)$ is its consumption rate. With all the simplifying hypotheses made, the aggregate stability condition finally boils down to the relation

$$f'(F)\varphi + g'(B)\beta - \dot{A} = g'(B)b(B) \quad . \tag{160}$$

Here the consumption rates φ, β and the substitution rate $\dot{A}$ are the *control variables* for sustained power management.

At a first glance, it seems quite easy to satisfy Eq. 160 in agreement with complementary societal objectives by an appropriate mix of choices for the control variables. This confidence is shattered, however, if we consider, for instance, the limit of fossil fuel depletion, i.e. the process $F \to 0$. Assuming that there is a sub-equilibrium for biomass production and consumption implying

$$\beta = b(B) \quad , \tag{161}$$

we are left with the condition

$$f'(F)\varphi - \dot{A} = 0 \tag{162}$$

to be satisfied in the vicinity of $F = 0$.

However, $f'(F) \gg 1$ for small F as pointed out above. As a consequence, either the consumption rate φ has to drop to almost zero or the photovoltaic-area expansion rate has to rise to almost infinity! This is certainly *not* a showcase for inter-generational equity: the full burden has to be borne anyway by the last generations "in power line", if the preceding generations do not refrain from consuming at a finite rate. On the other hand, if the first generations in line actually do renounce consumption options, then the fossil fuels are virtually useless and cannot be invested in economic and technological development around the globe ...

This example clearly demonstrates that we may run into serious difficulties with even the more sophisticated recipes for compound equilibrium management. Similar insights could be gained from studying the problem of *stabilizing the overall marine fish stocks* (*Safina*, 1995 [203]). Here it seems obvious that the sum total of wild and aquacultural fish has to be preserved, but a spatiotemporal "fair" implementation of such a plan is all but simple.

C. Dynamic Compound Stabilization.

The notion of "generalized equilibrium" as defined in the context of the Stabilization paradigm is wide enough to allow also for combinations of the interpretations explained in A and B. One might, for instance, only demand from geo-cybernetic management that it organized the *recurrent development of certain aggregate variables.* In doing so, however, we must avoid the transition to a blunt laisser-faire strategy. This can be accomplished, e.g., by stipulating maximum tolerance ranges for the variation of certain core entities (like potable water availability) in the sense of paradigm $\mathcal{P}_0$.

4.5.2 Passage to Equilibrium

The implementation of the Stabilization paradigm $\mathcal{P}_4$ is generally achieved through the following sequence of steps:

1. Definition of the *admissible* set of generalized equilibria.

2. Exploration of the coevolution space $\mathbf{C}$ and management pool $\mathfrak{M}$ in search of available generalized equilibria $\mathbf{P}(\hat{\mathbf{P}}, \hat{t}; t \mid \mathbf{M}^*_{(4)})$ in accordance with Step 1.

3. Selection of the *preferable* generalized equilibrium, in the case that more than one of them exist.

4. Confirmation of the *accessibility* from $\mathbf{P}_0$ for the chosen generalized equilibrium. If our geo-cybernetic system does not depend explicitly on time, then a necessary and sufficient condition is

$$\boldsymbol{\Pi}(\hat{\mathbf{P}} \mid \mathbf{M}^*_{(4)}) \subset \mathfrak{U}(\mathbf{P}_0) \quad . \tag{163}$$

5. Qualification of the optional *passages* to $\mathbf{P}(\hat{\mathbf{P}}, \hat{t}; t \mid \mathbf{M}^*_{(4)})$ from $(\mathbf{P}_0, 0)$ and, perhaps, selection of the optimal one according to additional criteria.

We will not be able to say much about the first three steps here, which mainly require normative considerations. Let us therefore assume that a number of admissible generalized equilibria (of the Clark or Daly type, for instance) have been detected and ranked according to some set of criteria. In the rest of this section we will be concerned with Step 4 and Step 5, respectively.

Let us first illustrate what Step 4 is all about. For that purpose, we return once more to our two-dimensional toy universe and restrict the set of admissible generalized equilibria to coevolution fixed points

$$\tilde{\mathbf{P}}_i \equiv \mathbf{P}(\mathbf{M}^i_{(4)}) \quad , i = 1, 2, \ldots \quad , \tag{164}$$

where the $\mathbf{M}^i_{(4)}$ are stabilizing constant managements. A typical constellation is sketched in Fig. 28. In this example, we immediately observe that

$$\tilde{\mathbf{P}}_1 \notin \mathfrak{U}(\mathbf{P}_0), \tilde{\mathbf{P}}_2 \in \mathfrak{U}(\mathbf{P}_0) \quad , \tag{165}$$

so only the second geo-cybernetic fixed point can be approached from the starting point $\mathbf{P}_0$.

When confronted with the full coevolution-management problem, however, the application of the seemingly straightforward criterion (163) may not be feasible or practical any more: why should we trace out the entire accessible universe $\mathfrak{U}(\mathbf{P}_0)$ to confirm the accessibility of a given generalized-equilibrium candidate? Again, it may be more efficient to employ an *inverse approach*, i.e., to start out with the equilibrium in question and to determine its basin of access. Actually the most clever way to prove the attainability of the target state (dynamics) is the *explicit construction* of specific corridors or passages connecting it to $\mathbf{P}_0$. This task is still a highly challenging one, and its solution requires a thorough formal analysis of the structural elements involved.

Such an analysis can be built on previous insights (see, in particular, Sect. 4.3) and is much facilitated by introducing an *"accessibility relation"* between pairs of points in $\mathbf{C}$:

Let us assume in the following that our geo-cybernetics does *not* explicitly depend on time and let $\mathbf{P}_1$, $\mathbf{P}_2$ be arbitrary states in coevolution space. We write

$$\mathbf{P}_1 \curvearrowright \mathbf{P}_2 \tag{166}$$

if $\mathbf{P}_2$ can be reached from $\mathbf{P}_1$ by employing some management episode, i.e. within a finite period of time.

Evidently

$$\mathfrak{U}(\mathbf{P}) \;=\; \{\mathbf{P}' \in \mathbf{C} \mid \mathbf{P} \curvearrowright \mathbf{P}'\} \tag{167}$$

$$\text{and} \quad \mathfrak{U}^{-1}(\mathbf{P}) \;=\; \{\mathbf{P}' \in \mathbf{C} \mid \mathbf{P}' \curvearrowright \mathbf{P}\} \quad . \tag{168}$$

Note that the symbol "$\curvearrowright$" does *not* describe an equivalence relation (but see below): Obviously, we have

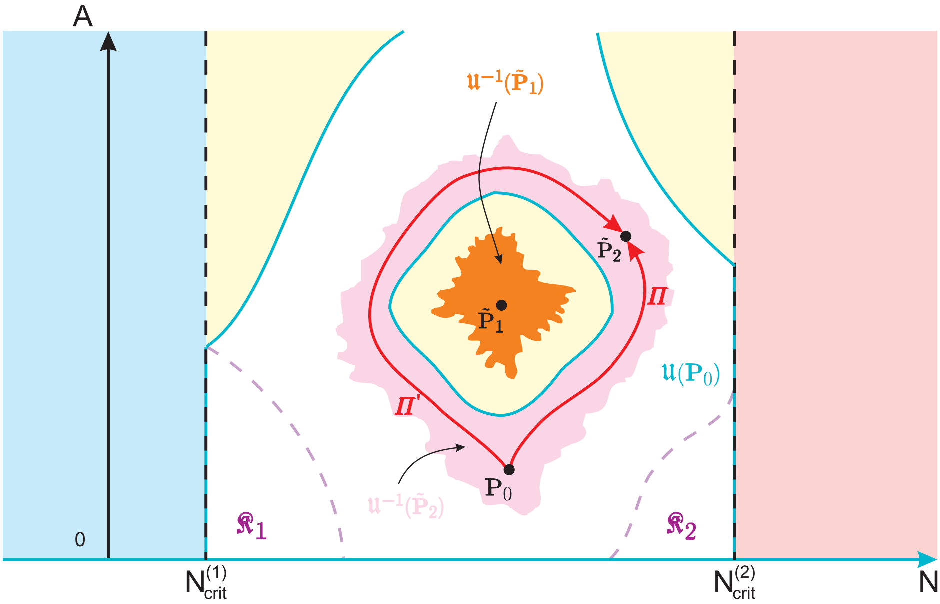


Figure 28. Illustration of pertinent elements involved in the implementation of the Stabilization paradigm. Here $\tilde{\mathbf{P}}_1$, $\tilde{\mathbf{P}}_2$ are admissible coevolution states that can be fixed by appropriate geo-cybernetic management. The preferable state $\tilde{\mathbf{P}}_1$ is unfortunately not accessible from $\mathbf{P}_0$ but the second best choice $\tilde{\mathbf{P}}_2$ is, as indicated by the respective basins of access, $\mathfrak{U}^{-1}(\tilde{\mathbf{P}}_1)$ and $\mathfrak{U}^{-1}(\tilde{\mathbf{P}}_2)$. As a matter of fact, there exist a multitide of coevolution segments which lead from $\mathbf{P}_0$ to $\tilde{\mathbf{P}}_2$. Two rather distinct ones are earmarked through their trajectory segments $\boldsymbol{\Pi}$ and $\boldsymbol{\Pi}'$, respectively.

$$\mathbf{P}_1 \curvearrowright \mathbf{P}_1 \quad , \tag{169}$$

but the *"symmetry property"*

$$\mathbf{P}_1 \curvearrowright \mathbf{P}_2 \quad \Rightarrow \quad \mathbf{P}_2 \curvearrowright \mathbf{P}_1 \tag{170}$$

is generally not fulfilled (due to the possible presence of critical manifolds as discussed in Sect. 4.4).

The *"transitivity property"*, on the other hand, is certainly satisfied: Let $\mathbf{P}_1, \mathbf{P}_2, \mathbf{P}_3 \in \mathbf{C}$ and

$$\mathbf{P}_1 \curvearrowright \mathbf{P}_2, \quad \mathbf{P}_2 \curvearrowright \mathbf{P}_3 \quad . \tag{171}$$

Then we can easily prove that

$$\mathbf{P}_1 \curvearrowright \mathbf{P}_3 \quad . \tag{172}$$

In a similarly straightforward manner it can be shown that the accessibility relations (171) imply

$$\mathfrak{U}(\mathbf{P}_3) \subset \mathfrak{U}(\mathbf{P}_2) \subset \mathfrak{U}(\mathbf{P}_1) \quad , \tag{173}$$

and

$$\mathfrak{U}^{-1}(\mathbf{P}_1) \subset \mathfrak{U}^{-1}(\mathbf{P}_2) \subset \mathfrak{U}^{-1}(\mathbf{P}_3) \quad . \tag{174}$$

More interesting are the relations between the accessible universes and the basins of access of states which are connected by management. Let us assume that $\mathbf{P}_1 \curvearrowright \mathbf{P}_2$ but $\mathbf{P}_2 \not\curvearrowright \mathbf{P}_1$, i.e. $\mathbf{P}_1$ cannot be approached from $\mathbf{P}_2$. As a consequence, we have

$$\mathfrak{U}(\mathbf{P}_1) \neq \mathfrak{U}^{-1}(\mathbf{P}_1) \quad , \tag{175}$$

$$\mathfrak{U}(\mathbf{P}_2) \neq \mathfrak{U}^{-1}(\mathbf{P}_2) \quad , \tag{176}$$

$$\mathfrak{U}(\mathbf{P}_1) \cap \mathfrak{U}^{-1}(\mathbf{P}_2) \neq \emptyset \quad , \tag{177}$$

$$\mathfrak{U}(\mathbf{P}_2) \cap \mathfrak{U}^{-1}(\mathbf{P}_1) = \emptyset \quad . \tag{178}$$

We skip the proof which is again straightforward and not that enlightening. It is most instructive, however, to put together all the topological information contained in Eqs. 173 to 178 within one simple picture as carried out in Fig. 29.

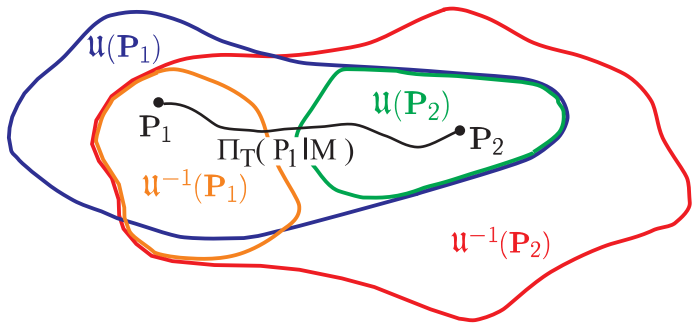


Figure 29. Exemplary topology of pertinent sub-sets of $\mathbf{C}$ in the case $\mathbf{P}_1 \curvearrowright \mathbf{P}_2$, $\mathbf{P}_2 \not\curvearrowright \mathbf{P}_1$. According to our assumption, there exists at least one connecting trajectory segment generated by some management $\mathbf{M}$ within a finite time interval $[0, T]$.

As a matter of fact, the *general statement*

$$\mathbf{P}_1 \curvearrowright \mathbf{P}_2 \Longleftrightarrow \mathfrak{U}(\mathbf{P}_1) \cap \mathfrak{U}^{-1}(\mathbf{P}_2) \neq \emptyset \tag{179}$$

is true for any pair of states in coevolution space, and this statement directly implies Eqs. 177 and 178 in the specific situation considered here. So the sets $\mathfrak{U}(\mathbf{P}_2)$ and $\mathfrak{U}^{-1}(\mathbf{P}_1)$ have to be well separated in Fig. 29. If these sets would touch or even overlap, then we would immediately observe that

$$\mathfrak{U}(\mathbf{P}_1) = \mathfrak{U}(\mathbf{P}_2), \quad \mathfrak{U}^{-1}(\mathbf{P}_1) = \mathfrak{U}^{-1}(\mathbf{P}_2) \quad , \tag{180}$$

and, consequently, $\mathbf{P}_2 \curvearrowright \mathbf{P}_1$ would hold in contradiction to our assumption.

In this case we might qualify the states $\mathbf{P}_1$ and $\mathbf{P}_2$ as "equivalent" in the sense of geo-cybernetic theory.

Definition 9: Consider an arbitrary couple of states $\mathbf{P}_1$, $\mathbf{P}_2$ in $\mathbf{C}$.

If

$$\mathbf{P}_1 \curvearrowright \mathbf{P}_2 \quad \text{and} \quad \mathbf{P}_2 \curvearrowright \mathbf{P}_1 \tag{181}$$

then we declare $\mathbf{P}_1$ and $\mathbf{P}_2$ as *geo-cybernetically equivalent* and write

$$\mathbf{P}_1 \sim \mathbf{P}_2 \quad . \tag{182}$$

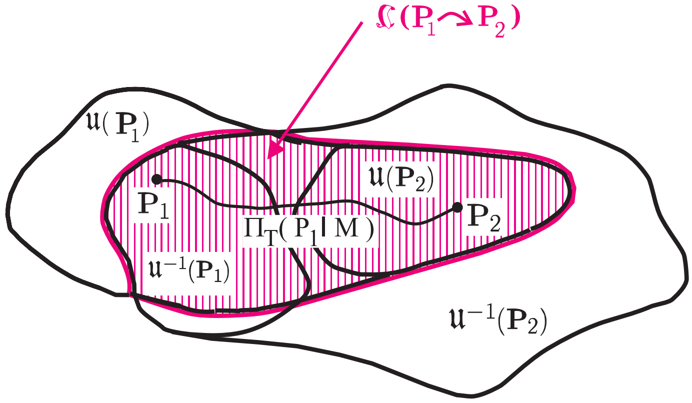
Note that the symbol "$\sim$" now describes a true equivalence relation in the strict mathematical sense, as the three required properties "reflexivity", "symmetry" and "transitivity" are evidently fulfilled. ■

Actually all coevolution states that are not separated by critical manifolds belong to the same *geo-cybernetic equivalence class*. These classes are most important for the Equitization paradigm $\mathcal{P}_3$ (see Sect. 4.4) but less relevant to the Stabilization paradigm $\mathcal{P}_4$, where the one-way accessibility matters.

Definition 10: Let $\mathbf{P}_1, \quad \mathbf{P}_2 \in \mathbf{C}$ and $\mathbf{P}_1 \curvearrowright \mathbf{P}_2$. Then

$$\mathfrak{C}(\mathbf{P}_1 \curvearrowright \mathbf{P}_2) := \mathfrak{U}(\mathbf{P}_1) \cap \mathfrak{U}^{-1}(\mathbf{P}_2) \tag{183}$$

is non-void according to Eq. 179. In fact, each point in this set is a potential intermediate state for geo-cybernetic transition from $\mathbf{P}_1$ to $\mathbf{P}_2$. $\mathfrak{C}(\mathbf{P}_1 \curvearrowright \mathbf{P}_2)$ is therefore called the *geo-cybernetic corridor from* $\mathbf{P}_1$ *to* $\mathbf{P}_2$. ■



In the exemplary situation sketched in Fig. 29 the corridor $\mathfrak{C}(\mathbf{P}_1 \curvearrowright \mathbf{P}_2)$ has the following shape:

We emphasize again that $\mathfrak{C}(\mathbf{P}_1 \curvearrowright \mathbf{P}_2)$ is a one-way street, as a rule. However, if $\mathbf{P}_1 \sim \mathbf{P}_2$ then

$$\mathfrak{C}(\mathbf{P}_1 \curvearrowright \mathbf{P}_2) = \mathfrak{C}(\mathbf{P}_2 \curvearrowright \mathbf{P}_1) \quad , \tag{184}$$

and we may denote this two-way street (supporting *coevolution loops* visiting both $\mathbf{P}_1$ and $\mathbf{P}_2$) by the symbol $\mathfrak{C}(\mathbf{P}_1 \sim \mathbf{P}_2)$. Let us point out that the geo-cybernetic corridors of any type do not have to be simply-connected sub-sets of $\mathbf{C}$.

The *dynamic* entity behind a static corridor $\mathfrak{C}(\mathbf{P}_1 \curvearrowright \mathbf{P}_2)$ is the family of coevolution episodes leading in finite time from $\mathbf{P}_1$ to $\mathbf{P}_2$.

Definition 11: Let us assume that $\mathbf{P}_2$ is accessible from $\mathbf{P}_1$. Therefore the *set of passing managements* $\tilde{\mathfrak{M}}(\mathbf{P}_1 \curvearrowright \mathbf{P}_2) \subset \mathfrak{M}$, is non-void. $\tilde{\mathfrak{M}}(\mathbf{P}_1 \curvearrowright \mathbf{P}_2)$ is determined by the following requirement:

For any $\tilde{\mathbf{M}} \in \tilde{\mathfrak{M}}(\mathbf{P}_1 \curvearrowright \mathbf{P}_2)$ there exists a minimum time $T(\tilde{\mathbf{M}}) < \infty$ such that

$$\mathbf{P}(\mathbf{P}_1, 0; T(\tilde{\mathbf{M}}) \mid \tilde{\mathbf{M}}) = \mathbf{P}_2 \quad . \tag{185}$$

Then the *geo-cybernetic passage* from $\mathbf{P}_1$ to $\mathbf{P}_2$, $Z(\mathbf{P}_1 \curvearrowright \mathbf{P}_2)$, is defined as

$$Z(\mathbf{P}_1 \curvearrowright \mathbf{P}_2) := \left\{ \mathbf{P}_{T(\tilde{\mathbf{M}})}(\mathbf{P}_1, 0; t \mid \tilde{\mathbf{M}}) \;\middle|\; \tilde{\mathbf{M}} \in \tilde{\mathfrak{M}}(\mathbf{P}_1 \curvearrowright \mathbf{P}_2) \right\} \quad . \tag{186}$$

As a consequence, we have

$$\mathfrak{C}(\mathbf{P}_1 \curvearrowright \mathbf{P}_2) = \bigcup_{\tilde{\mathbf{M}} \in \tilde{\mathfrak{M}}(\mathbf{P}_1 \curvearrowright \mathbf{P}_2)} \boldsymbol{\Pi}_{T(\tilde{\mathbf{M}})}(\mathbf{P}_1, 0 \mid \tilde{\mathbf{M}}) \quad . \tag{187}$$

(For the sake of clarity, we have abstained from employing the full notation indicating mangement *episodes* $\tilde{\mathbf{M}}_{T(\tilde{\mathbf{M}})}$ in Eqs. 186 and 187.) ■

If our geo-cybernetic problem does not depend explicitly on time and the target generalized equilibrium is simply a "sustainable" coevolution state $\tilde{\mathbf{P}}$, then "all" we have to do is to identify and analyse the passage $Z(\mathbf{P}_0 \curvearrowright \tilde{\mathbf{P}})$. If this set is non-void then it will be called a *stabilizing passage*. If $Z(\mathbf{P}_0 \curvearrowright \tilde{\mathbf{P}})$ contains more than one element, then the question of the right choice for the actual transition path segment $\mathbf{P}_{T(\tilde{\mathbf{M}})}(\mathbf{P}_0, 0; t \mid \tilde{\mathbf{M}})$ arises. Before dealing with these issues in some depth, let us emphasize that the implementation of the Stabilization paradigm generally confronts us with a more complicated situation:

Let

$$\mathbf{S}(t) := \mathbf{P}(\hat{\mathbf{P}}, \hat{t}; t \mid \mathbf{M}^*) \tag{188}$$

be some generalized equilibrium produced by the stabilizing management $\mathbf{M}^* \equiv \mathbf{M}^*_{(4)} \in \mathfrak{M}$. Let $\tau \geq 0$ and

$$\begin{aligned} \mathbf{S}_\tau(t) &:= \mathbf{S}(t)\Big|_{t\geq\hat{t}+\tau} \\ &= \mathbf{P}(\hat{\mathbf{P}}_\tau, \hat{t}+\tau; t \mid \mathbf{M}^*) \ , \end{aligned} \tag{189}$$

where

$$\hat{\mathbf{P}}_\tau := \mathbf{P}(\hat{\mathbf{P}}, \hat{t}, \hat{t}+\tau \mid \mathbf{M}^*) \equiv \mathbf{S}(\hat{t}+\tau) \ . \tag{190}$$

According to our previous definitions, $\mathbf{S}_\tau(t)$ is again a generalized equilibrium for any choice of τ. Therefore $\mathbf{S}(t)$ defines a *class*

$$C[\mathbf{S}] := \{\mathbf{S}_\tau(t) \mid 0 \leq \tau < \infty\} \tag{191}$$

of stable, i.e. *recurrent* coevolution paths, and it makes sense *to identify the generalized equilibrium with the whole class*. Note that the closed hulls of all the associated coevolution trajectories are identical:

$$\overline{\boldsymbol{\Pi}(\mathbf{S}_\tau)} = \overline{\boldsymbol{\Pi}(\mathbf{S}_0)} \ , \tag{192}$$

where $\mathbf{S}_0 \equiv \mathbf{S}$. This statement is trivial for simple stable coevolutions like fixed states or periodic orbits but less so for "strange" recurrent motion in $\mathbf{C}$.

The parameter τ may be conceived here as a control variable which allows for determining *when* (and where) the environmental system enters the target equilibrium coevolution. In order to exercise wise control, however, we have to identify and analyse the overall *stabilizing passage* $Z(\mathbf{P}_0 \curvearrowright C[\mathbf{S}])$, which connects the initial state $\mathbf{P}_0$ to the generalized equilibrium $C[\mathbf{S}]$. $Z(\mathbf{P}_0 \curvearrowright C[\mathbf{S}])$ consists of coevolution path segments $\mathbf{P}_{\hat{t}+\tau(\tilde{\mathbf{M}})}(\mathbf{P}_0, 0; t \mid \tilde{\mathbf{M}})$, where $\tilde{\mathbf{M}} \in \tilde{\mathfrak{M}}(\mathbf{P}_0 \curvearrowright C[\mathbf{S}])$ is an appropriate management sequence such that for $\tau(\tilde{\mathbf{M}}) < \infty$ we have

$$\mathbf{P}_{\hat{t}+\tau(\tilde{\mathbf{M}})}(\mathbf{P}_0, 0; \hat{t}+\tau(\tilde{\mathbf{M}}) \mid \tilde{\mathbf{M}}) = \mathbf{S}(\hat{t}+\tau(\tilde{\mathbf{M}})) \ . \tag{193}$$

Thus the entire management sequences $\mathbf{M}^{**}$ that bring about transition to and maintenance of stable coevolutionary motion are composed in the following way:

$$\mathbf{M}^{**}(t) = \begin{cases} \tilde{\mathbf{M}}(t) & , \quad 0 \leq t \leq \hat{t}+\tau(\tilde{\mathbf{M}}) \\ \mathbf{M}^*(t) & , \quad \hat{t}+\tau(\tilde{\mathbf{M}}) \leq t \end{cases} \ , \tag{194}$$

$$\text{assuming} \quad \tilde{\mathbf{M}}(\hat{t}+\tau(\tilde{\mathbf{M}})) = \mathbf{M}^*(\hat{t}+\tau(\tilde{\mathbf{M}})) \ . \tag{195}$$

The investigation of the stabilizing passage $Z(\mathbf{P}_0 \curvearrowright C[\mathbf{S}])$ may become rather involved, especially when our geo-cybernetics depends explicitly on time and, consequently, there are no static corridors $\mathfrak{C}(\mathbf{P}_0 \curvearrowright C[\mathbf{S}])$. For descriptive reasons we will therefore restrict ourselves mainly to simple generalized equilibria like fixed states, and autonomous dynamics.

Assume that the target equilibrium is a sustainable coevolution state $\tilde{\mathbf{P}}$. In order to prove the accessibility of $\tilde{\mathbf{P}}$ from $\mathbf{P}_0$ by explicitly constructing the geo-cybernetic corridor $\mathfrak{C}(\mathbf{P}_0 \curvearrowright \tilde{\mathbf{P}})$ or some *sub-corridor* $\bar{\mathfrak{C}}(\mathbf{P}_0 \curvearrowright \tilde{\mathbf{P}}) \subset \mathfrak{C}(\mathbf{P}_0 \curvearrowright \tilde{\mathbf{P}})$, the *stepping-stone approach* may be particularly useful:

Draw an appropriate line (not necessarily a straight one) in coevolution space, which connects $\mathbf{P}_0$ to $\tilde{\mathbf{P}}$, and choose a sequence $\{\mathbf{P}_l\}; l = 1, \ldots, L$, of roughly equidistant intermediate points. Then try to verify the accessibility relations

$$\mathbf{P}_l \curvearrowright \mathbf{P}_{l+1} \tag{196}$$

one by one, starting from the target state, i.e. beginning with

$$\mathbf{P}_L \curvearrowright \tilde{\mathbf{P}} \ . \tag{197}$$

Note that $\mathbf{P}_0 \curvearrowright \tilde{\mathbf{P}}$ holds if all the intermediate relations are fulfilled, as the finite sum of finite passage times is again finite. If certain accessibility relations do not hold, however, try to devise appropriate intermediate detours – quite similar to the way we identify a stepping-stone passage across a shallow brook. Such a procedure also resembles the analytic continuation of functions in the complex plane $\mathbb{C}$, but we have to emphasize that the latter task will be much better defined and easier to achieve, in general.

Within the geo-cybernetic context the stepping-stone approach may become feasible with excessive computer assistance only, as the exploration of multiple combinatorial options tends to be extremely time-consuming.

4.5.3 Quality of Passage

If the desired generalized equilibrium $C[\mathbf{S}]$ is really accessible then, usually, there exist a variety of ways to approach it from $\mathbf{P}_0$. What are the criteria for selecting the transitory management (episode) $\tilde{\mathbf{M}} \in \tilde{\mathfrak{M}}(\mathbf{P}_0 \curvearrowright C[\mathbf{S}])$? In the following, we briefly discuss several plausible modes of determining the concrete avenue to stability.

Example 1 ("Gentleness"):
The most conspicuous feature of any access to $C[\mathbf{S}]$ is the *geometry* of the connecting coevolution trajectory segment $\boldsymbol{\Pi}_{T(\tilde{\mathbf{M}})}(\mathbf{P}_0, 0 \mid \tilde{\mathbf{M}})$ with respect to the target structure. The generalized equilibrium may be approached, e.g., *directly* or *smoothly* or *asymptotically*. This is illustrated in Fig. 30 under the assumption that $\mathbf{S}$ is a periodic orbit in coevolution space. If the Global Subject $\mathcal{S}$ actually picks SD paradigm $\mathcal{P}_4$, then one of the crucial decisions of this "Earth System pilot" will be the choice between bringing about stabilization in a *crash-halt* or a *soft-landing scenario*.

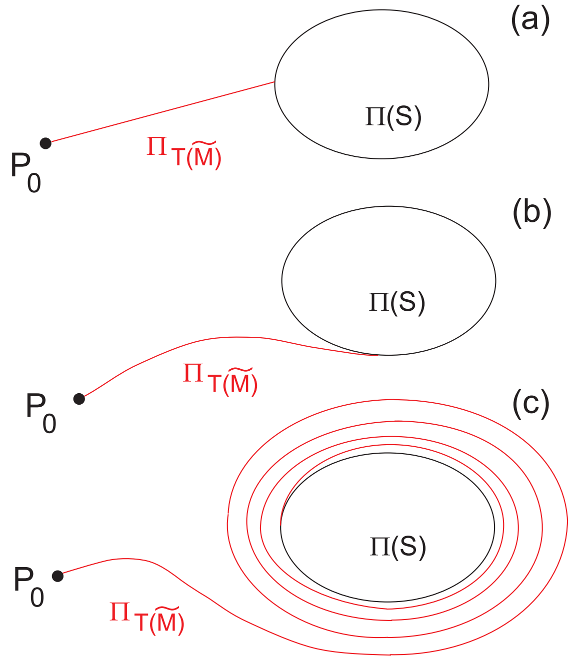


Figure 30. Various ways of approaching the periodic coevolution orbit $\mathbf{S}$, arranged in the order of increasing gentleness. **(a)** Geodesic passage, i.e. minimizing the length of the connecting trajectory segment. **(b)** Tangential passage, i.e. observing differentiability requirements. **(c)** Encircling passage, i.e. gradually relaxing to periodic motion.
Note that the passage nevertheless has to comply with the condition $T(\tilde{\mathbf{M}}) < \infty$.

Example 2 ("Duration"):
An obvious and particularly popular criterion for transitory management is the time needed for entering the target equilibrium. One could, for instance, search for the *minimum passage-time management* $\tilde{\mathbf{M}}^* \in \tilde{\mathfrak{M}}(\mathbf{P}_0 \curvearrowright C[\mathbf{S}])$, such that

$$T(\tilde{\mathbf{M}}^*) \leq T(\tilde{\mathbf{M}}) \quad \text{for any} \quad \tilde{\mathbf{M}} \in \tilde{\mathfrak{M}}(\mathbf{P}_0 \curvearrowright C[\mathbf{S}]) \quad . \tag{198}$$

Such a time-optimal approach, however, may involve sub-optimal or even unpleasant features regarding other criteria like gentleness.

Rather than minimizing the duration of passage to equilibrium, the Global Subject may have to organize the transition to stable coevolution in a quite *limited stretch of time*. Such a pressure for action might arise from the foreseeable exhaustion of pertinent natural resources or, more probably, from the time restrictions on the political mandate of national and global decision makers: the public may either lose patience and ask for more radical action or install a restorational regime, if the transition process takes too long.

If the time limit is set to be $\hat{T}$, say, then the main geo-cybernetic task is to identify the *sub-passage*

$$Z_{\leq \hat{T}}(\mathbf{P}_0 \curvearrowright C[\mathbf{S}]) \subset Z(\mathbf{P}_0 \curvearrowright C[\mathbf{S}]) \quad , \tag{199}$$

which contains the coevolution path segments that are run through in no more than $\hat{T}$ time units. This sub-passage is therefore generated by management episodes

$$\tilde{\mathbf{M}} \in \tilde{\mathfrak{M}}_{\leq \hat{T}}(\mathbf{P}_0 \curvearrowright C[\mathbf{S}]) \subset \tilde{\mathfrak{M}}(\mathbf{P}_0 \curvearrowright C[\mathbf{S}]) \quad , \tag{200}$$

that satisfy

$$T(\tilde{\mathbf{M}}) \leq \hat{T} \quad . \tag{201}$$

The actual management sequence employed may be singled out from the elements of $\tilde{\mathfrak{M}}_{\leq \hat{T}}(\mathbf{P}_0 \curvearrowright C[\mathbf{S}])$ eventually by convenience considerations.

Example 3 ("Costs"):
Another eligible criterion for qualifying the management sequences contained in $\tilde{\mathfrak{M}}(\mathbf{P}_0 \curvearrowright C[\mathbf{S}])$ is the costliness of passage to equilibrium. As a pre-requisite for such an evaluation we need a functional

$$G[\mathbf{P}(\mathbf{P}_0, 0; t \mid \tilde{\mathbf{M}})] \equiv G(t \mid \tilde{\mathbf{M}}) \tag{202}$$

that determines the *incremental economic costs* along the coevolution path segment $\mathbf{P}(\mathbf{P}_0, 0; t \mid \tilde{\mathbf{M}})$. To be more precise, $G(t \mid \tilde{\mathbf{M}})$ measures the current costs per time unit in percentage of gross global product, which arise from employing the geo-cybernetic management $\tilde{\mathbf{M}}$ instead of doing nothing to steer the Earth System ("Business as Usual").

The overall incremental costs of the transitory management $\tilde{\mathbf{M}}$ are then given by

$$G(\tilde{\mathbf{M}}) := \int_0^{T(\tilde{\mathbf{M}})} G(t \mid \tilde{\mathbf{M}})\, dt \quad . \tag{203}$$

One could now look for the management sequence $\tilde{\mathbf{M}}^*$ that *minimizes the total costs* of passage to equilibrium, i.e.

$$G(\tilde{\mathbf{M}}^*) \leq G(\tilde{\mathbf{M}}) \quad \text{for any} \quad \tilde{\mathbf{M}} \in \tilde{\mathfrak{M}}(\mathbf{P}_0 \curvearrowright C[\mathbf{S}]) \quad . \tag{204}$$

From the point of view of economics, however, it makes more sense to keep the temporal (for instance, annual) costs of geo-cybernetic management below a certain *threshold* $\hat{G} \in \mathbb{R}$. This defines again a sub-set

$$\tilde{\mathfrak{M}}_{\leq \hat{G}}(\mathbf{P}_0 \curvearrowright C[\mathbf{S}]) \subset \tilde{\mathfrak{M}}(\mathbf{P}_0 \curvearrowright C[\mathbf{S}]) \tag{205}$$

of passing management sequences which satisfy

$$G(t \mid \tilde{\mathbf{M}}) \leq \hat{G} \quad \text{for} \quad t \in [0, T(\tilde{\mathbf{M}})] \quad . \tag{206}$$

The signatory states of the Framework Convention on Climate Change (*UN*, 1995 [236]) are clearly confronted with problems of that kind: What amount of "mitigation costs" for stabilizing the atmospheric CO_2-concentration, or even the climate, is still tolerable for the various players involved? However, note that all their problems would vanish into the air if the set

$$\tilde{\mathfrak{M}}_{\leq 0}(\mathbf{P}_0 \curvearrowright C[\mathbf{S}]) \tag{207}$$

turned out to be non-void: this is the set of *"no-regret options"* for passage to equilibrium.

Let us finally point out that, instead of the purely economic costs, also the social, ethical, or ecological costs of transitory management may (or must) be considered. An integrated evaluation can be based again on the "Lagrangian" $L(\mathbf{P})$.

4.6 Complex Paradigms

Now that we have finished our tour d'horizon of the *pure SD paradigms* listed in Tab. 1, we might ask ourselves which of these paradigms will be chosen by the Global Subject $\mathcal{S}$ as the relevant guiding light for geo-cybernetic management. We will not, however, try to give an answer that obviously has to transpire from a democratic election process rather than from a scientific selection procedure.

We shall instead point out that in future reality (or real future, if you like) such an election process will probably not generate a clear-cut decision for one single paradigm. So $\mathcal{S}$ may have to match almost incommensurate SD strategies, and we will briefly investigate in the rest of this section the formal aspects arising from the task of satisfying *coincident* pure paradigms.

Let us begin with the observation that a multi-objective mandate can reduce or enhance the decision dilemmata which tend to plague the actors in most control problems. Specifically within our geo-cybernetic context, we have to remember that some of the pure paradigms may provide us with a precise recipe for determining *the* "correct" management sequence $\mathbf{M}^*$ (Optimization, Equitization), while the other paradigms leave us with considerable ambiguity on that score. So, given a desired coincidence of several pure paradigms, the worst case arises if the unique management sequences selected according to the respective rules of the individual paradigms are not identical. We may qualify such a situation as the *competition of pure paradigms*. The best case, on the other hand, arises if the individual paradigms define a sequence of nested sub-sets of $\mathfrak{M}$ where the innermost set might embrace one single element only, namely $\mathbf{M}^*$. We may qualify this situation as the *cooperation of pure paradigms*.

In practice, however, neither the competition nor the cooperation of pure paradigms will occur "by accident" and the Global Subject will be confronted with a quite mixed case. Such cases can be successfully dealt with by defining *complex SD paradigms*, where the individual components are *ranked* or *compared* in a clear-cut and consistent manner. An appropriate methodology has been developed in the last decades by *multicriterion decision theory* (see, e.g., *Bell* et al., 1977 [17]). In the following we will briefly discuss the most important ways of constructing complex paradigms and some of the problems associated with these constructions.

Whether we deal with just one SD paradigm or several of them simultaneously, the ultimate goal of all our efforts is to identify the "best management $\mathbf{M}^*$ for running planet Earth". The distinct pure paradigms provide us with specific information (or even algorithms) for selecting $\mathbf{M}^*$, and practically all this information may be compressed into *quality functionals* $Q_{\mathcal{P}_l}[\mathbf{P}(\mathbf{M})]$, where the index $l = 1, \dots, L$ counts the eligible fundamental strategies (see Sect. 3). Our analysis of complex paradigms will be based on these functionals, which we assume to be scalar entities for the sake of simplicity. For any $\mathcal{P}_l$ there exists a non-void set $\mathfrak{M}^*_{(l)} \subset \mathfrak{M}$ of available management sequences such that

$$Q_{\mathcal{P}_l}[\mathbf{P}(\mathbf{M})] \leq Q_{\mathcal{P}_l}[\mathbf{P}(\mathbf{M}^*_{(l)})] \tag{208}$$

for all $\mathbf{M}^*_{(l)} \in \mathfrak{M}^*_{(l)}$ and arbitrary $\mathbf{M} \in \mathfrak{M}$.

Example 1 ("Pareto Efficiency"):
Let us assume that the Global Subject has to comply with all L SD paradigms simultaneously. This will not pose any problem if

$$\mathfrak{M}^{**} := \mathfrak{M}^*_{(1)} \cap \mathfrak{M}^*_{(2)} \cap \ldots \cap \mathfrak{M}^*_{(L)} \neq \emptyset \quad , \tag{209}$$

i.e., if there is at least one management sequence $\mathbf{M}^{**}$ that maximizes all quality functionals at the same time. A pictorial representation of such a situation is given in Fig. 31.

Eq. 209 applies, for instance, when the coincident paradigms $\mathcal{P}_1, \dots, \mathcal{P}_L$ are *indifferent* with respect to each other, so any management sequence $\mathbf{M} \in \mathfrak{M}$ can be split up in the following way:

$$\mathbf{M} = (\mathbf{M}_1, \dots, \mathbf{M}_L) \quad , \tag{210}$$

where the *management component* $\mathbf{M}_l$ acts exclusively on processes pertinent to $\mathcal{P}_l$, and in no way affects the compliance with all the other pure paradigms. If, for example, the economic growth mechanisms around

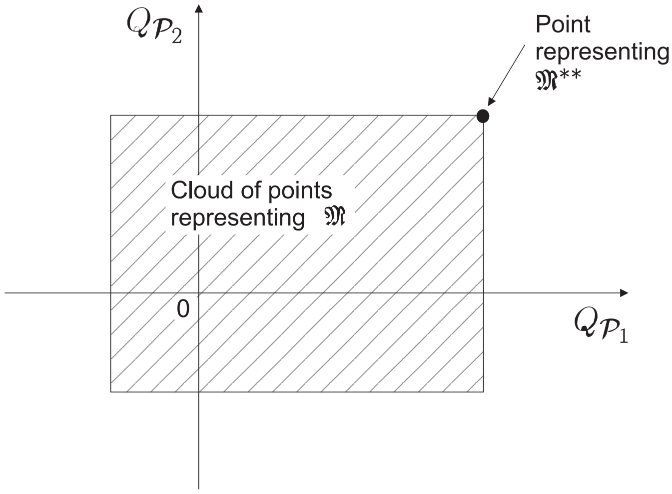


Figure 31. Assuming $L = 2$, the "option space" $\mathfrak{M}$ is projected onto the "quality plane" $\mathbb{R}^2$ through the map $q(\mathbf{M}) = (Q_{\mathcal{P}_1}[\mathbf{P}(\mathbf{M})], Q_{\mathcal{P}_2}[\mathbf{P}(\mathbf{M})])$. Note that this map is generally not injective, so many different management sequences may lurk behind one single dot in $\mathbb{R}^2$. The elements in $\mathfrak{M}^{**}$ are optimal with respect to $\mathcal{P}_1$ *and* $\mathcal{P}_2$ and therefore generate the *upper-right corner point* of the $\mathfrak{M}$-cloud, which has to be *locally rectangular*.

the globe could be completely decoupled from the state of the natural ecosphere, then Optimization and Pessimization strategies might be pursued in parallel.

As a consequence of the general *separability* of $\mathbf{M}$, the quality functionals would be of the type

$$Q_{\mathcal{P}_l}[\mathbf{P}(\mathbf{M})] = Q_{\mathcal{P}_l}[\mathbf{P}(\mathbf{M}_1, \ldots, \mathbf{M}_L)] \equiv Q_{\mathcal{P}_l}(\mathbf{M}_l) \quad . \tag{211}$$

Thus

$$\begin{aligned} Q_{\mathcal{P}_l}[\mathbf{P}(\mathbf{M}_1, \ldots, \mathbf{M}_l, \ldots, \mathbf{M}_L)] &= Q_{\mathcal{P}_l}(\mathbf{M}_l) \\ &= Q_{\mathcal{P}_l}[\mathbf{P}(\overline{\mathbf{M}}_1, \ldots, \mathbf{M}_l, \ldots, \overline{\mathbf{M}}_L)] \end{aligned} \tag{212}$$

for any choice of the L-1-tupel of management components

$$(\overline{\mathbf{M}}_1, \ldots, \overline{\mathbf{M}}_{l-1}, \overline{\mathbf{M}}_{l+1}, \ldots, \overline{\mathbf{M}}_L) \quad . \tag{213}$$

Eq. 212 directly implies that the $\mathfrak{M}$-cloud in quality space is *globally rectangular*, as exemplified in Fig. 31. In particular, $\mathfrak{M}^{**} \neq \emptyset$, and this sub-set of $\mathfrak{M}$ consists of management sequences of the form $(\mathbf{M}_1^*, \ldots, \mathbf{M}_L^*)$, where each component $\mathbf{M}_l^*$ maximizes the respective quality functional $Q_{\mathcal{P}_l}$.

In general, however, Eq. 209 will *not* be satisfied and we have to deal with really conflicting multiple objectives. This situation is typically reflected by the shape of the $\mathfrak{M}$-cloud in L-dimensional quality space. If we generalize the formalism sketched in the context of Fig. 31, then this "cloud" is given by the set

$$Q(\mathfrak{M}) := \{q(\mathbf{M}) \mid \mathbf{M} \in \mathfrak{M}\} \subset \mathbb{R}^L \quad , \tag{214}$$

where

$$q(\mathbf{M}) := (Q_{\mathcal{P}_1}[\mathbf{P}(\mathbf{M})], \ldots, Q_{\mathcal{P}_L}[\mathbf{P}(\mathbf{M})]) \quad . \tag{215}$$

As a rule, the boundary of $Q(\mathfrak{M})$ is *curvilinear*, as illustrated in Fig. 32.

Under these generic circumstances a *complex paradigm* is defined by the obligation to ensure at least *Pareto efficiency*, i.e., choose management sequences only that generate points on the Pareto frontier. The corresponding sub-set $\mathfrak{M}_F \subset \mathfrak{M}$ is determined in the general case by the following requirement:

$\mathbf{M} \in \mathfrak{M}_F \Leftrightarrow$ There is no $\overline{\mathbf{M}} \in \mathfrak{M}$ such that

$$\begin{aligned} Q_{\mathcal{P}_l}[\mathbf{P}(\overline{\mathbf{M}})] > Q_{\mathcal{P}_l}[\mathbf{P}(\mathbf{M})] &\text{ for some } l \in \{1, \ldots, L\} \text{ and} \\ Q_{\mathcal{P}_{l'}}[\mathbf{P}(\overline{\mathbf{M}})] \geq Q_{\mathcal{P}_{l'}}[\mathbf{P}(\mathbf{M})] &\text{ for } l' \neq l \ . \end{aligned} \tag{216}$$

Note that Pareto efficiency is a rather weak selection criterion, so we may be stuck with a considerable amount of geo-cybernetic ambiguity if we built our complex paradigm upon this criterion.

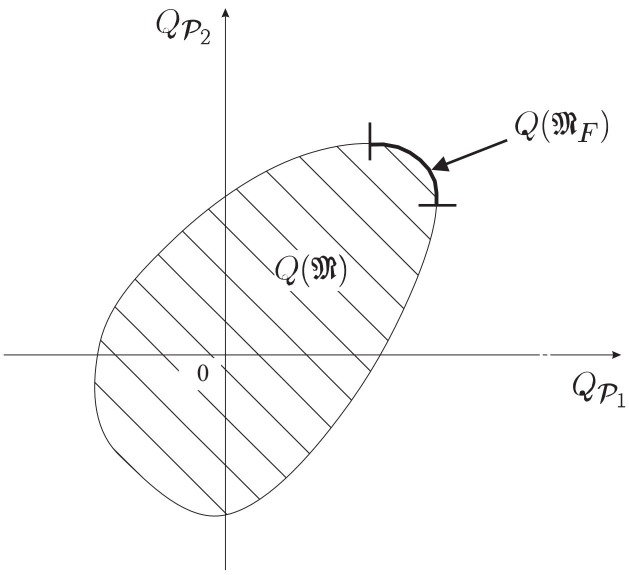


Figure 32. Typical shape of the $\mathfrak{M}$-cloud, $Q(\mathfrak{M})$, in the two-dimensional setting familiar from Fig. 31. Instead of an optimal cornerpoint, $Q(\mathfrak{M}^{**})$, we now observe an extended *Pareto frontier,* $Q(\mathfrak{M}_F)$. Moving along this boundary segment of $Q(\mathfrak{M})$ consistently improves the quality with respect to the one paradigm, yet worsens the quality with respect to the other. Moving away from $Q(\mathfrak{M}_F)$ to other parts of $Q(\mathfrak{M})$, however, necessarily worsens the quality with respect to *both* paradigms.

Example 2 ("Hierarchical Order"):
The integration of coincident pure paradigms within one complex paradigm is rather straightforward when the $\mathcal{P}_l$ involved can be *ranked* in an unambiguous way. Such a ranking may directly result from the preferences of $\mathcal{S}$, i.e. from the "democratically averaged" volitions of all actors in the global E & D process. The so-established hierarchy of pure paradigms defines a *"super-paradigm"* for management selection, which operates like this:

Let Λ be a permutation of the set $\{1, 2, \ldots, L\}$ such that $\mathcal{P}_l$ is on level $\lambda = \Lambda(l)$ of the paradigm hierarchy. So, if we introduce the symbol ${}^{\lambda}\mathcal{P}$ to indicate the pure paradigm of λ^{th} priority, we have the relation

$$\mathcal{P}_l = {}^{\Lambda(l)}\mathcal{P} \quad . \tag{217}$$

Conversely

$${}^{\lambda}\mathcal{P} = \mathcal{P}_{\Lambda^{-1}(\lambda)} \quad , \tag{218}$$

where Λ^{-1} is the permutation inverting Λ.

Let us further introduce sub-sets ${}^{(\lambda)}\mathfrak{M}^*$ of $\mathfrak{M}$ in the following inductive way:

$${}^{(1)}\mathfrak{M}^* := \mathfrak{M}^*_{\Lambda^{-1}(1)} \quad . \tag{219}$$

For $\lambda = 1, \ldots, L-1$ we define ${}^{(\lambda+1)}\mathfrak{M}^*$ to be the quality-maximizing sub-set of ${}^{(\lambda)}\mathfrak{M}^*$ with respect to paradigm ${}^{(\lambda+1)}\mathcal{P}$, i.e.,

$${}^{(\lambda+1)}\mathfrak{M}^* \subset {}^{(\lambda)}\mathfrak{M}^* \tag{220}$$

and

$$Q_{{}^{\lambda+1}\mathcal{P}}\left[\mathbf{P}({}^{(\lambda)}\mathbf{M}^*)\right] \leq Q_{{}^{\lambda+1}\mathcal{P}}\left[\mathbf{P}({}^{(\lambda+1)}\mathbf{M}^*)\right] \tag{221}$$

for all ${}^{(\lambda+1)}\mathbf{M}^* \in {}^{(\lambda+1)}\mathfrak{M}^*$ and arbitrary ${}^{(\lambda)}\mathbf{M}^* \in {}^{(\lambda)}\mathfrak{M}^*$.

The operational scheme for the super-paradigm in question, namely the ordered set $({}^1\mathcal{P}, {}^2\mathcal{P}, \ldots, {}^L\mathcal{P})$, is now readily formulated in terms of a selection algorithm. In the first step, determine the set ${}^{(1)}\mathfrak{M}^*$, which is optimal with respect to the top-priority pure paradigm. If ${}^{(1)}\mathfrak{M}^*$ contains more than one element, identify the sub-set ${}^{(2)}\mathfrak{M}^*$, which is *conditionally* optimal with respect to the second-most important pure paradigm, and so on. The end product of this algorithm is the set ${}^{(L)}\mathfrak{M}^* \subset \mathfrak{M}$, which is supposed to account for all possible ecological, economic, social and cultural preferences and values. Any remaining management ambiguity has to be removed ad hoc.

Let us conclude here with a specific example of a potential super-paradigm for managing humanity's interference with the Earth's climate. With respect to this crucial aspect of geo-cybernetics the following hierarchy of pure paradigms seems appropriate:

$$\begin{aligned}({}^1\mathcal{P}, {}^2\mathcal{P}, {}^3\mathcal{P}, {}^4\mathcal{P}) &= (\mathcal{P}_2, \mathcal{P}_4, \mathcal{P}_3, \mathcal{P}_1) \equiv \\ &\equiv (\text{Pessimization}, \text{Stabilization}, \text{Equitization}, \text{Optimization}) \quad . \end{aligned} \tag{222}$$

Thus the grand strategy is to avoid catastrophe domains at any rate, to achieve climate stabilization far away from the disaster zones, to bring about stability in an equitable way in consideration of the needs of the developing countries and, finally, to carry out the climate management in the most cost-effective way. We will come back to this super-paradigm at the very end of our essay.

Example 3 ("Conversion"):
The basic assumption here is that all possible pure paradigms may matter, but that their respective qualities can be converted into one single "currency" – US dollars, letters of indulgence, neg-entropy, or what have you. In other words, we are able to define a *generalized quality functional*

$$Q[\mathbf{P}(\mathbf{M})] := \sum_{l=1}^{L} \alpha_l Q_{\mathcal{P}_l}[\mathbf{P}(\mathbf{M})] \quad , \tag{223}$$

which measures the overall "value" of a given coevolution $\mathbf{P}(\mathbf{M})$ in appropriate common units. The fixed *weights* $\alpha_l; l = 1, \ldots, L$, are specific conversion factors that reflect the comparative importance of the distinct pure paradigms for the global community. Usually we have

$$\alpha_l \geq 0 \quad \text{for all} \quad l \quad , \tag{224}$$

and a normalization condition

$$\sum_{l=1}^{L} \alpha_l = 1 \tag{225}$$

may be satisfied without loss of generality.

The resulting complex paradigm operates in an obvious manner: simply try to identify the set $\mathfrak{M}^* \subset \mathfrak{M}$, the elements of which maximize the generalized coevolutionary quality, i.e.,

$$Q[\mathbf{P}(\mathbf{M})] \leq Q[\mathbf{P}(\mathbf{M}^*)] \tag{226}$$

for all $\mathbf{M}^* \in \mathfrak{M}^*$ and arbitrary $\mathbf{M} \in \mathfrak{M}$.

We emphasize that all sorts of cost-benefit analyses of geo-cybernetics measures (like reduction of greenhouse-gas emissions) rely, implicity but heavily, on the convertibility of distinct E & D qualities through the concept of "monetizing".

* * *

We close this section with several remarks.

(i) Total quality functionals for the comparison of pure paradigms do not have to be of the linear-combination type as expressed in Eq. 223.
A more general ansatz assumes that

$$Q[\mathbf{P}(\mathbf{M})] = H\left(Q_{\mathcal{P}_1}[\mathbf{P}(\mathbf{M})], \ldots, Q_{\mathcal{P}_L}[\mathbf{P}(\mathbf{M})]\right) \quad , \tag{227}$$

where the function H may be *non-linear* in some or all of its arguments.

(ii) Neither a complete hierarchy nor a full convertibility of coincident pure paradigms may transpire from a global volition survey. As a matter of fact, a *"caste system"* of paradigms is more likely to result from democratic election processes. This means that there is a macro-hierarchy of paradigms, where each caste may contain several convertible elements – but convertibility does not apply across the "class barriers". The operational scheme for the corresponding complex paradigm is easily constructed by amalgamating the procedures described in Examples 2 and 3, respectively.

(iii) Finally, we should point out that the relationship between pure and complex paradigms, as we have defined them, is quite different from the relationship between pure and *mixed* strategies in mathematical game theory (see, e.g., *Binmore*, 1990 [24]). Mixed strategies refer to the *aleatoric choice* of tactics from a set of pure game strategies according to a given probability distribution, while complex paradigms are basically deterministic concepts. The latter restriction may and has to be relaxed very often, however, for the practical purposes of geo-cybernetics. This relaxation affects primarily the implementation of management sequences as we will discuss in Sect. 6.

5. Integrated Modelling: Exploring Virtual Planetary Futures

The general structure of the task as defined by geo-cybernetics is the same as the problem structure encountered in *ordinary control theory* (see, e.g., *Bellmann*, 1957 [18]; *Pontryagin*, 1962 [186]; *Lee* and *Markus*, 1967 [131]; *Dantzig* and *Veinott*, 1968 [53]). There is archaeological evidence that, e.g., the control of irrigation systems in Mesopotamia was a well-developed art at least by the 20th century BC, but a serious scientific study of the field began only after World War II. Control theory can be viewed as the art of regulating the environment, in the physical, biological, or even social sense, and geo-cybernetics "simply" extends this art to the global scale.

The selection of overall objectives, or paradigms, is undoubtedly a crucial element of any control exercise – we have extensively discussed this aspect regarding global environmental management in the last section. Yet other elements matter as well, for instance, the various types of possible readjustments of an initially chosen control strategy. We may analyse the *problem anatomy* of geo-cybernetics by comparing it to the task of navigating a ship in foreign-going trade. We will encounter many analogies, but there are fundamental differences as well: managing the coevolution is certainly a unique challenge and asks also for techniques that cannot be provided by traditional control theory and empirics.

The following table lists and confronts the main control aspects of navigation at sea and geo-cybernetics, respectively.

Table 2: Elements of Control

Number of Element	**Foreign-Going Trade**	**Geo-Cybernetics**
1	*Selection of targets and boundary conditions* by orderer (ship-owner, charterer etc.). Example: Ship cargo X to harbour Y before deadline Z at minimal costs and risks	*Selection of pure or complex paradigm* according to cosmos of individual and collective preferences as reflected particularly by the ethical-voluntative component $\mathcal{V}$ of the Global Subject $\mathcal{S}$
2	*Installation of crew*, mainly composed of *executive staff* (captain, officers, etc.) and *technical staff* (navigators, machine operators, etc.)	*Election or emergence* of the *executive component* $\mathcal{M}$ of $\mathcal{S}$, i.e. political institutions and representatives in charge of international E & D management. $\mathcal{M}$ is assisted by a crowd of established scientific and technical advisors, constituting the *component* $\mathcal{B}$ ("Global Brain") of the Global Subject
3	*Synopsis of available relevant information*, e.g., nautical charts, data on climate and ocean currents, information about accessible harbours and political conditions in stop- over countries, files on cargo and crew. Based on that information, *composition of a navigation model* for planning games	*Survey of all available information* about – the Earth System – external driving forces – control options and instruments. Based on that information, *composition of (qualitative and quantitative) simulation models* for coevolution gaming exercises

continued on next page

continued from previous page

Number of Element	**Foreign-Going Trade**	**Geo-Cybernetics**
4	*Determination of course*, i.e. optimal cruising strategy within the framework of the map exercise, using elementary logic and geometry, nautical instruments, risk analysis, expert knowledge, etc.	*Determination of optimal management sequence* $\mathbf{M}^*$ within the framework of coevolution modelling, using mathematical calculus, numerical search algorithms, educated guesswork, etc., as employed by the representatives of $\mathcal{B}$
5	Navigation, i.e. *translation pre-calculated of cruising strategy into real motion* at sea through control devices. Steering is supported by *instruments* indicating vessel parameters and *relative* movement with respect to transport medium (e.g., speedometer)	Geo-cybernetic action, i.e. *implementation of* $\mathbf{M}^*$ through the organs of $\mathcal{M}$. Coevolution management is supported by sets of *indicators* monitoring, e.g., actor compliance with geo-cybernetic agreements and *relative* movement in coevolution space
6	*Location*, i.e. checking of absolute geographical position for course validation by means of fixed sky- or landmarks	*Determination of absolute position* in coevolution space, in particular with respect to catastrophe domains and political target states. Example: Inspection of actual CO_2-concentration in atmosphere as a complement to continuous emission monitoring
7	*Course correction* if absolute information reveals deviation from *pre-calculated optimal cruising strategy*	*Readjustment of E & D measures* if absolute information reveals insufficiency of envisaged steps to keep coevolution on *desired track*
8	*Local evading manoeuvres* in response to short-term information about *unpredictable events* (iceberg, storm, etc.)	*Episodical small-scale modification* of coevolution strategy due to *stochastic phenomena* (volcanic eruption, political crisis, etc.)
9	*Major revision of cruising strategy* due to additional *information of great (i.e. large-scale and/or long-term) moment* Example: Shutdown of Suez Canal as a consequence of war	*Revision of entire management strategy* $\mathbf{M}^*$ due to – new scientific insights into the basic functioning of the Earth System – new technological breakthroughs extending the options of coevolution management, i.e. additional *information of global importance*
10	*Re-evaluation of targets and boundary conditions* as a consequence of overall development of facts and interests	*Substitution of initial coevolution paradigm* by a new one reflecting modified knowledge and attitude of Global Subject

Our table is obviously an extremely compressed account and comparison of two rather involved control problems, and a number of comments could be made. We will confine ourselves, however, to just two direct remarks.

(i) A fundamental difference between foreign-going trade and geo-cybernetics becomes evident when considering, for instance, Element 3: while sea passages to distant shores are, in principle, repeatable enterprises that may draw heavily on former experience, the man-made passage of the Earth System through coevolution space is a one-way trip of a unique vessel. Thus, any experience in steering this vessel has to be gathered along the way. This fact dramatically enhances the *importance of simulation modelling*, as we will discuss a bit later.

(ii) At least four different types of revisionary actions are involved in any complex control exercise (Elements 7 to 10). The order in which these readjusting steps and the other elements listed above have to be executed is not completely fixed. As a matter of fact, certain control measures like episodical course correction in response to stochastic events may be necessary over and over again. This general observation implies that the Global Subject has to perform its geo-cybernetic task with utmost *flexibility*. The latter is *even more important than precision*, as we will explain in Sect. 6 which deals with "Fuzzy Control".

In the rest of this section, we will focus on those two technical aspects that are most important and characteristic for the control object considered in geo-cybernetics, namely (full or partial) *"Earth System modelling"* and *"sustainability indication"*.

Let us first re-emphasize that our planet is a *historical unicum* and thus suitable for experimental investigation and testing only in a very restricted sense. This almost self-evident observation rules out the conventional heuristic approach as employed especially in the natural sciences. Physics, for instance, which is often considered to be the model discipline of the 20th century, basically deals with *ahistoric universals* and therefore, probably unconsciously, carries on the tradition of Abelard's mediaeval scholasticism (*Gilson*, 1955 [88]). According to *Popper* [187] the methodological credo of physics can be summarized as follows:

Based on evidence of any type, construct a hypothesis with respect to the behaviour of a given universal (e.g., a quark or a black hole). In the next step of the heuristic process, set up experiments with individual representatives of the universal considered. Reject the hypothesis — for all representatives everywhere and forever — if it is falsified by one single spatiotemporal observation ("event"). Retain the stock of yet unfalsified hypotheses as knowledge ready for recall. Note that, according to this recipe, our net wisdom can only grow if the production rate of hypotheses exceeds the falsification rate. Present-day science seems to satisfy the latter condition quite easily ...

Regardless of the quality (and falsifiability!) of Popper's epistemological hypothesis in view of the real research process, the methodo-logic just outlined does certainly *not* apply to Earth System Analysis. We are not willing or allowed to sacrifice the integrity of the one and only planetary specimen we have got for the sake of scientific progress. So most of those wonderful geo-experiments we might design are not at our disposal.

As a consequence, we are left with a fundamental epistemological and ethical dilemma. If anybody makes conjectures about, say, the impacts of CO_2-tripling in the atmosphere or of the shut-down of the Conveyor Belt or of the loss of 90% of the planet's biodiversity – do we *really* want to put these conjectures to the test? Yet the degree of truth of any such hypothesis is crucial as regards any mitigative or adaptive action of the Global Subject. Thus we can formulate the following "theorem" of Earth System Analysis:

"Hypotheses about Global Change are the less falsifiable the more they are relevant to humanity!"
(*Schellnhuber*, 1997 [206])

So, whenever the rejection or validation of a truly pertinent conjecture about the Earth System takes place, then this evaluation is brought about "by accident", i.e., as the result of economic, political, etc. action without scientific rhyme or reason. There is some hope, of course, that the careful inspection of accessible geological palaeo-archives (ice cores, lacustrine sediments, stromatolites and so on) will reveal the responses of the planetary ecosystem to certain major perturbations. However, note that this very system has evolved considerably since the fixation of the proxy data at hand (through plate-tectonic motion, for example), so the Earth System analyst is in a similar position as the historian who tries to make predictions about the future of a given society: the lessons of the past may provide useful hints, but they may also turn out to be completely worthless because some decisive control factor or boundary condition has changed.

There is one way out of this dilemma, however, namely *virtual* falsification or verification of Global Change hypotheses with the help of *artificial copies of the Earth System* or of crucial parts of the latter. These copies are (geo-)cyberspace representatives of *integrated simulation models* that can be perceived as *synthetic universals* substituting the individual real system in question. The so-created digital globes or regions provide us with testbeds for no-regret experimentation with major manipulations or perturbations of the ecosphere-anthroposphere complex: a runaway greenhouse event, e.g., in virtual computer reality may cost us one CPU year on the most advanced CRAY machine, but not our lives! In such a case, we simply restart the digital game and try to employ a more careful strategy. In this way we may eventually be able to explore the *plume of potential coevolutionary futures* as generated from the present state of the Earth System by the management options contained in $\mathfrak{M}$.

Note that simulation exercises have become a valuable training technique in many fields of complex decision-making, where reality gaming is ruled out or at least problematical for practical and principal reasons (see, for instance *Dörner*, 1996 [59]). In particular, the military-industrial sector has discovered the usefulness and convenience of cyberspace simulation, as exemplified by the recently booming activities in digital tank battles, air force encounters, or nuclear weapon explosions. The Pentagon even seems to be planning a complete digital inventory of the Earth's surface ("Project Number 2851") for all conceivable types of cyberspace warfare. Why shouldn't we make full use of the knowledge and methods involved for less destructive purposes like the preservation of our environment?

Before reviewing briefly the character and state-of-the-art of integrated modelling in Global Change research, let us emphasize two points.

First, a mysterious law of evolution seems to warrant a dynamic balance between humanity's means to destabilize its life support systems and its means to prevent such a destabilization. The ozone hole over Antarctica, for example, was detected with the help of sophisticated remote-sensing equipment (*Farman* et al., 1985 [68]) "just in time" to alarm the world public and to initiate counter-measures which seem sufficient to keep negative impacts at a tolerable level. Furthermore, there is considerable evidence that the breathtaking development in supercomputing will soon enable our climatologists to provide us with the necessary "on-line" information for appropriate climate protection policy. In the same way, the advent of integrated simulation modelling appears to be in good time for making the geo-cybernetic dream come true. So the global civilization seems to subsist in a perpetual state of "self-organized criticality" (*Bak* et al., 1987 [12]; *Bak* and *Chen*, 1991 [11]; *Drossel* and *Schwabl*, 1992 [62]; *Andrade*, 1995 [5]; *Bak*, 1997 [10]), where *fluctuation and regulation power nearly compensate* each other. However, note that even self-organized critical systems collapse when they go too far astray ...

Second, the power of simulation modelling of the environment and development process must not be overestimated. If used properly, integrated models prove to be excellent instruments for exploring the topology of the coevolution space, for detecting the presence or even the proximity of catastrophe domains, for analysing the sensitivity of pertinent Earth System parameters with respect to perturbations. Yet these models will seldom be able to make precise predictions about quantities of interest due to notorious *cognitive uncertainties*, which tend to grow non-linearly with the size of the forecast range. The situation becomes worse if we take into account "*voluntative noise*", i.e. the a-priori stochasticity inherent in human decision making. So whenever we employ simulation models of Global Change, we should be well aware of the fact that such models will never serve as "history machines". We will demonstrate in Sect. 6, however, how decision–makers (including $\mathcal{S}$) can profit tremendously even from imperfect models.

5.1 Integration and Integrity

Simulation modelling tends to be a "high-tech enterprise" with respect to the methodologies and the equipment involved. However, the modelling does not have to be a "high-soph(istication) venture" as well, if the system to be mimicked is just *complicated*, but not truly complex. The simulation of the collective dynamics of thousands of interacting molecules in a liquid is, for instance, a straightforward exercise when the equations of motion are well-defined and adequate hard- and software is available. Simulation modelling simply replaces unfeasible analytical prediction by brute-force numerical forecasting in such a case.

However, what are we going to do if the system considered exhibits *genuine complexity*, if it cannot be decomposed neatly into identical or similar elements of well-known properties, and if the interrelations between the constituents vary largely in character, range, strength, explicitness, crispness, etc.? Then the system in question is characterized by *fundamental inhomogeneity* that cannot be reduced or reproduced by concise algorithms. Note that the latter qualification excludes from the club even intricate objects like fractals as these may be constructed from a compact set of generating rules. Truly inhomogeneous systems cannot be mimicked by "ordinary" simulation modelling any more – we have to resort to *"integrated modelling"*.

Integrated modelling tries to catch the nature of the system without attempting to create a one-by-one cyberspace copy of it. In order to achieve this, almost incommensurable parts and pieces, widely differing spatiotemporal scales, outright reductionistic disciplinary descriptions, and clearly distinct actor levels have to be coupled. Even more important, the notoriously inhomogeneous information structure and precision with respect to the various system components and processes has to be harmonized intelligently by a spectrum of methods ranging from mathematical analysis to gaming exercises and educated guesswork (*Dowlatabadi* and *Morgan*, 1993 [61]). As a consequence, integrated modelling (*Nakićenović* et al., 1996 [161]) sometimes appears to be less a science than an art, which primarily draws on intuition and imagination. We prefer, however, to describe it as an ingenious way to *preserve the integrity of the object to be simulated without violating scientific integrity*. The latter imperative requires that any unavoidable assumption, approximation, simplification or omission is clearly identified and acknowledged in each step of the simulation enterprise. In particular, much care has to be devoted to data quality assessment.

Rather diverse issues in Earth System science may be tackled by integrated simulation modelling, for instance,

- the emergence of quaternary glaciations as a non-linear co-operative response of atmosphere, hydrosphere, biosphere and pedosphere to rather weak insolation fluctuation of the Milankovich type,
- the multidimensional costs and benefits of long-term climate change management, and
- the potential development of highly vulnerable regions (like the semi-arid Northeast of Brazil or the Maghreb) under the driving forces of Global Change.

But whatever topic is dealt with, two main principles have to be observed, namely

(i) *Relative Comprehensiveness*, and
(ii) *Weak Endogeneity.*

Here the qualifications "relative" and "weak", respectively, are crucial, as absolute comprehensiveness and full endogeneity are almost impossible to achieve in complex systems analysis.

The first principle refers to the fact that integrated modelling is primarily supposed to answer specific questions or even to solve certain problems; it is less concerned with creating novel micro-elements of disciplinary methodology. Therefore, *all* the system's components and processes *pertinent to the issue considered* have to be identified and taken into account, while the complementary elements should be ignored in an intelligent way.

The second principle refers to the notorious *closure problem* for the scientific description of an open or semi-open system, which is non-trivially coupled to an external world. As it would be neither feasible nor reasonable to model the outside universe in comparable detail to the system in question, *the import-export relations have to be taken care of* in an efficient and rather smart manner. Note that even "Earth Models" can only provide extremely selective descriptions of our planet, ignoring, e.g., the dynamics of the Earth's mantle, or the micro-organismic cosmos, or the ultimately complex sphere composed of billions of human souls. So there is always an inside and an outside world, separated by ill-defined borderlines (or, in general, border hyper-surfaces).

Evidently, these two principles of integrated simulation modelling are interrelated. Both imperatives may be complied with simultaneously by the following operational recipe:

(a) *Identify and account* for all those pertinent system components whose properties have to be evaluated in order to deal competently with the issue at stake;
(b) *Exogenize* all those elements of either the system itself or of the "outer universe" which are influenced by the pertinent system components, yet do not affect them, by truncation;
(c) *Exogenize* all those elements of either the system itself or of the "outer universe" which are not influenced by the pertinent system components, yet do affect them, by scenarios, look-up tables, proxy data or the like;
(d) *Neglect* all other elements, irrespective of their affiliation to the inner or the outer world.

A symbolic illustration of this strategy is given in Fig. 33.

For any given simulation task the general modelling design as epitomized by Fig. 33 has to be cast in a specific mould that accounts for the character and the peculiarities of the complex environmental system in question. Let us consider, for instance, the so-called "integrated assessment models" (*Kaya* et al., 1993 [120]; *Nakićenović* et al., 1994 [160]; *Nakićenović* et al., 1996 [161]; for a recent review see *Schellnhuber* and *Yohe*,

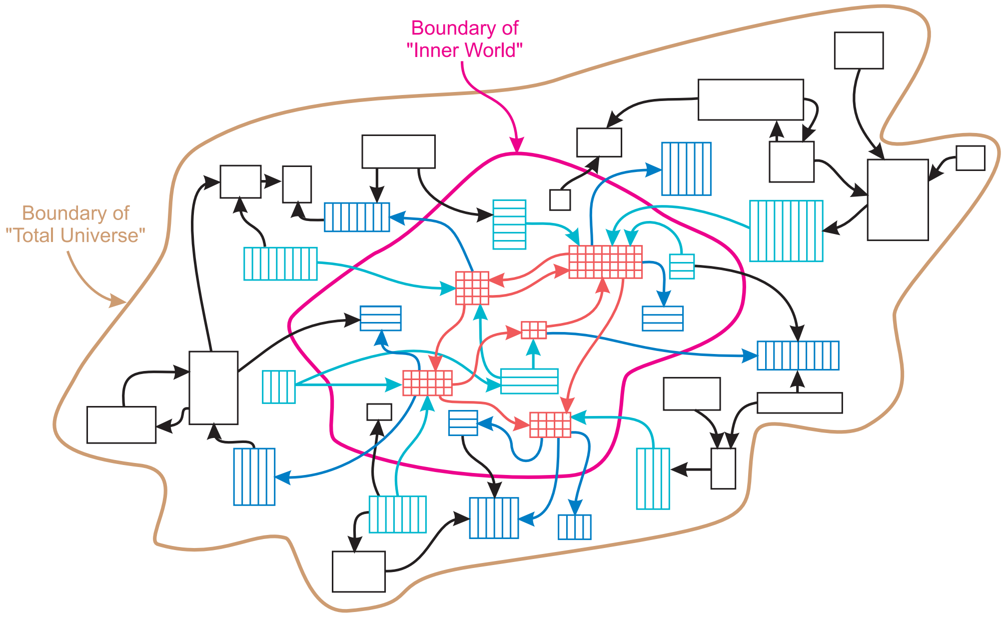


Figure 33. Wiring diagram and cut-off strategy for a fictitious system to be simulated by integrated modelling. The "inner world" (as delimited by the *pink membrane*) embraces all pertinent elements (*full red hatching*) as well as additional components irrelevant to the issue under investigation. Among the latter, those components directly influencing the pertinent system elements are indicated by *horizontal green hatching*, and those components directly influenced by the relevant elements by *horizontal blue hatching*, respectively. The remaining inner components are characterized by a *black contour*. The same indicative logic applies to the components of the "outer world" (as delimited by the *brown contour*) that encompasses the core domain of interest. Note, however, that the *hatching* of outer elements is vertical. According to the modelling strategy described above, all the *red arrows* must be taken care of by dynamic coupling, all the *green arrows* should be taken care of by appropriate scenarios or input from independent external simulation, and the remaining *blue* and *black arrows* may be neglected.

1997 [208]) which are supposed to serve as scientific detectors of optimal climate protection strategies. In this case, there is no need of geographical exogenization as the object at stake is the entire globe. By way of contrast, a number of relevant processes like demographic development and technological progress cannot be completely endogenized in these models because such processes are strongly affected by factors well outside the climate-related sub-cosmos of reality. Appropriate global scenarios, calibrated by empirical and theoretical wisdom about local societal dynamics and cultural specifica, will have to do the closure job here. If we wish to construct, on the other hand, a regional integrated model, then a "nesting approach" will be eligible: within the limited focal area as many elements of the overall inventory as possible should be endogenized through coupled simulation. There is, however, an "outside world" (in the true sense of the word) whose influences can be represented by the outputs from coarse-grained global models for the evolution of, say, climate, economy and life-style.

Apart from their degree of integration according to the general principles just discussed, simulation models of complex E & D objects may differ strongly with respect to *realism and sophistication*. The latter qualifications have to correspond to basic determinants or limiting factors such as purpose, ambition or resources (regarding time, data, computer equipment, etc.). By and large, we may distinguish here four main types of models.

A. Tutorial models.

These models mainly serve as "cyberspace toys" that help us, on the one hand, to *train our skills* for the rough climate of the "serious" simulation world and, on the other hand, to *identify fundamental effects and phenomena* characteristic of the system under investigation. Tutorial models are, therefore, rather barbaric and eclectic in nature; they tend to heavily reduce or mutilate the original entity and to keep just the crudest outlines of the remainder! If executed properly, however, such atrocious simplifications may be rewarded not just by savings in time and effort but also by a sharp exposition of the intrinsic mechanisms and major interrelations that shape the system's structure and behaviour. Figuratively speaking, this is *surgery using Occam's razor*, aiming to lay open dominant feed-back loops or catastrophic reaction paths in the entrails of the specimen. As a matter of fact, modelling through symbolic dynamics (*Robinson*, 1994 [197]; *Lind* and *Marcus*, 1995 [137]) often suffices to reveal characteristic properties of the system in question.

If we employ yet another metaphor and compare simulation modelling with the art of portrayal, then tutorial models correspond to the first and the last human documents of *abstract* painting as represented by the unknown genius of Lascaux and the well-known eccentric Picasso.

For illustrations of the tutorial approach we again refer to geophysiological models like the famous Daisy-World toy (*Watson* and *Lovelock*, 1983 [246]), which was devised to support the GAIA hypothesis. The rather simple non-linear mathematics of the Daisy-World parable actually encapsulate an extremely robust principle of homeorhetic self-control. As already indicated in Sect. 2, appropriate extensions of the original Daisy-World model reveal generic relations between structure and stability of complex eco-systems (*Svirezhev* and *von Bloh*, 1996 [227]; *von Bloh* et al., 1997 [243]).

B. Conceptual Models.
The models in this class generally attempt to catch the spirit of the original *in its entity*, but not necessarily to reproduce the proportions of the real counterpart. In other words, a conceptual model will reflect correctly the *topology* – the composition and connectivity – of the system to be simulated while the *metric* – the actual numbers along the dimensional axes involved – is of inferior interest.

So, in the best case, the modelling activity creates a *caricature* which is even more characteristic and recognizable than the original itself. The caricature does not have to preserve the dimensionality of the system: under certain conditions even zero-dimensional simply-wired box models may successfully simulate the *qualitative behaviour* of the real object. The model is supposed to generate, in particular, the right phase diagram, i.e. the true mosaic of (dynamic) equilibrium states in parameter space up to some homeomorphic distortion.

The construction of conceptual simulation models is an extremely difficult task. The risk of conjuring up a "Dalí", i.e. a beautiful but surrealistic misconception of the original, is rather high, especially when fundamental processes are not well understood. Some of the current efforts are still rooted in the world models of first generation (*Meadows* et al., 1974 [150]). An important example for a carefully designed integrated global model of the conceptual type is TARGETS (*Rotmans* and *de Vries*, 1997 [201]), which is described in some detail also in this book (*Rotmans*, 1998 [200]). Another fraction of conceptual models consists mainly of stepwise extensions of climate models (*Gallee* et al., 1991 [78]; *Gallee* et al., 1992 [77]; *Stocker* et al., 1992 [224]; *Xiao* et al., 1997 [261]). Yet another illustration is provided by the "Potsdam Earth System Models" (POEM) for the entire ecosphere as composed of the interacting components atmosphere, hydrosphere, biosphere and pedosphere. The POEM hierarchy embraces models of widely differing sophistication and dimensionality, where the latter ranges from 0 to $2\frac{1}{2}$ (*Claussen* and *Ganopolski*, 1997 [45]; *Ganopolski* et al., 1997a [79]; *Ganopolski* et al., 1997b [80]).

C. Analogical Models.
According to a former statement, integrated simulation modelling is not supposed to create simply down-scaled copies of the original that take into account virtually all facets of reality. By way of contrast, pure geophysical simulation ventures like coupled ocean-atmosphere circulation models certainly go for that goal. The so-called analogical integrated models for the Earth System or large segments of it try at least partially to live up to the standards set by geophysical modelling: These models have to neglect, omit or simplify a multitude of traits of the original for the sake of feasibility, but they nevertheless attempt to mimic a number of pertinent (natural and socio-economic) dimensions *true to scale*. This means, in particular, that analogical modelling tries to preserve some spatiotemporal metric through *geographical explicitness*. The resulting 3-dimensional construction is then animated by a portfolio of dynamic prescriptions, including partial differential equations and discrete decision rules of the cellular-automaton type.

If we employ our painting metaphor once again, then analogical modelling corresponds to *naturalistic* portrayal as has been mastered perfectly by, e.g., Dürer, Velázquez or Leibl. Among the most advanced and powerful models of the "isomorphic" type, the IMAGE family (*Alcamo* et al., 1994 [3]) plays a leading role.

D. Hybrid Models.
Many integrated (simulation or assessment) models are concocted from rather disparate ingredients. In particular, some of the intellectual devices introduced for conducting cost-benefit analyses of anthropogenic climate change are composed in a rather ill-defined way of tutorial, conceptual and analogical modules. This is partly due to uneven availability of the necessary components from the various disciplines involved, but

also to the continuing dominance of economists in this adolescent field. It is, of course, perfectly legitimate to focus on the things one understands best.

Some of these difficulties may be surmounted by modelling teams, which are assembled *ab initio* according to transdisciplinary criteria and which try to harmonize the inhomogeneous cognitive pool by projecting the latter on a uniform level of sophistication. The resulting *reduced-form* or *effective* integrated models are thus tuned to the weakest scientific module involved and do not run the risk of producing numbers of unwarranted precision. All "integrationists" should be warned of apodictive use of exact figures by the famous joke about the museum over-attendant who told the visitors that the dinosaur on exhibit was 90,000,006 years old. Upon questioning, the man explained that he had been told the dinosaur was 90 million years old when he was hired six years before (*Paulos*, 1995 [173]).

Another way of handling strong disparaties and uncertainties in integrated modelling is *"fuzzification"* (see Sect. 6 for detailed references). Much of the analysis of the complex system considered may consist of qualitative reasoning based on expert knowledge, educated guesswork, comparative case studies, and scientific intuition. In spite of this, it may be useful and reasonable to present the outcome of this reasoning in a geographically explicit form, for instance by a set of regional maps. There is nothing wrong with such a procedure, if the inherent vagueness of the results is properly expressed. Fuzzy set theory provides an elegant technique to achieve that. The strategy to be employed in such a case may be illustrated by the so-called "Syndromes Concept", a hybrid-type activity dedicated to the integrated assessment of Global Change (*Schellnhuber* et al., 1997 [207];

WBGU, 1997a [85]; *WBGU*, 1997b [86]). This activity starts out at the top phenomenological level by identifying the generic functional patterns of problematic civilization-nature interactions (the "syndromes"). The syndromes are finally made visible as partially overlapping, patchy structures representing the "clinical pictures" of the global environment. The most advanced analysis so far has been performed for the so-called Sahel syndrome, which represents the cause-effect complex governing the overexploitation of marginal land by displaced people and/or underprivileged segments of the population (*Cassel-Gintz* et al., 1997 [40]).

* * *

Now that we have briefly reviewed the various types of integrated models up and running, we may ask ourselves whether there is a "*natural evolution*" within the scientific world towards a "superior model species". The question is particularly valid with respect to global integrated modelling that is supposed to ultimately mimic the dynamic behaviour of the entire Earth System. By intuition, we may postulate that one should start out with the most simple variety and end up with the most complex one. We are, therefore, tempted to presume that the evolution arrow clearly points from tutorial to analogical integrated models.

Unfortunately (or fortunately?), the answer is not that straightforward: tutorial models may be highly sophisticated, e.g., from a mathematical point of view, while analogical models might constitute just a dull, uninspired aping of what is taken for "reality". As a matter of fact, the degree of abstraction, approximation and generalization which is respectively considered necessary or tolerable, largely depends on the *disciplinary bias* of the individual scientist confronted with the integration challenge. Physicists, for example, tend to put their trust almost naively in universal spatiotemporal principles reigning nature *and* society; thus they strive for utmost simplicity as represented by zero-dimensional models cast in differential equation form. By way of contrast, psychologists insist on describing *each single* individual or ethnic group or culture in its full complexity, which embraces not just the physiological facts but also a universe of "inner dimensions". When it comes to the question of geographic resolution of an integrated simulation model, we may therefore formulate – tongue-in-cheek – the following "scale theorem":

"Natural scientists prefer a scale smaller than $1 : 10^6$;
geographers prefer the scale $1 : 1$;
social scientists prefer a scale larger than $10^6 : 1$."

This jocular and outrageous statement should not be taken seriously, yet it contains some grain of truth ...

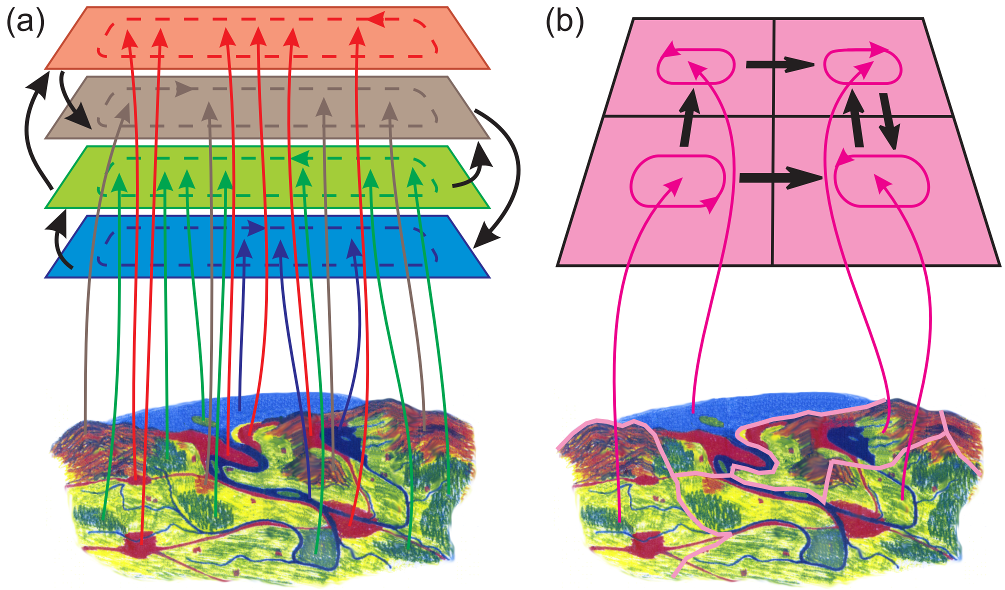


Figure 34. Alternative lumping strategies for constructing zero-dimensional global integrated models. **(a)** Aggregation of sectoral elements from all over the world and dynamic coupling of the resulting sub-sphere modules. **(b)** Aggregation of regional multi-sectoral inventories and dynamic coupling of the resulting simulation cells.

We should emphasize, anyway, that a marked "biodiversity" in integrated modelling will subsist in the medium term and will provide us with a fertile heuristic pool for all sorts of Earth System analyses. In spite of this, a certain average trend towards hybrid or "collage" models can be observed.

As far as the *collage technique* is concerned, fundamentally different philosophies can be identified, especially when it comes to global simulation. If such a model is assembled from a plethora of components in a cut-and-glue manner, then the integration of these modules consists of basically two steps:

(i) *Aggregation* by compressing and summarizing fine-grained information;
(ii) *Wiring* by constructing appropriate dynamic interfaces between the lumps emerging from (i).

Let us actually focus on the first step, which is directly related to "integration" in the mathematical sense of the word, i.e. in the sense of an operation which collapses a whole range of data onto a resulting single entity. We recognize that at least two alternative strategies for this procedure are available in the context of Earth System Analysis. The *traditional strategy* is to consider the disciplinary sub-spheres of the planet, like the atmosphere, the biosphere or the world economy, separately and to integrate out most geographical details within each of these global sectors. The resulting fields of suitable dimensionality are finally connected in a way that can animate the substitute of the real system. Most of the existing "World Models", like the ones in the famous Forrester-Meadows family (*Forrester*, 1971 [74]; *Meadows* et al., 1974 [150]; *Meadows* et al., 1992 [149]), are constructed along these lines.

By way of contrast, a completely different "Frankensteinian" assembling technique might be adopted. This *alternative strategy* seeks for a decomposition of the Earth's surface into an ensemble of sufficiently well-defined natural or administrative geographical units ("geotopes") like river catchments, culture domains or countries. By integrating out most of the ecological and socio-economic variables representing the total inventory of a given individual cell, the corresponding geotope module is generated. Finally, the resulting modules have to be wired with a special emphasis on the lateral import-export relations regarding water, energy, substances, species, goods, etc.

Fig. 34 sketches and compares the two fundamental integration techniques just described.

A crucial question is, of course, whether the end product, i.e. the integrated model, depends on the mode of assembling, or – speaking in mathematical terms – whether the *sectoral* and the *geographical* "integration" may be freely *interchanged*. As the operations involved are certainly of the non-linear type, a lot of care has to be invested here.

We should also point out that the second composition strategy is *inherently parallel* and should therefore lend itself to computational simulation with distributed resources. We may even dream of a "world model" in the literal sense, which is run on a communicating network where the nodes are formed by selected computers based at the respective geotopes.

5.2 Playing the Game

Let us assume that we have created a sound and operable integrated model of the interacting complex composed of the ecosphere $\mathcal{N}$ and the anthroposphere $\mathcal{A}$. This is a necessary condition for geo-cybernetic map exercises, yet not a sufficient one. According to the control systematics described at the beginning of this section, three *main ingredients* have to be added:

(i) The certain as well as the possible *external driving forces and perturbations* of natural origin. Most of these factors can be provided by astrophysical and geophysical analysis.

(ii) The *pool of control options* $\mathfrak{M}$ at the disposal of the executive component $\mathcal{M}$ of the Global Subject. The portfolio of E & D measures includes legal, political, economic, educational and technological elements. This pool has to be explored, modelled and simulated at least as carefully as the $\mathcal{N}$-$\mathcal{A}$ "hardware".

(iii) The *spectrum of methods capable of determining optimal solutions* $\{\mathbf{M}^*\}$ of the geo-cybernetic exercise for any given SD paradigm $\mathcal{P}$. Among these methods, which have to be employed by the "intellectual" component $\mathcal{B}$ of $\mathcal{S}$, we can identify several distinct types, namely
- mathematical analysis in the tradition of classical control and optimization theory;
- numerical search algorithms of deterministic and/or stochastic character (Newtonian techniques, dynamic programming, Monte Carlo methods, evolutionary procedures, etc.);
- educated computer-assisted guesswork, based on advanced expert and data management systems.

Then, finally, the E & D planning game has to be played with all these beautiful though sometimes elusive toys ... The players as recruited from the "Global Brain" $\mathcal{B}$ are supposed to dice for the hypothetical optimal control strategy $\mathbf{M}^*$ under the given boundary conditions. However, note that the geo-cybernetic map exercise has a remarkably dynamic and even *self-referential* character (as observed already in Sect. 3): instead of just playing the game with fixed rules, we may modify these rules; we may watch ourselves playing, modifying, and responding to our own actions; and *we may model all this including the modelling itself and the implications thereof*!

Some of the so-called "Integrated Assessment Models" (IAMs) for climate change management, which we have briefly mentioned above, try to take into account at least the most elementary aspects of this truly intricate situation. Such models may be qualified as "Evolutionary IAMs" (*Schellnhuber* and *Yohe*, 1997 [208]) because they allow for readjustable strategies, i.e. *mid-course corrections due to endogenous (and exogenous) learning* (see, e.g., *Kelly* and *Kolstadt*, 1996 [121]; *Dowlatabadi* and *Morgan*, 1993 [61]; *Lempert* et al., 1994 [134]).

However, that is only a first step towards genuine self-referentiality: Beyond the digestion of accidental cognitive shocks from an independent knowledge-producing machinery responsible for "the scientific progress", we may *integrate the latter process* into our map exercise. As a consequence, appropriate measures for improving the boundary conditions for knowledge production about $\mathcal{N}$, $\mathcal{A}$, and $\mathfrak{M}$ itself have to be considered a part of an optimal control strategy, as well as the flexible and versatile design of elements of the management pool, in order to make maximum capital out of potential new insights. This means, in particular, that the rigid reservoir $\mathfrak{M}$ has to be replaced by an evolutionary one.

We may even go one step further by allowing also for the evolution of the SD paradigm in the course of the geo-cybernetic process, and by *trying to anticipate such an evolution* within the framework of the simulation game! One has to be extremely careful, however, not to run this way into logical paradoxes or vicious circles. In order to avoid some of the intellectual pitfalls lurking behind self-referentiality and to bring the entire reasoning down to Earth (!), we can make use of a "human interface" between the virtual and the real world.

The interface is provided by exemplary *policy exercises* (*Tòth*, 1986 [229]; *Tòth*, 1988 [230]; *Tòth*, 1989 [231]) for E & D decision-makers, who are playing the geo-cybernetic game interactively on the model surface, and who are assisted and observed by the "pilots" from the scientific expert community. The test persons are to be recruited from politics, from economy or from the reservoir of public pressure groups and movements. The exercises may be perceived as "study courses for global environmental management based on simulated control", and these courses should reveal crucial elements of the intrinsic dynamics of Earth System steering. Note, in particular, that policy exercises of that kind properly reflect the *reality of geo-cybernetics* – however great our ignorance about the precise functioning of the $\mathcal{N}$-$\mathcal{A}$ complex may be. For the test persons *are* the "global players", the very actors that will shape the future of this planet to a sufficient extent. It is they, after all, who have to interpret the vague SD paradigms ventilated by society, who have to adopt and correct the coevolution path under considerable cognitive and voluntative uncertainty, and who have to learn from wrong advice and decisions. *So watching these players is a bit like watching the manufacturing of the environmental future* (or the future environment, if you like).

5.3 Orientators and Indicators: From Virtual to Real Reality

Once the ideal coevolution-management strategy $\mathbf{M}^*$ has been determined within the framework of our geo-cybernetic map exercise through some combination of the techniques described above, this brainchild has to be *converted into an adequate sequence of real control actions.* These actions are supposed to bring the $\mathcal{N}$-$\mathcal{A}$ tanker on to the right course with respect to the preferred SD paradigm and, most importantly, to keep it there. Such a task can only be completed if a perpetual stream of information links the virtual to the real reality and helps to bridge the gap between theoretical and practical operation. The geo-cyberneticist needs, in particular, *on-line data* describing the current position of the system in coevolution space as well as the present status of the propulsive equipment and the control devices. The corresponding stages of the navigation process have been identified and described as the Elements 5 to 9 of the "control table" presented at the beginning of this section (Tab. 2).

However, note that a virtual "Earth manager" in the planning game is capable of digesting instantaneously the full bulk of data provided by the digital sources, and that this electronic agent might even be able to evaluate the information prospectively for any desired time horizon. By way of contrast, the real geo-cyberneticist generally only disposes of rather patchy and fragmentary data, which is nevertheless far beyond his/her receptive and ruminative capacities. As a consequence, the human agents have to be provided with "the essential information" only, preferably *compressed into concise orientators and indicators* that decisively facilitate the various control decisions to be made. As a matter of fact, we will subsequently subsume any type of decision-supporting criteria under the common term "indicators", as the word "orientator" has recently acquired a rather specific scientific meaning (*Bossel*, 1996a [29]; *Bossel*, 1996b [30]).

Given a complex environmental system like a landscape or the total ecosphere, appropriate indicators are supposed to keep us informed on

– the system's *status* (instantaneous-local indicators),
– the system's *dynamics* (differential-infinitesimal indicators), and
– the system's overall *evolution* (integrated-global indicators).

Under more technical aspects, geo-cybernetic indicators may be classified according to their degree of compositional or operational complexity. We distinguish between

– *simple* indicators (e.g., the CO_2-concentration in the atmosphere as measured in ppmv),
– *compound* indicators (e.g., the "Human Development Index" (*UNDP*, 1990 [240])), and
– *systemic* indicators (e.g., the number and strength of positive feedback loops promoting soil degradation by marginal agriculture).

As reflected by the suggested terminology, systemic indicators are devised for detecting and evaluating generic systems properties like complexity, versatility, stability, resilience, brittleness, connectivity, autonomy, criticality, and so on.

Qualities of the type just listed have primarily been discussed and explored by ecosystems theory, but even there the task of constructing adequate indicators has by no means been completed. Concise criteria to indicate, for instance, the "pristinity" or, even more difficult, the "robustness" of a biotope are not yet available.

A crucial question is whether indicators should be endowed with *normative functions*, which allow value judgements to be read off directly. Within the context of the canonical approach to control theory, any conceivable indicator is meant to support the implementation of a *pre-determined* ideal strategy and to be instrumental in correcting unintentional deviations (due to human or technical failure, for instance) from the desired course. In other words, all sorts of valuation acts are performed already before or during the planning game, and the indicators are purely analytical tools for realizing the geo-cybernetic ideal.

However, what are we going to do if both the long-term coevolution desideratum $\mathbf{P}^*(t)$ and the generating management sequence $\mathbf{M}^*(t)$ are not definable – because of fundamental ethical and political disagreement among the decision makers and/or serious cognitive deficiencies that cannot be fixed by the scientific community? Under such circumstances the geo-cyberneticist has to resort to the "ultimato ratio", namely to steer the system *at short sight* by using certain indicators as the primary information basis for any navigational decision without reference to some teleological optimum.

It is evident that indicators of the type needed here have to act as *normative on-line monitors*, which continuously signal the quality of the system's state and the temporal modifications thereof. Instantaneous normative indicators may evaluate, e.g., whether a tentative change of state would represent an immediate improvement for the ecosphere, for humanity as a whole or for selected indigenous cultures. To give more specific examples, such an indicator might detect the proximity of locally critical manifolds in real coevolution space, or identify the direction of maximum relative increase in global or regional prosperity.

As a matter of fact, the present sustainability debate is about to marginalize the importance of integrated long-term concepts and strategies for perpetual coevolutionary progress, and to back an opportunistic ad-hoc management instead. This trend, however, is not so much the result of judicious reasoning as of the persisting lack of consensus regarding geo-cybernetic paradigms and paths. As a consequence, *so-called sustainability indicators are often taken for the entity they are supposed to indicate* – we are on the right track if monitor X, which has been devised according to the instructions of, say, the Commission on Sustainable Development (CSD), exhibits a green light! Such an attitude is reminiscent of the rather naive identification of guaranteed socio-cultural progress with certain minimum growth rates of gross national product (say, 3 % p.a.).

From the point of view of Earth System Analysis, simplistic approaches based on local sustainability indication are rather problematic. It is a fact, well-established by both practical experience and scientific reasoning, that small-scale and short-term optimal response may eventually head for disaster *if the response is not guided by a holistic strategy* (see also the following section). This has to be borne in mind when assessing the usefulness of the plethora of products at present produced by an entire SD indicator industry (see the aforementioned references, particularly those on pp. 30, 31 and 34). The reader who is not familiar with the habits of this sector should be warned of perceiving each and every specimen presented as "the real thing", which convicts nature or humanity of any possible aberration with factual authority. Actually many indicators promoted in the field of Global Change and Sustainable Development are more or less sophisticated *hybrids* of real variables (*"observables"*) and simulated activities (*"simulables"*). Meteorological research, for instance, frequently makes use of "computer-ameliorated observations" where patchy data gathered from the available monitoring stations are complemented or "improved" by simulation modelling. This is illustrated by the semi-artificial statistics that have been employed recently to furnish proof to the anthropogenic enhancement of the natural greenhouse effect (*Hegerl* et al., 1997 [103]; *Hasselmann*, 1997 [100]; *Kaufmann* and *Stern*, 1997 [119]; *Hasselmann*, 1997 [99]).

* * *

We conclude this section with the statement that it is not always (in fact, rather seldom) reasonable to stick to a pre-determined ideal course: due to newly emerging information, not the implementation of the optimal strategy may have to be adjusted but the strategy itself! This implies various types of intentional course corrections, namely evading manoeuvres, revision of cruising design, or re-evaluation of targets as summarized in the control table (Tab. 2). The subtle interplay between planning and perpetual readjustment in order to produce a winning strategy will be discussed in some detail in the following section.

6. Fuzzy Control: Soft Decision Making under Uncertainty *or* A Tale of Two Demons

Suppose that the “Global Subject” had made up its/her/his “Global Mind” and definitely selected a pure or a complex SD paradigm to be realized. However, is it actually possible to control the E & D process?

We might, of course, immediately dismiss this question by qualifying it as either unacceptable or irrelevant: for all present efforts related to global E & D policy certainly rely on the fundamental hypothesis that coevolution *can* be influenced, intentionally and significantly, for the better! Losing that *faith* would leave us with such unpleasant alternatives as total resignation or paralysis. In addition, note that even a deliberate resolution on the part of humanity to act *not at all* as a global entity would be thwarted, anyway, by the real existence of countless visible and invisible threads already inter-linking almost all the people on this planet.

The sheer existence, though, of some global E & D policy does not warrant success, so the crucial question regarding the *feasibility of global environmental management* remains. The Earth System, as defined in Sect. 3 (see Eq. 16), is probably among the most complex dynamic entities in the universe. It is composed of myriads of constituents that mostly interact non-linearly at all conceivable spatiotemporal scales. The ozone-hole lesson teaches us that this system *can* be destabilized by human interference, but what about command in the sense of positive perturbation? The laws of thermodynamics, stating that entropy-enhancing “destruction” is much easier to achieve than entropy-reducing “creation”, do not provide much encouragement here. Shouldn't we conclude that the whole notion of geo-cybernetics is, at best, foolishness, and, at worst, perilous demagogy?

Instead of rushing to such conclusions, let us elaborate a bit on the problem of controlling complex systems like “spaceship Earth”. Evidently, the two main aspects to be considered are

(i) the *effectiveness* of available steering options, and
(ii) the *knowledge* (or, even more important, the ignorance) about the functioning and evolution of the system in question.

The first aspect, concerning the manoeuvrability of truly big and complicated vessels in high-dimensional phase space, will be dealt with below. Let us beforehand turn to the second aspect, which is closely related to the daunting complexity of the system to be controlled.

Our *systemic wisdom* is notoriously *uncertain*, *fragmentary* or *fuzzy* with respect to the

– components and compositions,
– characters and dynamics of relevant processes,
– initial, current and boundary conditions, and
– external perturbations

involved. The total ignorance may be functionally decomposed into *cognitive* and *voluntative* elements, where the first class can be further sub-divided into *removable* and (for all practical purposes) *irremediable* deficiencies. This taxonomy needs some specification:

1. The ensemble of removable cognitive uncertainties defines the scientific domain, where intensive research may finally generate *precise information.*

2. The ensemble of practically irremediable cognitive uncertainties embraces all those elements and processes of the complex system in question, which are rigorously determined – in principle – by the laws of nature yet *cannot be specified crisply* at a given point in time.
   It seems to be impossible, for instance, to monitor in full detail the prevailing stress and strain fields in the Earth's crust, although we are dealing here with a well-defined problem of “19th century” continuum mechanics. As a consequence, deterministic geophysical processes enter our perception as aleatoric tectonic phenomena culminating in the insidiousness of earthquakes or volcanic eruptions. In much

the same way, extrinsic perturbations of our ecosphere, like fluctuations in solar activity, meteorite bombardment or passage of cosmic dust plumes, appear to be purely stochastic in nature.

3. Fundamentally irremediable voluntative uncertainties "simply" result from the *"freedom of will" of billions of individuals*, which constitute the driving-force cosmos of the anthroposphere. Thus any predictions about the further development of the Earth System are cursed by a self-referential vagueness of almost quantum-mechanical character. As a matter of fact, some eminent physicists are at present striving to explain the incalculability of human decision-making from the theory of quantum fluctuations (see, e.g., *Penrose*, 1974 [179]) . . . . In spite of this *fundamental indeterminacy at the individual actor level*, we are capable of formulating and validating useful statistical laws concerning the behaviour of large samples of co-operating and/or competing human beings (see, e.g., *Schweitzer*, 1997 [214]). Thus "socio-thermodynamics" may come into being as a novel scientific field in the approaching decades.

For the purpose of our discourse, we assume that the respective SD paradigm selected by the Global Subject is consistent with the tohubohu of innumerable micro-level voluntative processes, yet contains a holistic element that transcends the summation of atomic will vectors. The emergence of global decision-making from the individual acts of volition of micro-, meso- and macro-actors (ranging from single consumers to entire nation states) is a most subtle topic, though, which cannot be dealt with in any detail here. We will slightly touch upon it only in the concluding section.

6.1 The Teleological Dream: Laplace's Demon and Contemporary Company

Having specified the major sources of uncertainty regarding the Earth System, *what can we do about them*? While our ignorance of the first kind may be considerably reduced by intensified research (focusing, for example, on the dominant atmosphere-hydrosphere-biosphere interactions or the crucial relations between social dynamics and environmental resource use), there is no decent way to eliminate our ignorance of the third kind. Even the brutal suppression of individual "degrees of freedom" by totalitarian regimes ultimately fails, as evidenced by history. Voluntative indeterminacy may be, at best, "tamed" or "civilized" by democratic processes resulting in medium-term political mandates for social executives.

So it is the *second type* of uncertainty which really gives us a headache. If even the biogeophysical part of the Earth System, the ecosphere, obstinately retained its character of a huge roulette wheel generating random events – how could we even dare to hope for prediction, let alone control of coevolution? *Do we have to resort to metaphysics for salvation*?

A fictional solution to this dilemma is in fact provided by the recent debate among physicists concerning the post-Newtonian mechanistic paradigm. Imagine a godlike creature, who knows at a given point in time the *simultaneous positions and momenta of all particles in the universe*. By integrating the well-defined Hamiltonian equations of motion, our creature would be able, in principle, to predict the further development of the universe along with its inventory. This supernatural being is a brain-child of the French polymath Pierre Simon Laplace and therefore goes by the name of *"Laplace's Demon"*.

We will not deal here with the predicaments inflicted on the poor ancien-régime demon by the quantum mechanics revolution. Even if we restrict ourselves to the realm of classical mechanics as reigning the macroscopic world, we have to recognize that modern physics sets a considerably higher standard for the miraculous creature: the demon actually lacks any long-term predictive power unless it knows all initial conditions for all particles with *infinite precision*! The latter statement is a consequence of the deterministic chaos that prevails in many non-linear dynamic systems possessing more than one degree of freedom. The non-linearities involved namely induce the existence of so-called *hyperbolic points* in the system's phase space causing "sensitive dependence on initial conditions". Hyperbolic points can be viewed as dynamic crossroads, where alternative passages lead to globally different system evolutions. (For popular introductions into the theory and phenomenology of deterministic chaos see, e.g., *Stewart*, 1989 [223] or *Ruelle*, 1991 [202].

Deterministic chaos can already be observed (and probably most impressively) in rather simple systems which by no means deserve the label "complex". Since the days of Henri Poincaré, whose monumental essay ignited the "non-linear revolution" (*Poincaré*, 1899 [185]), the *three-body problem* (see Fig. 35) has served as a paradigm and an icon of chaotic behaviour.

The forces indicated in Fig. 35 obey Newton's law, i.e.,

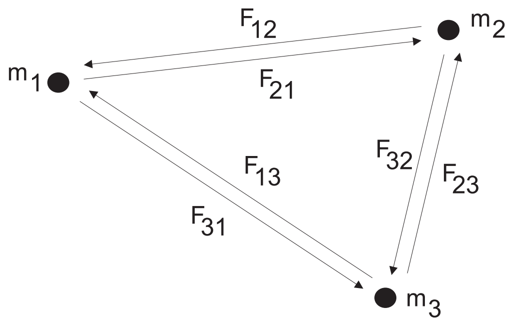


Figure 35. Simplest version of a celestial three-body system – point masses interact through standard gravitational forces.

$$\mathbf{F}_{ij} = Gm_i m_j \frac{(\mathbf{r}_i - \mathbf{r}_j)}{\| \mathbf{r}_i - \mathbf{r}_j \|^3} \quad ; \quad i, j = 1, 2, 3 \quad , \tag{228}$$

where m_i, r_i denote the mass and the position vector, respectively, of the i-th body, and G is the gravitational constant.

A rigorous proof that the three-body dynamics is generically *non-integrable* ("chaotic") has been achieved only recently (*Xia*, 1994 [260]). This rather technical statement has a quite dramatic corollary for the solar system: the long-term stability of this "astronomical clockwork" turns out to be a mere illusion, although excessive computer simulations indicate that it will not decay in the next ten million years ... Other numerical experiments reveal the non-stability of the asteroid belt (see Sect. 1), the chaotic dance of Hyperion (one of Saturn's satellites) and even the irregularity of Pluto's trajectory (*Wisdom* et al., 1984 [252]; *Wisdom*, 1985 [251]; *Sussman* and *Wisdom*, 1988 [226]; for a review, see also *Peterson* (1993) [180]).

Given the fact that even the motion of simple celestial systems defies any concise analytic description, it seems that only a demon which is by far superior to Laplace's creature might be able to predict the fate of a truly complex system like planet Earth. Does this definitely mean *"Lasciate ogni speranza, voi que entrata!"* for *human* geo-cyberneticists? The answer is *"No"*.

We have to realize that the natural sciences – and particularly modern theoretical physics – apotheosize the mundane cosmos of complex systems into a theatre world where only supernatural beings might survive the chaotic rat-race. However, we do not need demons in order to do very well in our non-linear everyday world! Let us support this contention with a few examples:

Example 1 (Swinging Child):
Without having the foggiest idea of Hamiltonian mechanics, not to mention parametric resonance or KAM theory (*Arnold*, 1978 [7]), almost any child is able to "operate" a garden swing regularly with any desired amplitude. This can be observed in spite of the fact that even a considerably simplified version of the physical child-swing system (the mathematical double pendulum, see Fig. 36 and Sect. 2) exhibits deterministic chaos of the finest quality (*Richter* and *Scholz*, 1985 [196]).

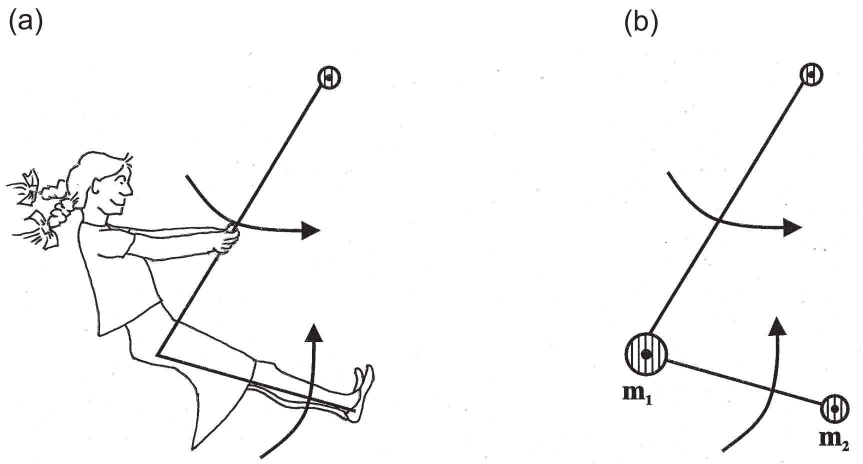


Figure 36. The double pendulum subject to a homogeneous gravitational field **(b)** represents a physical caricature of the swinging girl **(a)**. On closer inspection, the two "dynamic systems" prove to be rather different, of course.

Example 2 (People in a Hotel):
Imagine a huge crowd, say the fans of a famous rock band, waiting for admittance to a hotel where their idols are giving an autograph session. Once the entrance has been opened, a long multiple flight of revolving doors has to be passed through in order to push forward to the waiting stars. This rather typical situation of present-day life is sketched on the left-hand side of Fig. 37.

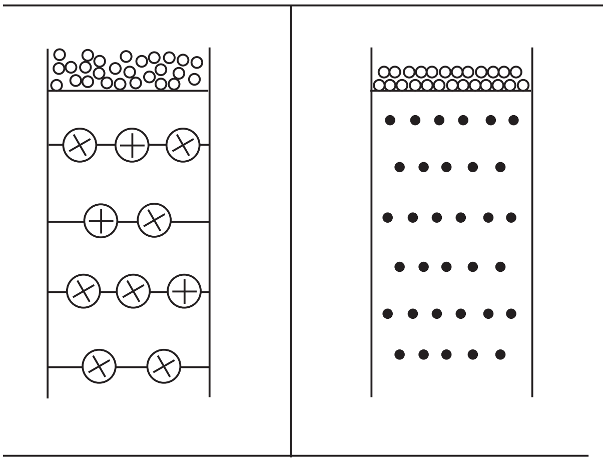


Figure 37. Comparison of human throng passage through flight of revolving doors (*left*) with physical passage of marbles through a nail-board (*right*).

In spite of the intricacy and explosiveness of the described situation, which may horrify not only the road managers of our rock band, the crowd will almost certainly manage to get along in an acceptably smooth way: only few individuals will collide, and probably no one will be squeezed in a revolving door and seriously hurt. (The validity of this assessment strongly depends, of course, on age, gender and mental state of the people involved.) This means that *a random sample of human beings solves, as a matter of routine, a most sophisticated dynamic problem which would even frustrate a Laplacian demon of the advanced non-linear type* ("Laplace-Poincaré demon"). The tremendous cognitive challenges involved here may be best illustrated by conceiving, in a first approximation, the members of the crowd as will-less particles, whose dynamics is completely determined by the basic laws of mechanics in conjunction with the specific set of initial and boundary conditions. The so-defined situation can be epitomized by the physical problem of marbles trickling down a tilted nail-board (see the right-hand side of Fig. 37): once the barrier on top of the board has been removed, the marbles will perform a gravitation-driven *chaotic* downward motion through a cascade of collisions with each other and the fixed nail-heads. Hereby the nails act like "hyperbolic points in position space", which may be passed by in two fundamentally different ways.

Note that the marbles problem is, in turn, a particularly complicated variant of the so-called *billiard systems*, the investigation of which has given rise to an entire branch of modern non-linear dynamics (see, e.g. *Tabor*, 1989 [228]). For the simplest types of billiards it can be proven rigorously, in fact, that these systems are under the rule of clear-cut deterministic chaos (see, for instance, *Sinai*, 1976 [218]). Thus for all practical purposes, it is *unfeasible* to predict precisely the motion of the marbles in a nail-board and to determine in advance, for example, the one which arrives first at the bottom line.

However, note also that the passage of the throng through the flight of revolving doors is infinitely more complicated than the marbles problem and is actually *unpredictable in principle.* This is due to the fact that the throng problem is dominated by a whole universe of *voluntative degrees of freedoms* that complement the physical ones. In addition, the former degrees of freedoms, i.e., the spontaneous locomotive decisions of the various individuals in the crowd are incalculable in nature – they cannot be monitored directly or even determined a priori by fellow fanatics or an external observer!

The reader might object here that voluntative indeterminacy generating cognitive uncertainty can be reduced significantly by *convention*: before the entrance door flies open, the waiting crowd could agree upon precise routing-schemes for each individual in order to keep subsequent chaos at bay. Yet even if the people involved were capable of working out such an agreement and were willing to comply with the accord, all pre-determined co-operative strategies would be wrecked in no time at all by the various *inherent hyperbolicities.* In summary, there seems to remain no scientifically justified way to survive the revolving-door race, but the trick is done each day with no or few casualties.

Example 3 (Traversing the Piazza San Marco):
Tourists who wish to cross the overcrowded St. Mark's Square in a certain direction on a sunny August afternoon are confronted with a manoeuvring problem not dissimilar to the revolving-doors predicament just discussed. Again, experience tells us that the seemingly unfeasible control task can be solved with a tolerable amount of effort and trouble. It is evident, however, that any conceivable type of *fixed initial instruction* of the actor in the sense of a locomotive ("ballistic") programme would completely fail and ultimately result in a fist fight with other tourists run down by our single-minded sleepwalker.

The cognitive and voluntative uncertainties involved here are generally the same as in the hotel episode. In addition, the Venetian holiday example provides us with a crucial new aspect of control, namely *global orientation*: even if the tourist succeeds in avoiding unpleasant encounters with other people, he/she may lose his/her general bearings in the jostling crowd. This can be avoided, however, by *sporadic re-orientation with the help of prominent landmarks* that repeatedly come into sight (say, the red-brick Campanile).

* * *

The purpose of our three examples was to demonstrate that individual or collective actors are very capable of *managing even the most complicated situations and of controlling the most complex dynamic systems in everyday life*. When analysing these miraculous achievements, it is necessary to distinguish between *passive performance* (like muddling through intricate terrain) and *active steering* (like intentionally influencing capricious processes).

However, the secret of success remains the same under all circumstances: passive or active control becomes incredibly effective through *perpetual revision and up-dating of approximative management strategies!* The strategies have to be tentative due to the *temporal vagueness and incompleteness* of the available local as well as global information about the system in question. The above-formulated intuitive-empirical principle for surviving in a ruleless and irregular world will therefore be referred to in the following as *"Fuzzy Control"*. We owe this nomenclature as well as pioneering insights into the overall issue to the work of *Zadeh* (1965) [262]. In the last two decades the general field of "fuzzy analysis" has become a flourishing branch of science and, in particular, engineering. Both the recent development of this field and the more formal description of the fuzzy control principle will be dealt with further below.

First we shall try to understand in some mathematical-quantitative way the basic philosophy of *iterated approximative control*, which proves to be so successful in the everyday-life situations described above. This analysis will provide useful hints for future transformation of the common-sense principle "Fuzzy Control" into a well-defined *scientific strategy for steering complex systems*. We will restrict ourselves, however, to illustrative examples of passive performance in very simple, and often even deterministic, situations. For the standard motivation and interpretation of fuzzy systems analysis, we refer the reader to the "classic" literature (see, e.g., *Zimmermann*, 1991 [263]; *Kandel*, 1986 [113]).

6.2 Newton's Root-Finding Method – a Paradigm for Fuzzy Control

Let us perform the following *Gedankenexperiment*: A plane is forced to land on a make-shift runway during a foggy night. The aircraft will be assisted by an optical localizer beam only. So the pilot tries to reduce the plane's velocity *in accordance with the distance-dependent brightness* of the ground-based light source. After considerable simplification, this problem may be formulated as a one-dimensional root-finding task:

We assume the vehicle's position to be described by the variable $x \geq 0$ and the beam source to be located at $\hat{x} = 0$. Let the perceptible brightness, $H(x)$, be a function of the (qualitative) shape depicted in Fig. 38, and let $H_0 \equiv H(0)$ denote the absolute brightness of the source.

Thus $H(x)$ is characterized by

– non-vanishing derivative for all values of x and particularly at the origin
– concave shape for small values of x
– approximately linear shape at intermediate distances from the source
– convex shape for large values of x, and
– asymptotic decay towards zero.

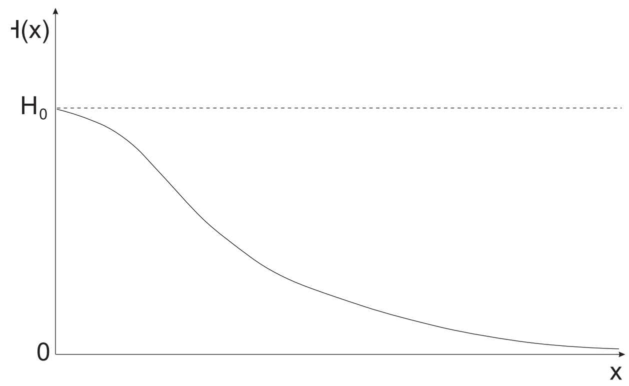


Figure 38. Perceptible brightness of localizer beam as a function of distance from its source, which is located at the origin.

The so-defined overall behaviour may serve as a not-too-unrealistic description of the combined effect of various physical processes involved (like absorption, scattering, defocusing, etc.). The crucial hypothesis is, anyway, that we are dealing with a *non-linear function.*

Introducing

$$f(x) := H(x) - H_0 \tag{229}$$

we have $f(0) = 0$, i.e., the target location $\hat{x} = 0$ is the unique root of the new function. Thus the pilot, who cannot determine the aircraft's absolute position x, is able to safely land the plane by "nullifying" the proxy distance measure f. In order to achieve this, only *local* brightness information and the calibration value H_0 are needed.

However, how to organize the actual root-finding process in an effective and robust way? From the plethora of available recipes we pick just two procedures, which represent *diametrically opposed search strategies* and, therefore, *fundamentally different control philosophies.*

A. Conventional Perturbation Theory:
Let us assume that the plane has already reached a position x_0 in the vicinity of the airport, so $f(x_0)$ is rather small. Let

$$\delta := \hat{x} - x_0 \tag{230}$$

denote the initial (directed) distance from the root, i.e., from the runway. Let us further assume that the local brightness can be measured sufficiently precisely for determining – with the help of standard aircraft instruments like the speedometer – not only the function value $f(x_0) \equiv f^{(0)}(x_0)$, but also *all the derivatives* $f^{(n)}(x_0)$. Then the root may be found by exploiting the *Taylor expansion* of f around x_0.

Note that

$$0 = f(\hat{x}) = f(x_0 + \delta) = \sum_{n=0}^{\infty} \frac{1}{n!} f^{(n)}(x_0)\delta^n. \tag{231}$$

Due to the fact that $f^{(1)}(x_0) \neq 0$ for all $x \geq 0$, we may slightly rearrange this equation to obtain

$$\delta + \sum_{n=2} \left[\frac{1}{n!} \frac{f^{(n)}(x_0)}{f^{(1)}(x_0)} \right] \delta^n = - \frac{f(x_0)}{f^{(1)}(x_0)} =: \varepsilon. \tag{232}$$

The quantity ε, which decays to zero at the origin, may be interpreted here as a *"smallness parameter"* for the perturbation analysis. Eq. 232 defines a power series in the variable δ, which can be formally inverted. To that end we make the ansatz

$$\delta(\varepsilon) = b_1\varepsilon + b_2\varepsilon^2 + b_3\varepsilon^3 + \dots , \tag{233}$$

where the quantities $b_l, l \in \mathbb{N}$, are real coefficients yet to be determined, and insert (233) in (232). For the resulting power series in ε to vanish identically, all the respective aggregated coefficients have to be zero. As a consequence, we obtain the following relations:

$$
\begin{aligned}
b_1 &= 1 \ , \\
b_2 &= -\frac{1}{2}\frac{f^{(2)}(x_0)}{f^{(1)}(x_0)} \ , \\
b_3 &= \frac{1}{2}\left[\frac{f^{(2)}(x_0)}{f^{(1)}(x_0)}\right]^2 - \frac{1}{6}\frac{f^{(3)}(x_0)}{f^{(1)}(x_0)} \ , \\
b_4 &= -\frac{5}{8}\left[\frac{f^{(2)}(x_0)}{f^{(1)}(x_0)}\right]^3 + \frac{5}{12}\frac{f^{(2)}(x_0)f^{(3)}(x_0)}{[f^{(1)}(x_0)]^2} - \frac{1}{24}\frac{f^{(4)}(x_0)}{f^{(1)}(x_0)} \ , \\
&\text{etc.}
\end{aligned}
\tag{234}
$$

Our pilot is now able to construct from the local optical information a *sequence* $\{x_n\}$ *of approximations* of the target position $\hat{x}$ *of monotonically increasing quality.*

This sequence is defined as

$$x_n := x_0 + \sum_{l=1}^{n} b_l \varepsilon^l \ , \ n \in \mathbb{N} \ , \tag{235}$$

and evidently converges to the desired root in an *exponential* way: Let

$$\varepsilon_{n+1} := x_{n+1} - x_n = b_{n+1}\varepsilon^{n+1} \ , \tag{236}$$

implying, in particular,

$$\varepsilon_1 = x_1 - x_0 = \varepsilon \equiv -\frac{f(x_0)}{f^{(1)}(x_0)} \ . \tag{237}$$

Thus the difference between successive approximations of $\hat{x}$ is of the order

$$\varepsilon^{n+1} = \varepsilon \cdot e^{\ln \varepsilon \cdot n} \ . \tag{238}$$

Note that the set $\{x_n\}$ does *not* represent a sequence of real stop-over points during the actual landing process, but a sequence of mathematical approximations in virtual navigation space. Within the framework of the perturbation approach, the pilot tries to compute *once and for all* via Eq. 235 an approximation of the highest possible order for the remaining travelling section $\Delta x := \hat{x} - x_0$. This approximation will form a fixed basis for the design of the landing manoeuvre. In other words, the chosen strategy relies on a single and rigid set of initial instructions of *utmost precision.* Here we strike a huge snag: Eq. 234 tells us that the computation of higher-order coefficients needed for satisfactory assessment of Δx becomes extremely involved and may be spoiled completely by minute errors infesting the bulk of derivative information! Thus the seemingly clever perturbation approach illustrates once more the predicament of teleological control strategies, even when the situation is by no means intricate.

B. Newton's Method:

Fortunately, there are much smarter ways of root-finding, so our aircraft does not have to be navigated by some sort of demon. All these recipes take advantage of the principle of *iterated use of weak or even imprecise local information*, and therefore belong to the set of *plesiological* strategies (where "plesios" is the Greek word for "near"). A famous example for strategies of this type, which are at the same time highly effective, robust and simple, is provided by Newton's root-finding method. It is worthwhile to analyse the latter method in some detail within the context of our Gedankenexperiment, as this analysis exposes, in a most transparent formal way, crucial elements of the rather mundane secret of controlling complex systems.

We now assume that the pilot is only able to determine at each position x the absolute value $f(x)$ and the first derivative $f^{(1)}(x)$ of the brightness measure f. This piece of local information allows, after all, for a *linear approximation* of the distance between the initial position $\bar{x}_0 (= x_0)$ and the target position $\hat{x}$. Thus the first estimate $\bar{x}_1$ of the runway's location is given by the simple formula (see Fig. 39)

$$\bar{x}_1 = \bar{x}_0 - \frac{f(\bar{x}_0)}{f^{(1)}(\bar{x}_0)} \ . \tag{239}$$

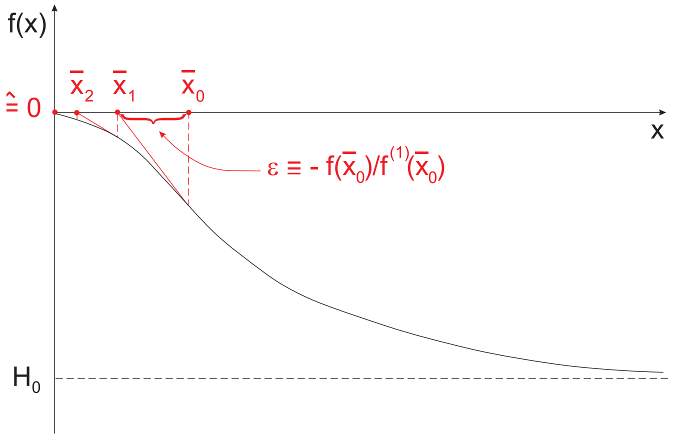


Figure 39. Approach to root of brightness measure $f(x)$ through iterated linear approximation based on local first derivative.

Now the critical point is that our pilot will orientate himself/herself by the "inaugural" estimate $\bar{x}$, yet will *not commit* himself/herself to this figure! For in the further course of the landing manoeuvre it may well turn out that the first distance approximation is quite a bit off target (as illustrated by Fig. 39). That is no tragedy, however, as the linear estimation procedure can be easily repeated – *but now from the new basis* $\bar{x}_1$.

Thus the second estimate for the target position is

$$\bar{x}_2 = \bar{x}_1 - \frac{f(\bar{x}_1)}{f^{(1)}(\bar{x}_1)} \quad , \tag{240}$$

and the general algorithm for continuing the approximation procedure is described by *Newton's famous formula*

$$\bar{x}_{n+1} = \bar{x}_n - \frac{f(\bar{x}_n)}{f^{(1)}(\bar{x}_n)} \quad ; n = 0, 1, 2, \dots \; . \tag{241}$$

The so-generated iterative approach to the root of a function is indicated for the brightness measure in Fig. 39. Note, however, that Newton's method only works if the first derivatives $f^{(1)}(\bar{x}_n)$ do not vanish.

Let us contrast the efficiency of this relatively primitive procedure with the convergence behaviour of the above-mentioned relatively complicated perturbation approach. This is achieved in a most lucid way by employing again the "perturbation (or smallness) parameter"

$$\varepsilon \equiv -\frac{f(\bar{x}_0)}{f^{(1)}(\bar{x}_0)} \quad , \tag{242}$$

which gains a direct meaning within the framework of Newton's method (see again, Fig. 39). Introducing

$$\bar{\varepsilon}_{n+1} := \bar{x}_{n+1} - \bar{x}_n, \tag{243}$$

where $\{\bar{x}_n\}$ is the *Newtonian sequence of approximations* of the target position $\hat{x}$, we have, in particular, $\bar{\varepsilon}_1 = \varepsilon$. Now the decisive step is to relate generally the quantity $\bar{\varepsilon}_{n+1}$ to its algorithmic predecessor $\bar{\varepsilon}_n$. Making ample use of Taylor expansion, we obtain

$$\begin{aligned} \bar{\varepsilon}_{n+1} &= -\frac{f(\bar{x}_n)}{f^{(1)}(\bar{x}_n)} = -\frac{f(\bar{x}_{n-1} + \bar{\varepsilon}_n)}{f^{(1)}(\bar{x}_{n-1} + \bar{\varepsilon}_n)} \\ &= -\frac{f(\bar{x}_{n-1}) + f^{(1)}(\bar{x}_{n-1})\bar{\varepsilon}_n + \frac{1}{2} f^{(2)}(\bar{x}_{n-1})\bar{\varepsilon}_n^2 + \mathcal{O}(\bar{\varepsilon}_n^3)}{f^{(1)}(\bar{x}_{n-1}) + f^{(2)}(\bar{x}_{n-1})\bar{\varepsilon}_n + \mathcal{O}(\bar{\varepsilon}_n^2)} \quad , \end{aligned} \tag{244}$$

where the "order of magnitude" symbol $\mathcal{O}(.)$ indicates powers of the smallness parameter and its iterates here.

However, note that

$$f(\bar{x}_{n-1}) + f^{(1)}(\bar{x}_{n-1})\bar{\varepsilon}_n = 0 \quad , \tag{245}$$

according to Eqs. 241 and 243. If we account for this fact in the nominator of Eq. 244 and expand the denominator of the same expression via the general formula for the function $\frac{1}{1+\xi}$, then we end up with the following result:

$$\bar{\varepsilon}_{n+1} = \left[-\frac{1}{2} \frac{f^{(2)}(\bar{x}_{n-1})}{f^{(1)}(\bar{x}_{n-1})} \right] \bar{\varepsilon}_n^2 + \mathcal{O}(\bar{\varepsilon}_n^3). \tag{246}$$

By repeating the whole calculation for $\bar{\varepsilon}_n$, we obtain

$$\bar{\varepsilon}_{n+1} = \left[\frac{1}{4} \frac{f^{(2)}(\bar{x}_{n-1})}{f^{(1)}(\bar{x}_{n-1})} \frac{f^{(2)}(\bar{x}_{n-2})}{f^{(1)}(\bar{x}_{n-2})} \right] \bar{\varepsilon}_{n-1}^4 + \mathcal{O}(\bar{\varepsilon}_{n-1}^6). \tag{247}$$

Concluding by induction, we ultimately find that the difference $\bar{\varepsilon}_{n+1} \equiv \bar{x}_{n+1} - \bar{x}_n$ is of the order of

$$\varepsilon^{2^n} = (e^{\ln \varepsilon})^{e^{(\ln 2)n}} = e^{(\ln \varepsilon) e^{(\ln 2)n}}. \tag{248}$$

This means that the Newtonian root-finding process converges *super-exponentially* fast!

* * *

Let us now draw the *conclusions* from our comparative analysis: we can certainly state that Newton's approach is vastly superior to conventional perturbation theory. This implies for our landing example that the pilot reaches the goal rapidly and safely, if he/she employs the *current (relatively imprecise) approximation as the point of departure for the succeeding estimation*, which is again relatively imprecise in nature. He/she will be far worse off by trying to work out a sophisticated perturbational determination of the target position in *one single step*.

We hasten to emphasize here that Newton's method typifies much more than an overall plain "wait and see" strategy. As a matter of fact, the Newtonian approach becomes so successful through a trick of ingenious simplicity, namely by making the desired root $\hat{x}$ of an arbitrary function $f(x)$ the *super-attractive fixed point of the associated Newton map* $N(x)$. To be specific, let us assume again, without loss of generality, that $\hat{x} = 0$, i.e. $f(0) = 0$, and $f^{(1)}(0) \neq 0$. Furthermore, we define the Newton map $N(x)$ by

$$N(x) := x - \frac{f(x)}{f^{(1)}(x)} \quad , \tag{249}$$

and we consider a small deviation $\xi := x - \hat{x}$ from the root, i.e., $|\xi| \ll 1$.

An excellent representation of $N(\xi)$ is therefore provided by the Taylor expansion

$$N(\xi) = N(0) + N^{(1)}(0)\,\xi + \frac{1}{2} N^{(2)}(0)\,\xi^2 + \mathcal{O}(\xi^3) \tag{250}$$

around the reference point $\hat{x} = 0$. However, straightforward calculation yields

$$N(0) = N^{(1)}(0) = 0 \quad , \tag{251}$$

so the root $\hat{x}$ of $f(x)$ is in fact a *fixed point of the map* $N(x)$ and the associated *Lyapunov exponent* (*Lyapunov*, 1949 [143]; for a modern review see, e.g. *Schuster*, 1988 [213])) vanishes. The latter fact qualifies the fixed point $\hat{x} = 0$ as *super-attractive* – in the terminology of non-linear dynamics – based on the following observation:

$$\begin{aligned} N(\xi) &= \frac{1}{2} N^{(2)}(0)\,\xi^2 + \mathcal{O}(\xi^3) \\ &= \frac{1}{2} \frac{f^{(2)}(0)}{f^{(1)}(0)} \xi^2 + \mathcal{O}(\xi^3) \quad . \end{aligned} \tag{252}$$

Repeated application of the Newton map N yields, therefore,

$$N^{(n)}(\xi) \equiv \underbrace{N \circ N \circ \ldots \circ N}_{n\ times}(\xi) = \left[\frac{1}{2} \frac{f^{(2)}(0)}{f^{(1)}(0)} \right]^n \xi^{2^n} + \mathcal{O}(\xi^{3 \cdot 2^{n-1}}) \quad . \tag{253}$$

Thus the initial deviation ξ is *contracted in a super-exponential way* under iterated mapping!

It should be mentioned here that the "jewel in the crown" of modern dynamic systems theory, the celebrated Kolmogorov-Arnold-Moser (KAM) Theorem proving the existence of ordered quasi-periodic motion under genuine non-linear circumstances, primarily rests upon *super-convergent analysis*. This analysis, in turn, is based on a sophisticated Newton's method for operator-valued maps. Thus most fundamental insights into the nature of deterministic chaos in conservative non-linear systems are owed to the Newtonian strategy of *perpetual readjustment of the approximation basis*. This statement includes the recent investigation of the famous 3-body problem discussed above. For a comprehensive discourse of the general topic we refer the reader to Berry's brilliant review (*Berry*, 1978 [23]), which formed the basis for our convergence assessments, and to the monographs by *Arnold* and *Avez* [8] and by *Lichtenberg* and *Liebermann* [136].

* * *

By now, we have illustrated via Newton's method the general principle of control by readjusted approximation within a purely *deterministic* context only – thus that control strategy appears less "fuzzy" than "lazy". Simple deterministic conditions prevail, in particular, whenever the crucial system variables can be described by analytic functions (in space and/or time). Then we may be able to *predict*, for instance, the complete future evolution of some observable F solely from the knowledge of the behaviour of this entity *in an arbitrary small section of its history*:

Let, e.g., $F(t)$ be analytic on the entire time axis t and assume that the tiny interval $(-\tau, \tau)$, where $0 < \tau \ll 1$, has been monitored carefully. Then all the derivatives $F^{(n)}(0), n \in \mathbb{N}$, can be computed at the instant $t = 0$ and the corresponding Taylor series, which converges for all $t > 0$, yields the complete "future" of the observable F. Even under the restriction that only a finite number of higher derivatives were available, we would still succeed in determining at least a polynomial evolution corridor via Lagrange's remainder formula.

The interesting aspect of such an observation is the insight that, in principle, forecasting may well do *without* any knowledge of the system's equations of motions – if only complete local information is available (but see the above-mentioned "curse of perfection" haunting Laplace's demon). Unfortunately, almost all relevant systems to be controlled are not of the simple, deterministic type: due to the multitude and non-analyticity of the pertinent functions involved, a naive global prognostic is not feasible for them. So, as a rule, any successful control strategy has to take into account and to master the handicap of fragmentary knowledge as well as apparent and/or genuine stochasticity. It is precisely under those circumstances, however, where the full power of perpetual readjustment based on updated local and global information, i.e. Fuzzy Control, unfolds. Before casting our still casual description of the latter principle into the mould of an authoritative definition, let us return once more to our aeronautical master example for demonstrating how to cope with uncertainty.

Here the unavoidable cognitive deficits can be represented concisely through the, possibly progressive, *imprecision in the determination of higher derivatives* of $H(x)$ or $f(x)$, respectively. The main sources of noise and/or error will be meteorological perturbations, aerosols and competing optical phenomena. Let us assume, therefore, that the actually locally measured derivatives scatter around the true values $f^{(n)}(x)$ according to *Gaussian statistics*. Introducing the *random derivative of n^{th} order* of f at the point x, $D_n(x)$, we thus presume that the probability for observing the value $D_n(x)$ is given by the formula

$$p(D_n(x)) = \frac{1}{(2\pi)^{1/2}\sigma_n} \exp\{\frac{1}{2}\frac{[D_n(x) - f^{(n)}(x)]^2}{\sigma_n^2}\} \quad , \quad n \in \mathbb{N} \quad . \tag{254}$$

Let σ_n denote the *standard deviation*, which will generally grow with the order n of the derivative, i.e.,

$$\sigma_n = \omega(n) \quad , \tag{255}$$

with

$$\omega(n) = \frac{1}{10} n^2 \quad , \tag{256}$$

for instance.

We have studied the influence of this stochastic complication on the landing (or root-finding) manoeuvre in some detail; the result can be summarized as follows: *Newton's method is largely resistant* to those stochastic distortions of the local information and finds its way unwaveringly to the target. By way of contrast, *conventional perturbation theory fails completely* as this technique does not take advantage of the option to correct faulty data in the course of rapprochement. We will illustrate this general finding by a very simple, yet non-trivial calculation. For that purpose, we consider instead of the still-too-complicated brightness measure $f(x)$ the mundane function

$$g(x) = \tan(\frac{\pi}{4} + x) - 1. \tag{257}$$

Evidently, $g(0) = 0$, i.e., $\hat{x} = 0$ and $g^{(1)}(0) \neq 0$.

We now compare the numerical performance of four distinct root-finding scenarios for this function, namely

(i) the *deterministic Newton's method*,
(ii) *Newton's method under uncertainty*, i.e. fuzzy derivative information,
(iii) the *deterministic perturbation method*, and
(iv) *the perturbation method under uncertainty.*

In each case we start our root-finding procedure from the point $x_0 = 0.2$ and generate a sequence $\{x_n\}$ of approximations of the root $\hat{x} = 0$. For the two noisy scenarios, the probability distribution of Eq. 254 is employed, but for the standard deviation we use the flat progression

$$\sigma_n = \frac{1}{10} \quad \forall \quad n \in \mathbb{N} \tag{258}$$

instead of (256). Tab. 3 contrasts the results, which are represented in the stochastic cases by *typical* sequences.

Table 3. Comparison of four basic root-finding scenarios for the test function $g(x)$ and the common point of departure $x_0 = 0.2$.

	Newton's Method		Perturbation Method	
	Deterministic	Noisy	Deterministic	Noisy
n	x_n	x_n	x_n	x_n
0	0.2	0.2	0.2	0.2
1	0.4476033 10^{-1}	0.5162266 10^{-1}	0.4476033 10^{-1}	0.4671267 10^{-1}
2	0.2061910 10^{-2}	0.4757890 10^{-2}	0.8406512 10^{-2}	0.1126749 10^{-1}
3	0.4257312 10^{-5}	0.9068513 10^{-5}	0.1140281 10^{-2}	0.4271971 10^{-2}
4	0.1812476 10^{-10}	0.6112070 10^{-6}	0.2275428 10^{-4}	0.3209610 10^{-2}
5	-0.5382865 10^{-21}	0.2854914 10^{-7}	-0.5181396 10^{-4}	0.3139614 10^{-2}
6	-0.1079167 10^{-42}	0.8589053 10^{-9}	-0.2210679 10^{-4}	0.3167149 10^{-2}
7		0.4926537 10^{-10}	-0.5976345 10^{-5}	0.3181912 10^{-2}
8		0.1745666 10^{-11}	-0.1124674 10^{-5}	

We clearly recognize that Newton's method is significantly slowed down by noise, but this type of Fuzzy Control still achieves its goal *exponentially fast*! The perturbation method, which already performs rather poorly under deterministic circumstances, rapidly *gets stuck in the noise* and leads us nowhere. These observations can be further corroborated by comparing the respective *ensemble behaviour* of multiple runs of Newton's method and the perturbation method, respectively, under uncertainty (see Fig. 40). The superiority of the fuzzy-control strategy is most impressively demonstrated by the fact that after 9 iterations, 100% of the Newtonian sequences have entered the 10^{-10}-neighbourhood of $\hat{x} = 0$, while 0% of the perturbation sequences have reached that domain!

6.3 Coping with Uncertainty: Grand Entrance of Maxwell's Demon

In much the same way as the fictitious pilot in our Gedankenexperiment, the heroes of everyday life are used to solving complex tasks with the help of fragmentary or noisy information: the secret of their success

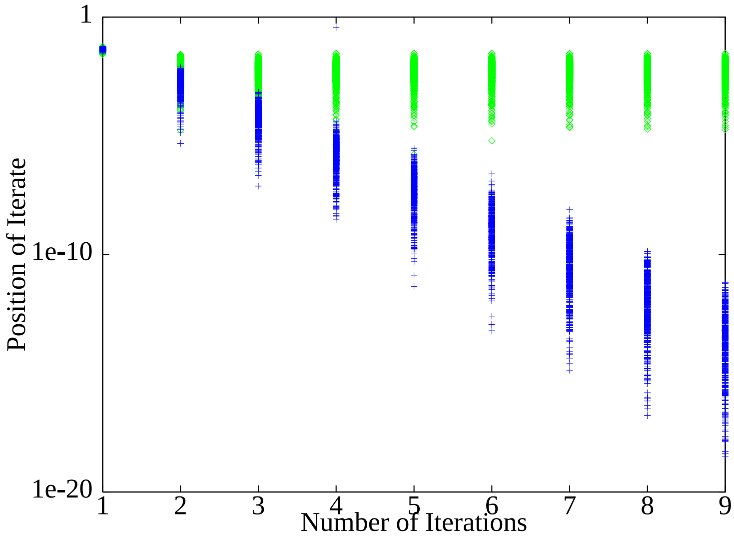


Figure 40. Statistical comparison of root-finding performance of Newton's method and perturbation method under noise for the function $g(x)$. The *blue crosses* depict the various Newtonian sequences generated by stochasticity, while the *green diamonds* indicate the perturbation sequences. Note the logarithmic representation of the position axis.

consists to a large extent in perpetual updating of decisions and behaviour in view of additional fuzzy local (in space and time) data. The child that flies a kite responds intuitively to the stochastic fluctuations in the prevailing wind conditions, and the pedestrian who fights his way through a crowd accounts successfully even for the fundamentally unforeseeable changes in direction of his fellow sufferers. By way of contrast, the insistence on a fixed predetermined sequence of actions will rapidly and inevitably generate embarrassing misadventures in such situations – regardless of the sophistication of the initial programming. We have ventilated these ideas quite a bit in the preceding sections.

However, note that successful iterative control strategies are generally not constructed as clearly as Newton's procedure, which manages to eliminate *exactly* the linear deviation from the target. Even "super-Newtonian methods" may be devised (e.g. by exploiting parabolic local approximations) that converge considerably faster than the familiar algorithm even in multi-dimensional settings. But for almost all purposes, *non-smart readjusting strategies* will do the job sufficiently well – if a *minimum responsiveness* to fresh information is warranted!

The latter principle and its miraculous performance under appropriate conditions may be best symbolized by yet another creature from the pandemonium of theoretical physics, namely *"Maxwell's Demon"*. This fabulous djinni was imagined by J.C. Maxwell in 1871, to illustrate the possibility of violating the Second Law of thermodynamics. The demon is capable of detecting and reacting to the motions of individual molecules. By operating, e.g., a microscopic "door" connecting two vessels filled with gases at the same temperature (see Fig. 41), the creature can generate excess energy from molecular chaos in order to perform *macroscopic work*. "All" the demon has to do is to allow fast-moving particles to pass from room A to room B and to allow slow-moving molecules to migrate only from B to A.

Information-Theoretical Excursion:
Laplace's Demon "only" needs to know the present condition of all molecules in the universe, as determined by their positions and momenta, in order to be able to provide the condition of those molecules at any later point in time. The creature by no means intervenes in the unfolding of cosmic history here. Its activity is pure prediction, its demonic talent consists exclusively in being able to comprehend all particle conditions simultaneously - an achievement that clearly transcends human perceptive capacities.

Maxwell's Demon, on the other hand, is a *creative* djinni, who can bring about order. The reason for this lies in the fact that it can handle "information" in a superior way. The demon is

– not provided with the present, but with target conditions (i.e., the desired order);

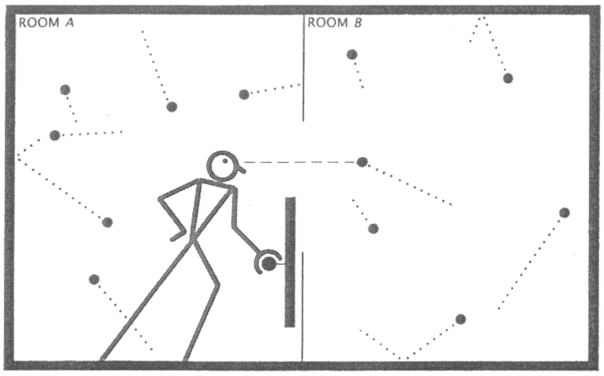


Figure 41. Maxwell's Demon, described in 1871 by James Clerk Maxwell, seems able to violate the second law of thermodynamics. The demon controls a sliding door that blocks a hole in a wall between rooms containing gas at equal temperatures and pressures. It observes molecules approaching the hole and opens and closes the door to allow fast-moving molecules to pass from room A to room B but not vice versa. Slow-moving molecules, conversely, are allowed to pass only from B to A. As the demon sorts, B heats up and A cools. According to the second law, a certain amount of work is required to create a temperature difference, but the work of sliding the door can be made negligibly small (taken from *Bennett* [19], courtesy of Jerome Kuhl).

– able to recognize molecular conditions autonomously (i.e., without being told);
– not simply a passive observer, but intervenes actively;
– acting continuously not just once;
– able to tune its intervention in view of the currently molecular conditions, namely by comparing them with the target ones.

The very last capability realizes a *negative feedback*, as introduced by N. Wiener as the fundamental phenomenon of his *cybernetics*. In this sense, the demon performs as a *steersman* ($\kappa\upsilon\beta\epsilon\rho\nu\eta\tau\eta\zeta$) who can control the Brownian motion of the gas particles. Thus the djinni should more precisely be referred to as the "*Maxwell-Wiener Demon*". ■

Whatever name we assign to it, Maxwell's demon has been a *tantalizing riddle* for theoretical physicists for more than a century now. Although several exorcising attempts have been made (for example, by *Brillouin* (1950) [32]), the troublesome case is not settled yet (see *Bennett*, 1987 [19], for a highly readable review of this topic).

We are not concerned here with the mutual consistency of physical axioms, but rather with the control paradigm represented by Maxwell's djinni. This *"plesi-visionary" creature* constitutes the perfect counterpart of the "tele-visionary" Laplace-Poincaré demon. The former owes its success not to the divine capability of exact global prognosis, but to its *animal obstinateness* in transforming strictly local (microscopic, to be precise) fuzzy knowledge into rough action. That is the proper way to defeat molecular stochasticity...

In spite of its stunning achievements, Maxwell's demon is not suitable to serve as the unique figurehead of complex-systems control. For the creature has to pay a price for its myopia implying the absence of *large-scale and long-term orientation* – and however vague this orientation may be, it often turns out to be indispensable. Without at least a *blurred panoramic view* of the total problem setting, the risk is quite high of passing through points of no return, of entering dead-end streets, of approaching abysses, etc. These are examples for wrong tracks that might be avoided with the help of an even quite imprecise *conception of the system as a whole.*

Because without some "holistic" orientation, no mountain range can be climbed over, no forest can be traversed and – in fact – no plane can be landed safely. Let us illustrate this general insight again within the context of our aircraft Gedankenexperiment. Our previous characterization of the pilot's task was certainly an over-simplistic one. For the aircraft commander has to distinguish by any means between the *"right"* and additional *"wrong" light sources* on the ground during the entire landing approach.

A formal caricature of this challenge is again provided by the task of finding the roots of a function – but this time of a function with *more than one root in its multi-dimensional domain.* For the sake of simplicity we restrict our demonstration to *complex* functions $f(z)$, defined in the entire plane $\mathbb{C}$. To be specific, we select as an example the innocent-looking cubic polynomial

$$f(z) = z^3 - 1, \tag{259}$$

which obviously has the roots

$$z^{(1)} = 1, z^{(2)} = e^{i\frac{2\pi}{3}}, z^{(3)} = e^{i\frac{4\pi}{3}} \tag{260}$$

situated on the unit circle.

We assume that $z^{(1)}$ corresponds to the target location, i.e., the position of the airport, while $z^{(2)}$ and $z^{(3)}$ are mock marks which bring disaster upon the unwary ones. Presupposing further that the value and the first derivative of f are available in each point of $\mathbb{C}$, we may again employ (the deterministic version of) Newton's method starting from an arbitrary initial position $z_0 \in \mathbb{C}$. This means that an iterative sequence $\{z_0, z_1, z_2, \dots\} \equiv \{z_n\}$ of vertices of the search motion is generated by the complex Newton map

$$N(z) := z - \frac{f(z)}{f^{(1)}(z)} = \frac{2z^3 + 1}{3z^2} \tag{261}$$

via the prescription

$$z_{n+1} = N(z_n); \quad n = 0, 1, 2, \dots \quad . \tag{262}$$

We observe that

$$\frac{df}{dz}(z^{(i)}) \neq 0 \quad \text{and} \quad \frac{dN}{dz}(z^{(i)}) = 0 \quad ; \quad i = 1, 2, 3, \tag{263}$$

so all the roots of f are in fact super-attractive fixed points of N.

Here we are specifically interested in determining the *basin of attraction* of the saving fixed point $z^{(1)}$, i.e. the set of all starting points z_0 that lead to the target through repeated application of the map (261). Let us formally define the latter set, denoted $A(z^{(1)})$, by

$$A(z^{(1)}) := \{z_0 \in \mathbb{C} |\ N^{(n)}(z_0) \to z^{(1)} \quad \text{as} \quad n \to \infty\} \quad , \tag{264}$$

where again

$$N^{(n)} \equiv \underbrace{N \circ N \circ \cdots \circ N}_{n \text{ factors}} \quad . \tag{265}$$

Let us point out that the analysis of the basins of attraction of iterated Newton maps derived from complex polynomials is a *legendary problem of pure mathematics*. The basic research on this topic is associated especially with the names of Cayley, Julia and Fatou (for more information, see *Peitgen* and *Richter* [178]).

One might presume that the basins of attraction of the three fixed points of $N(z)$, $A(z^{(1)})$, $A(z^{(2)})$, and $A(z^{(3)})$, constitute dull-looking simply-separated domains that cover $\mathbb{C}$ in a trivial way. Under such conditions it would be relatively easy to readjust an iterative sequence $\{z_n\}$, that happens to go astray, by mid-way corrections. However, a numerical investigation immediately convinces us that the above presumption is as wrong as can be: the three basins of attraction actually form an *infinitely-nested fractal structure* as depicted in Fig. 42.

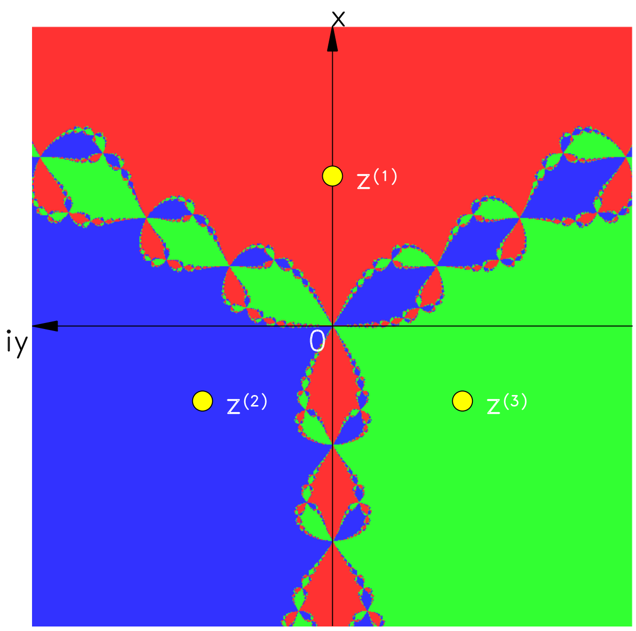


Figure 42. Basins of attraction of the fixed points of $N(z)$. $A(z^{(1)})$ is indicated in *red*, $A(z^{(2)})$ in *blue* and $A(z^{(3)})$ in *green*, respectively.

The basin structure shown in this figure is sometimes called the *Cayley fractal* and it belongs by now to the icons of "chaos science" – together with such famous comrades as the Mandelbrot set, the Hofstadter butterfly and the Lorenz attractor. The self-similar composition of Cayley's fractal may be derived and evaluated by analytic methods (*Nauenberg* and *Schellnhuber*, 1989 [163]).

From Fig. 42 it becomes clear that the Newtonian search motion for the root $z^{(1)}$ of $f(z)$ represents a highly non-trivial task, as $A(z^{(1)})$ is screened off by *fractal barriers*. Thus the design of appropriate mid-way corrections from positions that appear to be iterated to forbidden fixed points seems to be unfeasible. Things look black, in particular, when the starting point z_0 is situated somewhere in the infinitely intricate entrails of the pattern: the slightest imprecision in determining the initial position will imply a completely wrong prediction of the actual terminal reached through the Newtonian walk. So do we have to evoke a demon of the Laplace-Poincaré breed again?

No, we do not – but evidently Newton's myopic method has to be complemented by some element of *non-local information processing*. We will demonstrate in the following how this might be achieved. Our illustrative recipes have the advantage of being both easy to grasp and highly robust; they could be replaced, of course, by much more sophisticated procedures.

The first exemplary algorithm is sketched in Fig. 43.

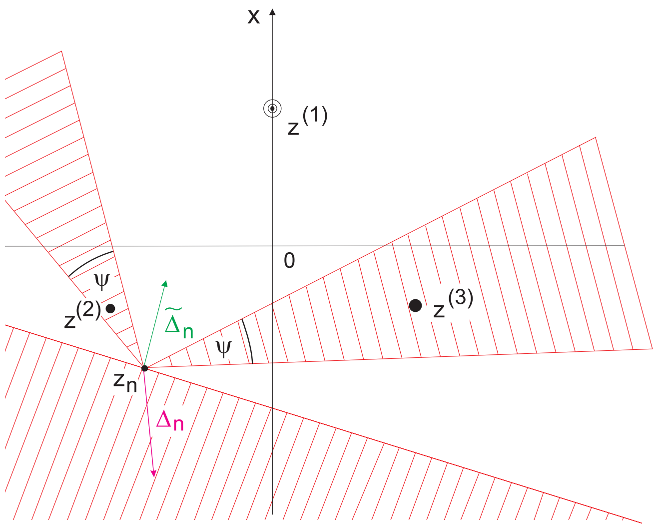


Figure 43. Modified Newtonian algorithm taking into account also (weak) global information about the location of the fixed points in the Cayley problem. The forbidden zones emanating from the intermediate position z_n (the far semi-plane of $z^{(1)}$ as well as Ψ-sectors with respect to $z^{(2)}$ and $z^{(3)}$) are *hatched in red*. Thus the "regular" Newton stride Δ_n is prohibited here; it is replaced by an aleatoric step $\tilde{\Delta}_n$ into the accessible domain.

The basic assumption here is that some rather imprecise information concerning the *directions* towards the distinct fixed points of $N(z)$ is available at each intermediate position visited "on the way home" – in addition to the knowledge of the Newtonian map $N(z)$ itself. As a consequence, it can be determined whether the next Newton step realizing the displacement

$$\Delta_n := z_{n+1} - z_n = -\frac{f(z_n)}{f^{(1)}(z_n)} = N(z_n) - z_n \tag{266}$$

leads *"forward"* (in the widest sense of the word) with respect to the target $z^{(1)}$ and, simultaneously, turns *"away"* (in a narrower sense) from the *fatal attraction points* $z^{(2)}$ *and* $z^{(3)}$. To be specific, we presuppose that it is possible to find out whether the angle defined by Δ_n at z_n lies within the far 180°-sector with respect to $z^{(1)}$ and/or within one/both of the Ψ-sectors with respect to $z^{(2)}$ and $z^{(3)}$, where Ψ is some angular uncertainty between 0 and $\frac{\pi}{2}$. If this is actually the case in one or the other way, then the regular (deterministic) Newton displacement Δ_n is discarded and replaced by an "allowed" step $\tilde{\Delta}_n$ selected by proper random choice. The resulting new position in $\mathbb{C}$ is subsequently identified with the $n+1$-th vertex of the walk, i.e.,

$$\tilde{z}_{n+1} := z_n + \tilde{\Delta}_n \quad , \quad \tilde{z}_{n+1} \to z_{n+1} \quad . \tag{267}$$

The amazing observation is that such an unsophisticated strategy really works: the so-constructed *hybrid algorithm* triumphs over fractality and *inevitably finds its way* through the self-similar barriers towards the target point $z^{(1)}$! We will not support this statement by numerical studies here; the performance of hybrid strategies will be demonstrated computationally instead for a slightly advanced procedure below.

Let us emphasize that the algorithm just described may be rather slow under certain circumstances and, in fact, only operates in a satisfactory way when

(i) the angle Ψ is chosen properly,
(ii) the length of regular Newtonian steps $\{\Delta_n\}$ is artificially bounded from above (especially important in the neighbourhood of the origin), and
(iii) the length of aleatoric steps $\{\tilde{\Delta}_n\}$ is moderately bounded from below (especially important in the neighbourhood of the false targets $z^{(2)}$ and $z^{(3)}$).

The overall strategy proposed here may be interpreted within the framework of our aircraft allegory in the following way. The pilot has at his/her disposal two qualitatively different means of orientation. The first one comes from crisp knowledge regarding the local ("microscopic") behaviour of the total brightness measure and allows the plane to be landed safely once the vicinity of the airport has been reached. The second one comes from vague information regarding some additional indicators (like the specific colour or polarization of light rays) that allows the approximate global ("macroscopic") directions towards the right and wrong targets, respectively, to be identified. The pilot adopts a hybrid strategy by implementing a precise linear approximation of the current distance from the runway – if the fuzzy complementary directional information is compatible with that step. If this is not the case, then an aleatoric displacement commensurate with global orientation is performed. This all boils down to the common practice of marking airport elements with headlights of unambiguous colours . . . .

Returning to the pure mathematics of the Cayley problem, let us propose and test a *more effective algorithm* for approaching the "correct" final point $z^{(1)}$ of the Newton map $N(z)$. That approach is considerably facilitated if we permit (restricted) displacements also *in the direction of* the "bad" points $z^{(2)}$ *and* $z^{(3)}$. An approximate realization of such an improved strategy is sketched in Fig. 44.

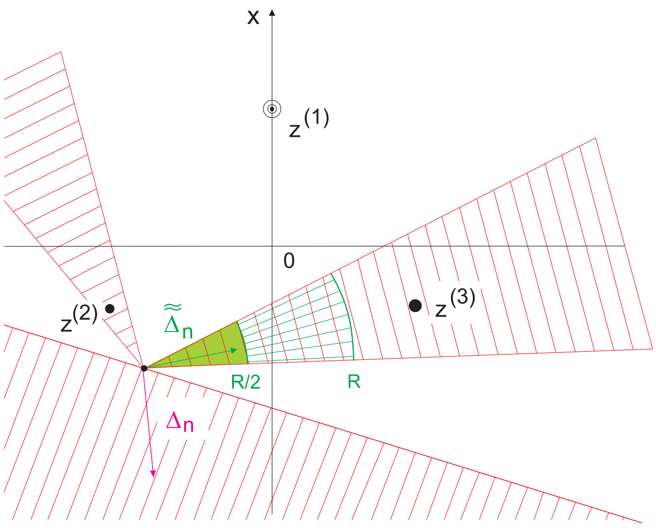


Figure 44. Improved hybrid algorithm taking into account also (intermediate) mesoscopic (or regional) information about the location of the wrong targets. Segments of radius $R/2$ of the Ψ-cones surrounding $z^{(2)}$ and $z^{(3)}$, respectively, are re-opened for deterministic or aleatoric movement (like the displacement $\tilde{\tilde{\Delta}}_n$) if the distance from z_n to the wrong fixed point considered is larger than R.

This second search procedure is similar to the first one, except for a crucial additional assumption: there exists now the possibility to determine whether the undesired roots of $f(z)$ are at a *minimum distance* $R > 0$ from the current position z_n. If the latter is actually the case for one (or both) of the undesired attraction points for Newton's method, then an appropriate tip of the forbidden Ψ-cone(s) associated with the wrong point(s) is declared accessible for deterministic or aleatoric displacements from z_n. For the sake of "safety", i.e. error tolerance, the re-opened sector is restricted to the radius $R/2$.

The new strategy amalgamates three distinct types of information, namely

(a) *precise microscopic knowledge* about $N(z)$ and its derivative at the current position,
(b) *intermediate mesoscopic knowledge* about a minimum distance R from the undesired roots of $f(z)$, and

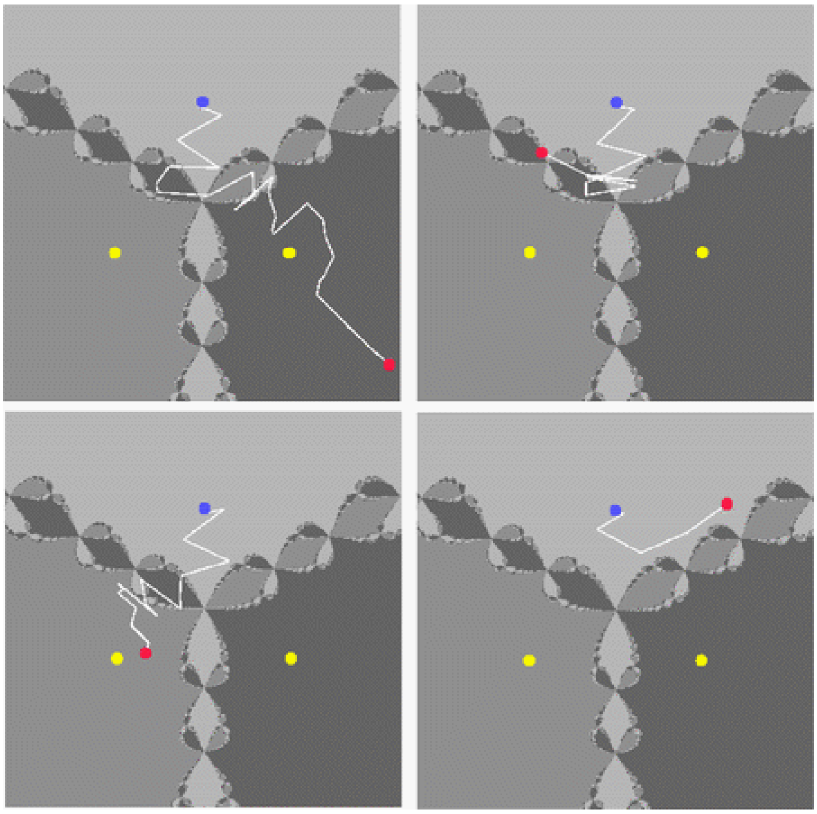


Figure 45. Typical trajectories of root-finding walks across the fractal Cayley structure (*grey background shading*) for improved hybrid search strategy. The different starting points z_0 are indicated in *red*, the undesired roots $z^{(2)}$ and $z^{(3)}$ in *yellow*, and the target point $z^{(1)}$ is marked in *blue*.

(c) the *vaguest possible macroscopic knowledge* about the angular sector to be searched for the desired root of $f(z)$.

In practice, the performance of this algorithm depends heavily on the tuning of the adjustable parameters Ψ and R. We have carried out this optimization exercise that leads to a hybrid search strategy, which does the job of root-finding in a multifractal world in a most reliable and effective way. Our findings are illustrated in Figs. 45 and 46; in both cases the choice $\Psi = \frac{\pi}{4}$ and $R = 0.3$ is made. In Fig. 46 the overall performance of the second algorithm is demonstrated. For that purpose we consider a cloud of 600×600 starting points z_0 which are homogeneously distributed over the complex square

$$\{x + iy \mid -2 \leq x, y \leq 2\} \quad . \tag{268}$$

The initial dust is successively iterated by the hybrid method towards the target point $z^{(1)}$ – much in the same way as a liquid is drawn down a sink.

From the two figures it becomes evident that some rather primitive modifications of the original Newtonian method *guarantee one-hundred percent success*, i.e., the rapid infallible convergence to the pre-selected root of $f(z)$ from any possible starting point. This is true in spite of the intimidating complexity of the mathematical landscape to be wandered through!

We may translate also this somewhat advanced hybrid algorithm into the context of our aircraft Gedankenexperiment. The pilot now makes simultaneous use of local, regional and global information. The *regional information* may be provided, e.g. by searchlights or some primitive type of radar equipment of range R for scanning the hazardous spatial sectors. If the mock targets are beyond the range of the detection gadget, then a (deterministic or aleatoric) step of maximum length $R/2$ towards the correct target seems to be a no-regret option.

We have to emphasize here that we can do very well *without precision* in our model world: even if the information concerning the derivative of the brightness measure f regarding the hazardous sectors associated with the mock targets, or concerning the finite searchlight cones, are *moderately noisy*, then the procedure proposed here still finds its way!

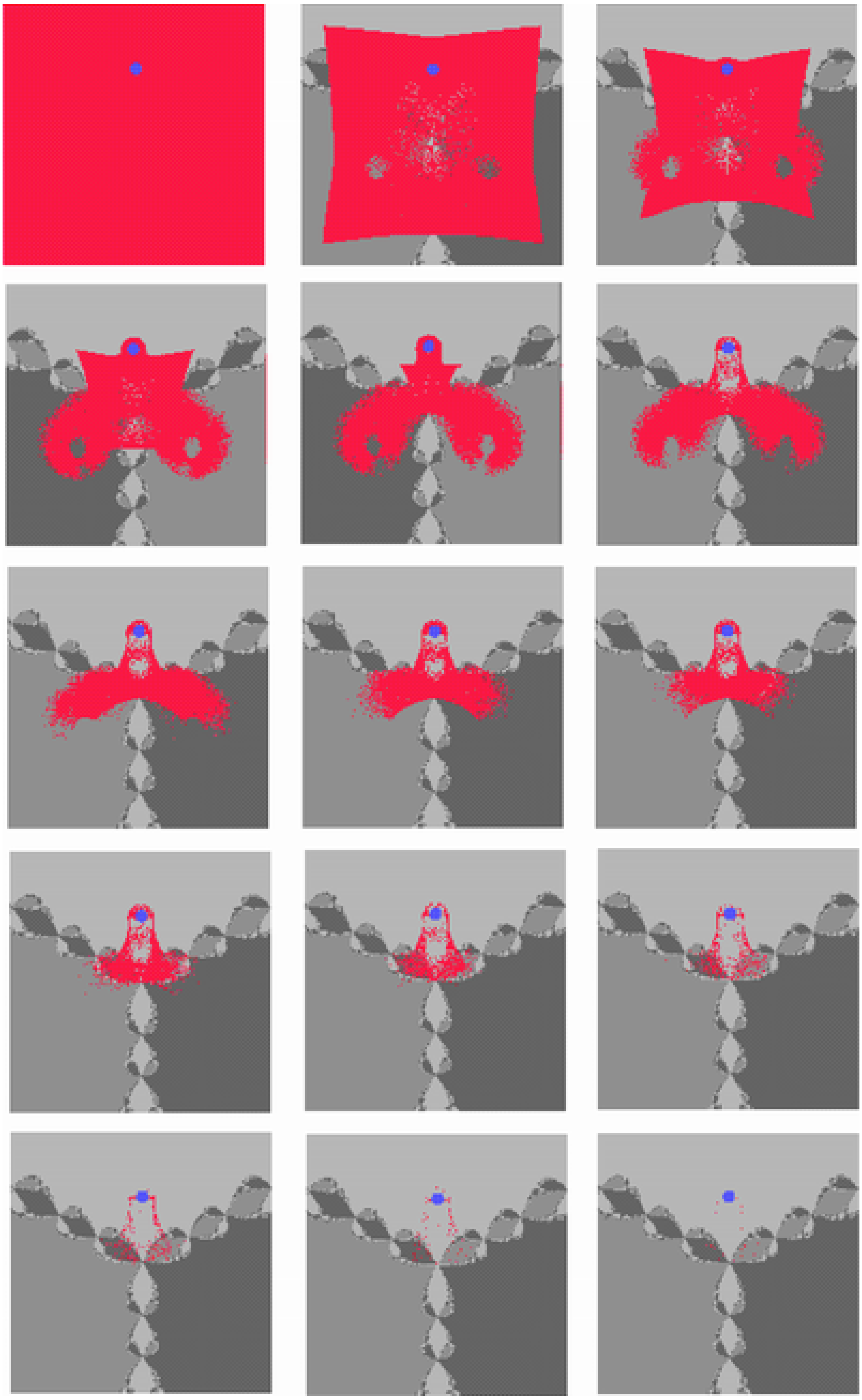


Figure 46. Stroboscopic coverage of the evolution of a quadratic starting set under improved hybrid iteration. The initial cloud embraces 600×600 points, and only 16 steps from a sequence of 44 iterations are presented for the sake of brevity. The target point $z^{(1)}$ is again marked in *blue*.

6.4 Fuzzy Control and Geo-Cybernetics

The lessons from our journey through allegoric domains can now be formulated. This will help us to face the real world again and its notorious problem of judicious decision-making under uncertainty. Summarizing as well as generalizing, we may say that Fuzzy Control is the (everyday) art of solving complex (or just complicated) tasks *by soft and imprecise measures* in a satisfactory (or even perfect) way. To be more specific, *the fundamental operational principle of Fuzzy Control* reads as follows:

> *Based on uncertain and/or fragmentary information, adopt a rough long-term and/or large-scale strategy, which has to be continuously readjusted in an approximate fashion according to all sorts of generally imprecise additional data.*

This principle of *soft decision-making under uncertainty* has three main ingredients:

1. *Existence of Leeway,*
2. *Moderate Responsiveness, and*
3. *Rough Panoramic View.*

Without *Ingredient 1*, any element of "fuzziness" would be absolutely forbidden – because only perfect action based on exact data could then produce the *unique solution* of the control problem in question. The expression "leeway" must not be restricted here to the option of deviating moderately from an ideal spatiotemporal course without wreaking havoc. As a matter of fact, and typically, the topological conditions of the pertinent high- or even ∞-dimensional control spaces have to be explored and scrutinized. Only if the (possibly precise) target structure corresponds to *open sets*, i.e. *solution corridors*, in the space of available control strategies, the imperfect steering can be employed successfully. In the case of crisp once-and-for-all decisions – like filling in a lotto coupon – the fuzzy-control principle is absolutely useless.

Without *Ingredient 2*, the influxes of fresh and/or complementary information in the course of the steering process would lead to nothing – perpetual readjustment according to improved data requires an adequate ability to react to new circumstances. "Adequateness" may be defined here via critical ratios between the *"velocities" of system variability*, *information updating* and *measure implementation*, respectively. The latter element is evidently crucial; it may be most negatively influenced by rigid rules and inflexible organs or institutions, for example.

Finally, without *Ingredient 3*, all softly-iterated control strategies would be necessarily myopic and dyspnoeic, in perpetual danger of entering potentially *disastrous cul-de-sacs*. By way of contrast, Fuzzy Control converts even most sparse and vague large-scale information into hints for *global orientation*, which may be revised, however, in the end stage of the control process – just like the local course. To illustrate this point, we consider a medical student who becomes increasingly concerned about her professional perspectives. The reason is that the "labour market for physicians" continues to look bleak for the n-th consecutive year. Although the latter observation provides only a most sweeping and unstable basis for long-term job re-orientation, the student may finally make up her mind to go for a position in the research department of a big pharmacy combine. And she may be right ...

In wrapping up the main insights from this section's discourse, let us return for the last time to our allegoric world of demons: Fuzzy Control requires a *humanized cross-breed of the teleological-contemplative Laplace-Poincaré demon and its plesiological-reactive Maxwellian comrade.* The hybrid creature is humanized insofar as the supernatural capabilities of the two original djinnis may be safely replaced by rather *amateurish skills* of the respective type. Even dull and slow individuals survive in an incredibly intricate and dynamic world – if they are not stubborn! The famous Russian mathematician and physicist A.N. Kolmogorov summarized the praise of *"correct imprecision"* in the phrase:

"It is better to be right than to be rigorous!"

* * *

The fuzzy-control principle in the form derived and summarized above has *by no means been sufficiently explored* yet. This statement holds with respect to its theoretical foundation, as well as with respect to its applicability to a wide variety of complex steering tasks. In recent years, however, the overall issue or certain aspects of it have become important research topics. Within this large field of scientific activities two specific lines of investigation can be identified:

The *first front* develops in the *tradition of* Zadeh and approaches the subject via the thematic sequence "fuzzy sets" – "fuzzy systems" – "fuzzy control" (see, for instance, *Kandel* and *Langholz*, 1993 [114]). The *second front* has emerged from the *modern theory of non-linear dynamics* and focuses on mastering deterministic-chaotic systems with the help of rather sophisticated methods (see, e.g., *Ott* et al., 1990 [170]; *Romeiras* et al., 1992 [198]); a remarkable paper on the virtual taming of El Niño's irregular appearance has been published quite recently (*Tziperman* et al., 1997 [235])). There have been actually efforts that try to combine those two lines of investigation for the analysis of relatively simple tasks like the manipulation of a bouncing ball on an oscillating table (see, e.g. *Karr* and *Gentry*, 1993 [116]).

In spite of all these impressive accomplishments, even more remains to be done in a field which has still not attained the attention it deserves in view of its *fundamental and practical importance*. The persisting gaps in our understanding are particularly large and deplorable regarding the task of active Fuzzy Control of *genuinely complex systems*. The well-known and well-explained showcases of deterministic chaos (like the mathematical double pendulum discussed earlier in this text) are almost exclusively very simply systems that consist of few components. One might conclude, therefore, that the control of many-component systems with non-linear interactions between their constituents was an impossible mission ...

Yet it would be wrong to draw such a sweeping and apodictic conclusion. First of all, *different types of complexity* have to be distinguished when we consider the rich cosmos of non-simple systems. The elaboration of a consistent (and concise) taxonomy for that cosmos is a gigantic task, however, and may always remain a scientific dream (see in this context, for instance, the efforts of *Haken*, 1983 [96]; *Holling*, 1987 [106], or *Chaitin*, 1987 [42], who inspect the complexity issue from rather different perspectives). However, let us advance three arguments that speak for the feasibility of active control of many truly complex non-linear systems – if the principle of iterated fuzzy adjustment is observed:

(i) The *non-linearity* of the systems in question, that is, the disproportionate (and sometimes even discontinuous) response to internal and/or external driving forces, can render such systems even *better to control than linear ones*! A necessary prerequisite for exploiting that characteristic is sufficient knowledge about the strategic variables and the sensitive (or critical) sectors of the dynamic complex considered. Then even *"inverse butterfly effects"* may be accomplished, i.e. the almost complete suppression of massive perturbations by non-linear attenuation mechanisms.

(ii) Complex systems are generally *highly structured* (for example, in a hierarchical way) and *intrinsically involved* by a multitude of interactions between their components – the latter property really inducing a definition. Now the number of interrelations, bonds and mutual restrictions grows, as a rule, over-proportionally with the system's size, so the *relative magnitude of degrees of freedom tends to decline*. It has to be emphasized here that this subtle and gradual reduction of transformability and variability is not exclusively due to trivial enhancement of connectedness, but also to *dynamic co-operative effects*. Haken's "Slaving Principle" (*Haken*, 1975 [95]) and Bak's "Theory of Self-Organized Criticality" as mentioned above (*Bak* et al., 1987 [12]) shed some light on the resulting stability and even resilience of many complex systems.
As a matter of fact, the trend towards *decreasing flightiness with increasing complexity* is massively supported by empirical observations: as mentioned before, it is rather difficult to discover concrete examples for deterministic chaos in large natural systems (like the atmospheric machinery). One pertinent reason for that failure is the fact that these multi-component systems generate their own quasi-stochastical noise which subdues and dissolves the sharp characteristics of strange attractors, fractal structures or similar specimens from the chaos zoo. Otherwise it would be completely hopeless, say, to go for climate predictions extending over several centuries ahead of us.

(iii) Finally, and especially when dealing with *environmental systems* that deserve our primary interest, we must not neglect the point that complex systems are often the *selective product* of remarkably *lengthy and intricate evolutionary processes*. The relatively high robustness of such systems is therefore by no means surprising.
Take for example the human body with its incredible adaptive and regenerative abilities – without these abilities our much-admired medical treatment would probably have no chance whatever of influencing the

physical conditions all that positively, without really understanding most of the physiological, biochemical and molecular mechanisms involved! A similar remark applies to the *Earth System* – independently of the specific interpretation of the ecosphere as a "super-organism" or just as a huge "biogeophysicochemical machine".

In summary, truly complex systems are much less inclined to the caprices and escapades of moderately simple ones, and they may often be influenced or even controlled *"the soft way"*. Note that it is virtually impossible to "hold together a swarm of fleas" (according to a familiar German saying), while a flock of sheep may be efficiently controlled by an indefatigable German shepherd, and a German crowd can usually be directed by a few loudspeaker announcements (the latter fact being a mixed blessing). Thus the steering of complex systems succeeds in particular when the internal regulative mechanisms are exploited in the sense of stimulated *fuzzy self-control*.

It has to be emphasized, however, that the controllability of complex systems dramatically subsides when these systems become *critical*, for instance, by approaching phase transition lines due to intrinsic dynamics or external driving forces. In such situations, self-amplifying processes might be ignited that lead to inevitable *transformations of structure and operating mode* of the system in question. Using again the human body as an illustration, we may think of crises as uncontrollable (and therefore deadly) auto-immune reactions or sudden circulatory collapses. The planetary ecosystem is no less susceptible to critical developments (see, e.g., the glaciation events triggered by minor fluctuations in insolation) – so it is imperative for humankind to *identify potential roads to criticality and to bypass them at a respectful distance ...*

* * *

This has been a long and winding, yet by no means exhaustive, excursion into the field of passive and active control of simple as well as complex systems. This field trip is no such thing as a proof of the feasibility of geo-cybernetics, but it should raise at least some hope in the realization of one or other variant of fuzzy global E & D management. This hope may only come true, however, if the general prerequisites for Fuzzy Control (see pp. 113 – 113) are specified in the geo-cybernetic context as follows:

1. Observance of the *precautionary principle*, i.e., securing of error-tolerant operating by judiciously staying away from the currently presumed civilizatory and ecological load limits (*"Leeway"*).

2. Creation and cultivation of *flexible instruments* for global E & D management, i.e., international consultation and decision mechanisms, institutions and infrastructures that allow for perpetual readjustment in accordance with cognitive and voluntative developments (*"Responsiveness"*). The present "geo-cybernetic" means, including the system of existing global conventions (*WBGU*, 1996 [84]), seem much too brittle from the point of view of systems analysis or operations research.

3. Incessant and *intensive exploration of virtual coevolution futures* in computer-animated model earth systems for identifying potential dead-end streets and catastrophe domains (*"Panoramic View"*).

These ingredients are especially instrumental in the very test case for fuzzy E & D management, namely *global climate protection policy*. For the latter task unites all main aspects of soft decision-making under uncertainty – the necessity to accept temporal "ecological overburdens" without losing all safety margins; the ability of short-term revisions of long-term greenhouse-gas emissions quota; the intelligent handling of the blurry crystal balls provided by climate and climate impact models, etc.

The interested members of the scientific community have recently begun to focus on the control-theoretical elements of the climate protection issue. For a recent review see, e.g., the book by *Nakićenović* et al. (1996) [161] and in particular the contributions by *Manne* (1996) [146], and *Kelly* and *Kolstadt* (1996) [121]. A topical taxonomy of the pertinent variety of *integrated assessment models* has recently been provided by *Schellnhuber* and *Yohe* [208], where the next-generation models are divided into three classes, namely *evolutionary models*, *guardrail models*, and *combinations of the two pure breeds* (see also the paper by *Hasselmann* and *Hasselmann* (1998) [101] in this book). All these new approaches are implicitly or explicitly suited for taking into account uncertainty and implementing the fuzzy-control principle. This is illustrated for the evolutionary class, e.g., by the papers of *Dowlatabadi* (1996) [60] and *Lempert* et al. (1994) [134], as mentioned already above.

The guardrail models, on the other hand, try to define "tolerable windows" (*WBGU*, 1996 [84]; *Tòth* et al., 1997 [233]; *Petschel-Held* and *Schellnhuber*, 1997 [181]) or "safe corridors" (*Alcamo* and *Kreileman*, 1996 [4]) for climate evolution, and to determine by inverse methods the admissible socio-economic dynamics. Such an approach is *domain-based* instead of trajectory-based and, therefore, easily fuzzified.

At the very end of this section, we would like to re-emphasize the essence of our argumentation in just a few sentences:

The future of the Earth System cannot be predicted – due to irreducible cognitive and voluntative uncertainties. Yet the global E&D process may be shaped – to a certain degree and in an iterative way. Allons corriger le futur!

7. Epilogue

Those who read these lines belong to one of two distinct groups:

The first (and probably dominant) breed embraces the people interested in the overall Esa subject, who therefore absorb the Prologue, "skim and skip" their way through the five main sections, and jump on to the final passages with a certain expectation for conclusions. However, how to conclude an emergent panorama?

The second breed represents those hardy readers who bravely struggle, along with the author, on the tortuous intellectual road to the very end. Some members of this group may actually deplore the *brevity* of my essay, which touches many subtle points quite superficially and downright ignores other important aspects. What I have produced is, in fact, rather a "Picture Book of Earth System Analysis and Sustainable Development" than a comprehensive manual of E & D management. I am convinced, however, that the "Anschauung" – a German notion that amalgamates vision and contemplation – is the most powerful tool for grasping truly complex correlations.

The general opinion about this piece of work will be shaped, anyway, by the real sovereign of popular as well as scientific literature, namely the non-reader ...

Instead of presenting crisp conclusions, I would like to re-emphasize in this brief final section the paramount importance of *wise and equitable* use of our ever-growing knowledge about the Earth System. The fundamental predicament of global modern society is that, at the same time, *too little and too much information is available.* We have discussed the various aspects of cognitive deficiency in some detail in the previous chapters, so let us just recall here that even our purely geophysical wisdom is a rather bizarre melange of "high-know" and sheer guesswork. However, note that geo-cybernetic success does not necessarily depend upon a perfect information basis: From a pragmatic point of view, we need not understand the things we *cannot* control, and – as pointed out in Sect. 6 – we need not understand *precisely* the things we actually can control!

The knowledge we do have, on the other hand, is more than sufficient to give rise to a plethora of serious problems, that may eventually shatter the ethical fundament of our civilization. With the increasing indicative and predictive power of the "Global Brain", we are rapidly approaching the second expulsion from the paradise of ignorance: Imagine that we could tell "wrong from right" in the sense of being able to foresee the entire cascade of long-term consequences of any possible interference with the regional or global environment. If we were ready to take full responsibility of some trigger action in the presence, we would therefore have to anticipate the infinite ensemble of so-generated potential E & D futures as spanned by the diverging tree of alternative decisions to be made in the course of time ahead. It is impossible to make *the* correct choice under these circumstances, because minuscule differences in the initial action might raise hell instead of establishing heaven on Earth; and who would dare to rate the well-being of the, say, 21st generation from now higher than the containment of environmental damages to the 35th generation, for instance?

If we think through this argumentation, then we may arrive at the conclusion that "Sustainable Development" is, above all, an *intellectual problem.* People have been exploiting non-renewable resources like the silver mines of Goslar or Potosí, or have been overexploiting renewable resources like the Mediterranean forests throughout history. They have done this, however, in a "state of innocence" due to the lack of reliable forecasts about the reserves and consequences passed onto their descendants. We are not enjoying this comfortable state anymore, as science and technology confront us relentlessly with the possible implications of any single step we take. So whether we like it or not, *we are morally obliged to behave in a sustainable way* and condemned to make nasty decisions like weighing the life of thousands of coastal settlers threatened by sea-level rise against the prosperity of industries elsewhere on the globe.

Some people will therefore long for the times of splendid ignorance, when they entered a supermarket without worrying for the subsistence of the ozone layer in the stratosphere. For them, and actually for all of us, the *certitude* that our knowledge about the global environment will always contain elements of *uncertainty* may provide some consolation. For this uncertainty preserves at least a pale reflection of arbitrariness, alternatively called freedom of will ...

Yet the problem of prospective decision making, fully conscious of the far-reaching consequences involved, remains. However, let us give rein for a moment: The Global Subject will have to take advantage of modern instruments for moulding and expressing its volition anyway. Why not turn to *"cyberspace democracy"*, where the actors and stake-holders in the coevolution process grind out crucial decisions via interactive planning games based on Earth System modelling? This would ensure a broad distribution of responsibility through equitable access to knowledge, if not wisdom.

Whatever geo-cybernetics will look like in the next millennium, it should contain one element of rationality which the contemporal E & D debate often lacks. I mean the willingness and the ability to assess problems by *the right order of magnitude and importance*. The present generation is, for instance, ready to take incredibly high social and ecological risks by carelessly promoting the replacement of cultures by lifestyle – a development that will ultimately eradicate hundreds of deeply-rooted regional civilizations. By way of contrast, billions of public US-Dollar, D-Mark or Yen are annually spent in the industrialized countries to fend off even the most marginal or elusive environmental menaces for the well-being of human individuals or pet species.

My favourite anecdote illuminating the reigning irrationality and inconsistency is the touching story about the Prince of Wales, who recently announced to switch from lead to bismuth ammunition for wildfowl hunting. The motivation behind this imperial act of environmental consciousness is to prevent the unintentional poisoning by scattered buckshot of those animals that escaped the gun. It seems that the Global Subject is still a long way from home ...

References

1. R. Abraham and J. E. Marsden. *Foundations of mechanics.* Benjamin/Cummings, Reading, Mass., 1977.
2. S. G. Akl. *Parallel Computation: Models and Methods.* Prentice Hall, Upper Saddle River, 1997.
3. J. Alcamo, editor. *IMAGE 2.0: Integrated Modeling of Global Climate Change.* Kluwer, Dordrecht, 1994. Reprinted from Journal of Water, Air and Soil Pollution, Vol. 76 Nos. 1-2, 1994.
4. J. Alcamo and G. J. J. Kreileman. Emission scenarios and global climate protection. *Global Environmental Change*, 6(4):305 pp., 1996.
5. J. S. Andrade. Self-organized criticality in the El Niño Southern Oscillation. *Physica A*, 215(3):331 pp., 1995.
6. V. I. Arnold. Instability of dynamical systems with several degrees of freedom. *Soviet Mathematics – Doklady*, 5:581 pp., 1964.
7. V. I. Arnold. *Mathematical Methods of Classical Mechanics.* Springer, New York, 1978.
8. V. I. Arnold and A. Avez. *Ergodic Problems of Classical Mechanics.* Benjamin, New York, 1968.
9. P. Baccini and P. H. Brunner. *Metabolism of the Anthroposphere.* Springer, Berlin, 1991.
10. P. Bak. *The Science of Self-Organized Criticality.* Oxford University, Oxford, 1997.
11. P. Bak and K. Chen. Self-organized criticality. *Scientific American*, 264(1):46 pp., 1991.
12. P. Bak, C. Tang, and K. Wiesenfeld. Self-organized criticality. *Physical Review Letters*, 59(4):381 pp., 1987.
13. W. L. Baker. Longterm response of disturbance landscapes to human intervention and global change. *Landscape Ecology*, 10(3):143 pp., 1995.
14. E. B. Barbier. *Economics, Natural-Resource Scarcity and Development.* Earthscan, London, 1989.
15. C. J. Barrow. *Developing the Environment: Problems and Management.* Longman Scientific & Technical, Essex, 1995.
16. R. J. Baxter. *Exactly Solved Models in Statistical Mechanics.* Academic, London, 1990.
17. D. E. Bell, R. L. Keeney, and H. Raiffa, editors. *Conflicting Objectives in Decisions.* Wiley & Sons, London, 1977.
18. R. E. Bellmann. *Dynamic Programming.* Princeton University, Princeton, 1957.
19. C. H. Bennett. Demons, engines and the second law. *Scientific American*, 257(5):108 pp., 1987.
20. P. Bergé. Chaos and unusual attractors. *Physikalische Blätter*, 46(7):209 pp., 1990.
21. P. Bergé, Y. Pomeau, and C. Vidal. *Order within Chaos.* Wiley & Sons, New York, 1984.
22. H. O. Bergesen and G. Parmann, editors. *Green Globe Yearbook 1996.* Oxford University, Oxford, 1996.
23. M. V. Berry. Regular and irregular motion. In S. Jorna, editor, *Topics in nonlinear dynamics. A tribute to Sir Edward Bullard*, number 46 in AIP conference proceedings, La Jolla, CA, 1978. American Institute of Physics.

24. K. Binmore. *Essays on the Foundations of Game Theory.* Basil Blackwell, Cambridge, 1990.
25. C. Blackburn, editor. *Summary, Conclusions, and Recommendations*, Global Change and the Human Prospect: Issues in Population, Science, Technology, and Equity, Research Triangle Park, NC, 1992. Sigma Xi, The Scientific Research Society.
26. P. M. Blaikie and H. Brookfield. *Land Degradation and Society.* Methuen, London, 1987.
27. D. Bohm. *Quantum Theory.* Prentice Hall, New York, 1951.
28. H.-R. Bork. *Bodenerosion und Umwelt.* Landschaftsgenese und Landschaftsökologie, No. 13. Technische Universität Braunschweig, Braunschweig, 1988.
29. H. Bossel. Deriving indicators of sustainable development. *Environmental Modeling & Assessment*, 1(4):193 pp., 1996.
30. H. Bossel. Ecosystems and society: implications for sustainable development. *World Futures*, 47:143 pp., 1996.
31. H. Breitmeier. *Ozonschicht und Klima auf der globalen Agenda.* Number 17 in Tübinger Arbeitspapiere zur internationalen Politik und Friedensforschung. Arbeitsgruppe Friedensforschung, Tübingen, 1992.
32. L. Brillouin. Thermodynamics and information theory. *American Scientist*, 38(4):594 pp., 1950.
33. W. S. Broecker. Chaotic climate. *Scientific American*, 273(5):62 pp., 1995.
34. L. R. Brown, C. Flavin, and S. Postel. *Saving the Planet.* Norton, New York, 1991.
35. N. Brown. *The Strategic Revolution: Thoughts for the Twenty-First Century.* Brassey's, London, 1992.
36. M. J. Budyko and G. S. Golitsyn. *Climatic Catastrophes.* Springer, New York, 1988.
37. M. Buitenkamp, H. Venner, and T. Wams. *Sustainable Netherlands.* Friends of the Earth Netherlands, Amsterdam, 1992.
38. H. B. Callen. *Thermodynamics and an Introduction to Thermostatistics.* Wiley, New York, 1985.
39. M. Carley and I. Christie. *Managing Sustainable Development.* University of Minnesota Press, Minneapolis, 1993.
40. M. A. Cassel-Gintz, M. K. B. Lüdeke, G. Petschel-Held, F. Reusswig, M. Plöchel, G. Lammel, and H. J. Schellnhuber. Fuzzy logic based global assessment of the marginality of agricultural land use. *Climate Research*, 8(2):135 pp., 1997.
41. L. Cesari. *Optimization Theory and Applications.* Springer, New York, 1983.
42. G. J. Chaitin. *Algorithmic Information Theory.* Cambridge University, Cambridge, 1987.
43. W. C. Clark. Managing planet earth. *Scientific American*, 261(3):46 pp., 1989.
44. W. C. Clark and R. E. Munn, editors. *Sustainable Development of the Biosphere.* Cambridge University, Cambridge, 1986.
45. M. Claussen and A. Ganopolski. *Klimasystemmodelle.* Umwelt- und Klimabeeinflussung durch den Menschen. VDI Verlag, Düsseldorf, 1997.
46. W. R. Cline, editor. *The Economics of Global Warming.* Institute for International Economics, Washington DC, 1992.
47. C. W. Cobb and J. B. Cobb. *The Green National Product - A Proposed Index of Sustainable Economic Welfare.* University Press of America, Lanham, 1994.
48. R. Costanza, R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. O'Neill, J. Paruelo, R. Raskin, P. Sutton, and M. van den Belt. The value of the world's ecosystem services and natural capital. *Nature*, 387(6630):253 pp., 1997.
49. W. Cronon. *Uncommon Ground. Towards Reinventing Nature.* Norton, New York, 1995.
50. H. E. Daly. Toward some operational principles of sustainable development. *Ecological Economics*, 2:1 pp., 1990.
51. H. E. Daly and J. B. Cobb. *For the Common Good.* Beacon Press, Boston, 1994.
52. H. E. Daly and K. N. Townsend, editors. *Valuing the Earth. Economics, Ecology, Ethics.* MIT Press, Cambridge, 1993.
53. G. B. Dantzig and A. F. Veinott Jr. *Mathematics of the Decision Sciences.* American Mathematical Society, Providence, 1968.
54. J. Darmstädter. Global Development and the Environment - Perspectives on Sustainability. Washington D.C., 1992.
55. P. C. W. Davies. *The Ghost in the Atom: A Discussion of the Mysteries of Quantum Physics.* Cambridge University, Cambridge, 1986.
56. J. de Rosnay. *L'homme symbiotique: regards sur le troisiéme millénaire.* Seuil, Paris, 1995.
57. E. A. Desloge. *Classical Mechanics.* Wiley, New York, 1982.
58. B. d'Espagnat. Quantum theory and reality (reprint). *Scientific American*, 241(5):158 pp., 1979.
59. D. Dörner. *The Logic of Failure: Why things go wrong and what we can do to make them right.* Metropolitan Books, New York, 1996.
60. H. Dowlatabadi. Adaptive management of climate change mitigation: a strategy for coping with uncertainty. Discussion paper, unpublished, Center for Integrated Study of the Human Dimensions of Global Change, Carnegie Mellon University, 1996.
61. H. Dowlatabadi and G. M. Morgan. Integrated assessment of climate change. *Science*, 259:1813–1814, 1993.
62. B. Drossel and F. Schwabl. Self-organized criticality in a forest-fire model. *Physica A*, 191(1-4):47 pp., 1992.
63. W. Ebeling, H. Engel, and H. Herzel. *Selbstorganisation in der Zeit.* Akademie-Verlag, Berlin, 1990.
64. M. Efinger and H. Breitmeier. *Zur Theorie und Praxis der Verifikation einer globalen Klimakonvention.* Number 3 in Berichte des Forschungszentrums Jülich. Arbeitsgruppe Friedensforschung, Jülich, 1992.
65. Environmental Impact Assessment Review (EIAR). Sustainable development. *Environmental Impact Assessment Review*, 12(1-2), 1992.

66. K. Falconer. *Fractal Geometry. Mathematical Foundations and Applications.* Wiley & Sons, Chichester, 1990.
67. S. Fankhauser. *Valuing Climate Change.* Earthscan, London, 1995.
68. J. C. Farman, B. G. Gardiner, and J. D. Shanklin. Large losses of total ozone in Antarctica reveal seasonal CO_x/NO_x interaction. *Nature*, 315(6016):207 pp., 1985.
69. Federal Planning Office of Belgium (FPOB). *Report of the workshop on indicators of sustainable development for decision-making*, Ghent, 1995. Submitted to the UN Commission on Sustainable Development.
70. J. Feichter, U. Lohmann, and I. Schult. The atmospheric sulfur cycle in ECHAM-4 and its impacts on the shortwave radiation. *Climate Dynamics*, 13:235 pp., 1997.
71. R. P. Feynman and A. R. Hibbs. *Quantum Mechanics and Path Integrals.* McGraw-Hill, New York, 1965.
72. W. H. Fleming and R. W. Rishel. *Deterministic and Stochastic Optimal Control.* Springer, New York, 1975.
73. Food and Agriculture Organization of the United Nations (FAO). *Lessons from the green revolution*, 1996. http://www.FAO.org/wfs/final/e/volume2/t06sum-e.htm.
74. J. W. Forrester. *World dynamics.* Wright-Allen, Cambridge, 1971.
75. Friends of the Earth Europe (FEE). *Towards Sustainable Europe.* Brussels, 1995.
76. B. Fritsch, S. Schmidheiny, and W. Seifritz. *Towards an Ecologically Sustainable Growth Society. Physical Foundations, Economic Transitions, and Political Constraints.* Springer, Berlin, 1994.
77. H. Gallee, J. P. van Ypersele, T. Fichefet, Marsiat C., C. H. Tricot, and A. Berger. Simulation of the last glacial cycle by a coupled sectorially averaged climate-ice sheet model. II. Response to insolation and CO_2 variations. *Journal of Geophysical Research*, 97:15713 pp., 1992.
78. H. Gallee, J. P. van Ypersele, T. Fichefet, C. H. Tricot, and A. Berger. Simulation of the last glacial cycle by a coupled sectorially averaged climate-ice sheet model. I. The climate model. *Journal of Geophysical Research*, 96:13139 pp., 1991.
79. A. Ganopolski, V. Brovkin, M. Claussen, and V. Petoukhov. A study of bio-geophysical feedbacks with a coupled climate-biosphere model CLIMBER-2. *Annales Geophysicae*, 15(II):352 pp., 1997.
80. A. Ganopolski, S. Rahmstorf, V. Petoukhov, and M. Claussen. Simulation of modern and glacial climates with a coupled climate model. *Nature*, 1997. Accepted.
81. A. Ganopolski and H. J. Schellnhuber. Influence of salinity on the structure of the thermohaline ocean circulation. Unpublished, 1997.
82. German Advisory Council on Global Change (WBGU), Annual Reports 1993-1997, English and German editions.
83. German Advisory Council on Global Change (WBGU). *World in Transition: The Threat to Soils. Annual Report 1994*, Economica, Bonn, 1995.
84. German Advisory Council on Global Change (WBGU). *World in Transition: Ways Towards Global Environmental Solutions. Annual Report 1995*, Springer, Berlin, 1996.
85. German Advisory Council on Global Change (WBGU). *World in Transition: The Research Challenge. Annual Report 1996*, Berlin, 1997. Springer.
86. German Advisory Council on Global Change (WBGU). *World in Transition: Ways Towards Sustainable Management of Freshwater Resources. Annual Report 1997*, Springer, Berlin, 1997. Forthcoming.
87. R. Gersonde, F. T. Kyte, U. Bleil, B. Diekmann, J. A. Flores, K. Gohl, G. Grahl, R. Hagen, G. Kuhn, F. J. Sierro, D. Völker, A. Abelmann, and J. A. Bostwick. Geological record and reconstruction of the late Pliocene impact of the Eltanin asteroid in the Southern Ocean. *Nature*, 390(6658):357 pp., 1997.
88. E. H. Gilson. *History of Christian Philosophy in the Middle Ages.* Sheed and Ward, London, 1955.
89. H. Goldstein. *Classical Mechanics.* Addison-Wesley, Reading, 1982.
90. R. Goodland, editor. *Environmentally Sustainable Economic Development: Building on Brundtland.* World Bank, Washington, 1991.
91. A. Gore. *Earth in the Balance - Ecology and the Human Spirit.* Houghton Mifflin Company, Boston, 1992.
92. J. R. Gribbin. *In Search of Schrödinger's Cat.* Black Swan Books, London, 1991.
93. R. B. Griffiths. Correlations in separated quantum systems: a consistent history analysis of the EPR problem. *American Journal of Physics*, 55(1):11 pp., 1989.
94. A. Grübler and A. McDonald. The drive to cleaner energy. *Options*, Winter 1995:8 pp., 1995.
95. H. Haken. Cooperative phenomena in systems far from thermal equilibrium and in non-physical systems. *Reviews of Modern Physics*, 47(1):67 pp., 1975.
96. H. Haken. *Advanced Synergetics.* Springer, Berlin, 1983.
97. P. R. Halmos. *Measure Theory.* Springer, Berlin, 1974.
98. G. A. Harrison and D. Jeffries. Human biology in urban environments. *Nature and Resources*, 12(1):2 pp., 1976.
99. K. Hasselmann. Climate change - are we seeing global warming? *Science*, 276(5314):914 pp., 1997.
100. K. Hasselmann. Multi-pattern fingerprint method for detection and attribution of climate change. *Climate Dynamics*, 13(9):601 pp., 1997.
101. S. Hasselmann and S. Hasselmann. Multi-actor optimization of greenhouse gas emission paths using coupled integral climate response and economic models. In *Earth System Analysis: Integrating Science for Sustainability.* Springer, Berlin, 1998. Contribution in this proceedings.
102. HDP, editor. *Global Change, Local Challenge*, volume 1 and 2 of *HDP Third Scientific Symposium 20-22 September 1995*, Geneva, 1996. Human Dimensions of Global Environmental Change Programme. Report 8.
103. G. C. Hegerl, K. Hasselmann, U. Cubasch, J. F. B. Mitchell, E. Roeckner, R. Voss, and J. Waszkewitz. Multi-fingerprint detection and attribution analysis of greenhouse gas, greenhouse gas-plus-aerosol and solar forced climate change. *Climate Dynamics*, 13(9):613 pp., 1997.

104. F. Hole. Environmental instabilities and urban origins. In G. Stein, editor, *Chiefdoms and Early States in the Near East: The Organizational Dynamics of Complexity*, number 18 in Monographs in World Archaeology. Prehistory, Madison, 1994.
105. F. Hole. Evidence for mid-Holocene environmental change in the western Habur drainage, Northeastern Syria. In *Third Millennium BC Abrupt Climate Change and Old World Social Collapse*, New Haven, 1994. Yale University. NATO Advanced Research Workshop, September 1994.
106. C. S. Holling. Simplifying the complex: the paradigm of ecological function and structure. *Journal of Operational Research*, 30:139 pp., 1987.
107. R. M. Hough, I. Gilmour, C. T. Pillinger, J. W. Arden, K. W. R. Gilkes, J. Yuan, and H. J. Milledge. Diamond and silicon carbide in impact melt rock from the Ries impact crater. *Nature*, 378:41 pp., 1995.
108. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 1995. Working Group I: The Science of Climate Change. Working Group II: Impacts, Adaptations and Mitigation of Climate Change. Working Group III: Economic and Social Dimensions of Climate Change*, Cambridge, 1996. University Press.
109. The International Geosphere-Biosphere Programme IGBP. *Global Change. Report 28, IGBP in Action: Work Plan 1994-1998*, Stockholm, 1994.
110. M. D. Intriligator. *Mathematical Optimization and Economic Theory.* Prentice-Hall, Englewood Cliffs, 1971.
111. U. Irmer. Personal communication, Federal Environmental Agency of Germany (UBA).
112. G. Julia. Sur l'iteration des fonctions rationelles. *Journal Mathematique Pure et Appl.*, 8:47 pp., 1918.
113. A. Kandel. *Fuzzy Mathematical Techniques with Applications.* Addison-Wesley, Reading, 1986.
114. A. Kandel and G. Langholz, editors. *Fuzzy Control Systems.* CRC Press, Boca Raton, 1993.
115. I. Kant. *Schriften zur Metaphysik und Logik.* Suhrkamp, Frankfurt a. M., 1991. Reprint.
116. C. L. Karr and E. J. Gentry. Control of a chaotic system using fuzzy logic. In A. Kandel and G. Langholz, editors, *Fuzzy Control Systems.* CRC Press, Boca Raton, 1993.
117. H. G. Kastenholz, K. H. Erdmann, and M. Wolff, editors. *Nachhaltige Entwicklung - Zukunftschancen für Mensch und Umwelt.* Springer, Berlin, 1996.
118. J. F. Kasting, O. B. Toon, and J. B. Pollack. How climate evolved on the terrestrial planets. *Scientific American*, 258(2):90 pp., 1988.
119. R. K. Kaufmann and D. I. Stern. Evidence for human influence on climate from hemispheric temperature relations. *Nature*, 388(6637):39 pp., 1997.
120. Y. Kaya, N. Nakićenović, W. D. Nordhaus, and F. L. Tòth, editors. *Costs, Impacts, and Benefits of* CO_2 *Mitigation*, Laxenburg, 1993. IIASA.
121. D. L. Kelly and C. D. Kolstadt. The climate change footprint: Will we see it before it is upon us? In N. Nakićenović, W. D. Nordhaus, R. Richels, and F. L. Tòth, editors, *Integrating Science, Economics, and Policy*, Laxenburg, 1996. IIASA.
122. G. Kirsch. *Neue Politische Ökonomie.* Werner, Düsseldorf, 1993.
123. T. R. Knutson and S. Manabe. Impact of increased CO_2 on simulated ENSO-like phenomena. *Geophysical Research Letters*, 8(21):2295 pp., 1994.
124. E. Kreyszig. *Introductory Functional Analysis with Applications.* Wiley, New York, 1978.
125. E. Kreyszig. *Statistische Methoden und ihre Anwendungen.* Vandenhoek & Ruprecht, Göttingen, 1991.
126. W. E. Krumbein and H. J. Schellnhuber. Geophysiology of carbonates as a function of bioplanets. In V. Ittekkot, S. Kempe, W. Michaelis, and A. Spitzy, editors, *Facets of Modern Biogeochemistry, Festschrift for E. T. Degens.* Springer, Berlin, 1990.
127. F. T. Kyte, L. Zhou, and J. T. Wasson. New evidence on the size and possible effects of a latePliocene oceanic asteroid impact. *Science*, 241:63 pp., 1988.
128. D. P. Landau. Theory of phase transitions beyond mean-field theory. In K. Binder and G. Cicotti, editors, *Euroconference on Computer Simulation in Condensed Matter Physics Chemistry*, Bologna, Italy, 1996. Italian Phys. Soc.
129. K. Lanius. *Die Erde im Wandel.* Spektrum, Heidelberg, 1995.
130. M. Latif, T. P. Barnett, M. A. Cane, M. Fluegel, N. E. Graham, H. von Storch, J.-S. Xu, and S. E. Zebiak. A review of ENSO prediction studies. *Climate Dynamics*, 9:167 pp., 1994.
131. E. B. Lee and L. Markus. *Foundations of Optimal Control Theory.* Wiley & Sons, New York, 1967.
132. S. M. Lélé. Sustainable development - a critical review. *World Development*, 19(607), 1991.
133. S. Lem. *Solaris.* Faber and Faber, London, 1991.
134. R. J. M. Lempert, M. E. Schlesinger, and J. K. Hammitt. The impact of potential abrupt climate changes on near-term policy choices. *Climatic Change*, 26:351 pp., 1994.
135. J. S. Lewis. *Rain of Iron and Ice: The Very Real Threat of Comet and Asteroid Bombardment.* Addison-Wesley, Reading, 1995.
136. A. J. Lichtenberg and M. A. Liebermann. *Regular and Stochastic Motion*, volume 38 of *Applied Mathematical Sciences.* Springer, New York, 1983.
137. D. Lind and B. Marcus. *An Introduction to Symbolic Dynamics and Coding.* Cambridge University, Cambridge, 1995.
138. E. N. Lorenz. Deterministic non-periodic flow. *Journal of the Atmospheric Sciences*, 20:130 pp., 1963.
139. R. Loske. *Zukunftsfähiges Deutschland: ein Beitrag zu einer global nachhaltigen Entwicklung.* Birkhäuser, Basel, 1996. Wuppertal Institut für Klima, Umwelt, Energie.
140. R. Loske and W. Sachs. *Industrial Societies & Sustainability: Proposals for Managing the Transition.* Humanities, UK, 1997.

141. J. E. Lovelock. *Gaia, The Practical Science of Planetary Medicine.* Gaia Books, London, 1991.
142. L. J. Lundgren, editor. *Views of Nature.* Swedish Council for Planning and Coordination of Research, Stockholm, 1993.
143. A. M. Lyapunov. Problème général de stabilité du mouvement. *Annals of Mathematics Studies*, 17, 1949. French translation of the original work of 1892.
144. S. Manabe and R. J. Stouffer. Century-scale effects of increased atmospheric CO_2 on the ocean-atmosphere system. *Nature*, 364:215 pp., 1993.
145. B. B. Mandelbrot. *The Fractal Geometry of Nature.* Freeman, New York, 1991.
146. A. S. Manne. Hedging strategies for global carbon dioxide abatement: a summary of poll results, EMF 14 subgroup - analysis for decisions under uncertainty. In N. Nakićenović, W. D. Nordhaus, R. Richels, and F. L. Tòth, editors, *Integrating Science, Economics, and Policy*, Laxenburg, 1996. IIASA.
147. R. M. May and G. Sugihara. Applications of fractals in ecology. *Trends in Ecology & Evolution*, 5(3):79 pp., 1990.
148. D. McKenzie-Mohr and M. Marien. *Visions of Sustainability.* Future. Butterworth-Heinemann, Oxford, 1994.
149. D. H. Meadows, D. L. Meadows, and J. Randers. *Beyond the Limits.* Chelsea Green Publishing Co., Post Mills, 1992.
150. D. L. Meadows, W. W. Behrens III, D. H. Meadows, R. F. Naill, J. Randers, and E. K. O. Zahn. *Dynamics of Growth in a Finite World.* Wright-Allen, Cambridge, MA, 1974.
151. G. A. Meehl, G. W. Branstator, and W. M. Washington. Tropical Pacific interannual variability and CO_2 climate change. *Journal of Climate*, 6(1):42 pp., 1993.
152. N. D. Mermin. Is the moon there when nobody looks? Reality and the quantum theory. *Physics Today*, 38(4):38 pp., 1985.
153. M. Milankovitch. Mathematische Klimalehre und astronomische Theorie der Klimaschwankungen. In W. Köppen and R. Geiger, editors, *Handbuch der Klimatologie.* Gebrüder Borntraeger, Berlin, 1930.
154. B. Moldan and S. Billharz, editors. *Sustainability-Indicators: Report of the Project on Indicators for Sustainable Development.* SCOPE 58. John Wiley, Chichester, 1997.
155. M. Montanari. *Der Hunger und der Überfluß: Kulturgeschichte der Ernährung in Europa.* Beck, München, 1995.
156. P. D. Moore, W. G. Chaloner, and P. A. Stott. *Global Environmental Change.* Blackwell Science, Oxford, 1996.
157. A. Mosier, W. J. Parton, D. Valentine, D. S. Ojima, D. S. Schimel, and O. Heinemeyer. CH_4 and N_2O fluxes in the Colorado shortgrass steppe: 2. Longterm impact of land use change. *Global Biogeochemical Cycles*, 11(1):29 pp., 1997.
158. R. A. Muller and G. J. MacDonald. Glacial cycles and astronomical forcing. *Science*, 277:215 pp., 1997.
159. R. E. Munn, J. W. M. La Riviére, and N. van Lookeren Campagne, editors. *Policy Making in an Era of Global Environmental Change.* Kluwer, Dordrecht, 1996.
160. N. Nakićenović, W. D. Nordhaus, R. Richels, and F. L. Tòth, editors. *Integrative Assessment of Mitigation, Impacts, and Adaptation to Climate Change*, Laxenburg, 1994. IIASA.
161. N. Nakićenović, W. D. Nordhaus, R. Richels, and F. L. Tòth, editors. *Integrating Science, Economics, and Policy*, Laxenburg, 1996. IIASA.
162. NASA. *Earth System Science.* NASA, Earth System Sciences Committee, Washington, 1988.
163. M. Nauenberg and H. J. Schellnhuber. Analytical evaluation of the multifractal properties of a Newtonian Julia set. *Physical Review Letters*, 62(16):1807 pp., 1989.
164. J. W. Negele. The mean-field theory of nuclear structure and dynamics. *Reviews of Modern Physics*, 54(4):913 pp., 1982.
165. W. D. Nordhaus. An optimal transition path for controlling greenhouse gases. *Science*, 258:1315 pp., 1992.
166. W. D. Nordhaus and J. Tobin. Is growth obsolete? In *Economic Growth*, number 46 in General Series, 96E, National Bureau of Economic Research, 1972. Columbia University.
167. J. B. Opschoor. *Environment, Economy and Sustainable Development.* Wolters-Noordhoff, Rotterdam, 1992.
168. J. B. Opschoor and L. Reijnders. Towards sustainable development indicators. In O. Kuik and H. Verbruggen, editors, *In Search of Indicators of Sustainable Development.* Kluwer Academic Publishers, Dordrecht, 1991.
169. J. B. Opschoor and J. v. d. Straaten. Sustainable development: an institutional approach. *Ecological Economics*, 7:203 pp., 1993.
170. E. Ott, C. Grebogi, and J. A. Yorke. Controlling chaos. *Physical Review Letters*, 64(11):1196 pp., 1990.
171. M. Papageorgiou. *Optimierung: statische, dynamische, stochastische Verfahren für die Anwendung.* Oldenbourg, München, 1991.
172. W. Pareto. *Traité de sociologie générale.* Payot, Lausanne, 1917.
173. J. A. Paulos. *A Mathematician Reads the Newspaper.* Penguin Mathematics. Penguin, London, 1995.
174. D. Pearce. *Economic Values and the Natural World.* Earthscan, London, 1993.
175. D. Pearce and R. K. Turner. *Economics of Natural Resources and the Environment.* Harvester Wheatsheaf, New York, 1990.
176. D. W. Pearce. *Blueprint 2: Greening the World Economy.* Earthscan, London, 1991.
177. D. W. Pearce, A. Markandya, and E. Barbier. *Blueprint for a Green Economy.* Earthscan, London, 1989.
178. H. O. Peitgen and P. H. Richter. *The Beauty of Fractals.* Springer, Berlin, 1988.
179. R. Penrose. *The Emperor's New Mind: Concerning Computers, Minds, and the Laws of Physics.* Oxford, Oxford University, 1989.
180. I. Peterson. *Newton's Clock: Chaos in the Solar System.* W. H. Freeman, New York, 1993.

181. G. Petschel-Held and H. J. Schellnhuber. The tolerable windows approach to climate control. In F. L. Tòth, editor, *Cost-benefit analyses of climate change: the broader perspective*. Birkhäuser, Basel, 1997.
182. S. G. H. Philander. *El Niño, La Niña and the Southern Oscillation*. Academic, New York, 1989.
183. K. T. Pickering and L. A. Owen. *An Introduction to Global Environmental Issues*. Routledge, London, 1994.
184. D. Pitt and P. Samson, editors. *Beyond the Biosphere: The Noosphere and Global Problems*. Routledge, London, 1997.
185. H. Poincaré. *Les methodés nouvelles de la mécanique céleste*. Gauthier-Villars, Paris, 1899.
186. L. S. Pontryagin. *The Mathematical Theory of Optimal Processes*. Interscience, New York, 1962.
187. K. R. Popper. *The Logic of Scientific Discovery*. Routledge, London, 1992. Reprint.
188. I. C. Prentice, M. T. Sykes, and W. Cramer. A simulation model for the transient effects of climate change on forest landscapes. *Ecological Modelling*, 65(1-2):51 pp., 1993.
189. S. Rahmstorf. Bifurcations of the Atlantic thermohaline circulation in response to changes in the hydrological cycle. *Nature*, 378:145 pp., 1995.
190. Rat von Sachverständigen für Umweltfragen (RSU). *Umweltgutachten 1994. Für eine dauerhaft-umweltgerechte Entwicklung*, Statistisches Bundesamt, Wiesbaden, 1994.
191. J. Rawls. *A Theory of Justice*. Harvard University, Cambridge MA, 1971.
192. S. Rayner. *Integrated Climate Change Assessment: Fairness and Equity Issues. An Overview*. Battelle Northwest National Laboratory, Washington DC, 1997.
193. M. Redclift. Reflections on the "Sustainable Development" debate. *International Journal of Sustainable Development and World Ecology*, 1(1):3 pp., 1994.
194. W. E. Rees. *Defining "Sustainable Development"*. University of British Columbia, Vancouver, 1989.
195. P. ReVelle and C. ReVelle, editors. *The Global Environment. Securing a Sustainable Future*. Jones and Bartlett, Boston, 1992.
196. P. H. Richter and H.-J. Scholz. *Das ebene Doppelpendel*. IWF Göttingen, 1985.
197. C. Robinson. *Dynamical Systems: Stability, Symbolic Dynamics, and Chaos*. CRC Press, Boca Raton, 1994.
198. F. J. Romeiras, C. Grebogi, E. Ott, and W. P. Dayawansa. Controlling chaotic dynamical systems. *Physica D*, 58(1-4):165 pp., 1992.
199. N. Rosen. *The dilemma of Einstein, Podolsky and Rosen, 60 years later*. Institute of Physics Pub., Bristol, 1996.
200. J. Rotmans. Global Change and Sustainable Development: Towards an Integrated Conceptual Model. In H.-J. Schellnhuber and V. Wenzel, editors, *Earth System Analysis: Integrating Science for Sustainability*, Berlin, 1998. Springer. Contribution in this Proceedings.
201. J. Rotmans and H. J. M. de Vries. *Perspectives on Global Change: The TARGETS Approach*. Cambridge University, Cambridge, 1997.
202. D. Ruelle. *Chance and Chaos*. Princeton University, New Jersey, 1991.
203. C. Safina. The world's imperiled fish. *Scientific American*, 273(5):46 pp., 1995.
204. P. A. Samuelson and W. D. Nordhaus. *Economics*. McGraw-Hill, New York, 1995.
205. P. Saunders. *Introduction to Catastrophe Theory*. Cambridge University, Cambridge, 1980.
206. H. J. Schellnhuber. Global environmental change: the physics and the metaphysics. *Global Environmental Change*, 1997. Submitted.
207. H. J. Schellnhuber, M. A. Cassel-Gintz, J. Kropp, G. Lammel, W. Lass, R. Lienenkamp, C. Loose, M. K. B. Lüdeke, O. Moldenhauer, G. Petschel-Held, M. Plöchel, and F. Reusswig. Syndromes of global change. *GAIA*, 6(1):19 pp., 1997.
208. H. J. Schellnhuber and G. W. Yohe. Comprehending the economic and social dimensions of climate change by integrated assessment. Proceedings of the WCRP-Conference, Geneva, 1997. Forthcoming.
209. F. Schmidt-Bleek. *Wieviel Umwelt braucht der Mensch? MIPS, das Maß für ökologisches Wirtschaften*. Birkhäuser, Berlin, 1994.
210. H. Schmitz. *Anaximander und die Anfänge der griechischen Philosophie*. Bouvier, Bonn, 1988.
211. E. Schrödinger. *Naturwissenschaften* 23:807 pp., 1935, translated in J. A. Wheeler and W. H. Zurek, editors, *Quantum Theory and Measurement*, Princeton University, Princeton, NJ, 1983.
212. I. Schult, J. Feichter, and W. F. Cooke. The effect of black carbon and sulfate aerosols on the global radiation budget. *Journal of Geophysical Research*, 1997. Accepted.
213. H. G. Schuster. *Deterministic chaos: an introduction*. VCH, Weinheim, 1988.
214. F. Schweitzer, editor. *Self-Organization of Complex Structures: From Individual to Collective Dynamics*. Gordon & Breach, London, 1997.
215. Scientific Committee on Problems of the Environment (SCOPE), Series No. 1-58, 1971-1997.
216. U. E. Simonis. *Beyond Growth. Elements of Sustainable Development*. Edition Sigma, Berlin, 1990.
217. U. E. Simonis. *Weltumweltpolitik*. Wissenschaftszentrum für Sozialforschung, Berlin, 1996.
218. Y. G. Sinai. *Introduction to Ergodic Theory*. Math. Notes 18. Princeton University, Princeton, 1976.
219. R. M. Solow. *An Almost Practical Step to Sustainability*. Resources for the Future, Washington, 1992.
220. J. H. Spangenberg. *Ein zukunftsfähiges Europa. Towards sustainable Europe*. Wuppertal Papers, Bd. 42. Wuppertal Institut für Klima - Umwelt - Energie, Wuppertal, 1995.
221. D. Sprinz and U. Luterbacher. International relations and global climate change. PIK Report 21, Potsdam Institute for Climate Impact Research (PIK), Potsdam, 1996.
222. N. Stehr and H. von Storch. Das soziale Konstrukt des Klimas, 1997. http://w3g.gkss.de/G/Mitarbeiter/storch/vdi.html.

223. I. Stewart. *Does God play Dice? The Mathematics of Chaos.* Basil Blackwell, Oxford, 1989.
224. T. F. Stocker, D. G. Wright, and L. A. Mysak. A zonally averaged coupled ocean-atmosphere model for paleoclimate studies. *Journal of Climate*, 5:773 pp., 1992.
225. M. B. Stoff, J. F. Fanton, and R. H. Williams, editors. *The Manhattan Project.* Temple University, Philadelphia, 1991.
226. G. J. Sussman and J. Wisdom. Numerical evidence that the motion of Pluto is chaotic. *Science*, 241(4864):433 pp., 1988.
227. Y. M. Svirezhev and W. von Bloh. A minimal model of interaction between climate and vegetation: qualitative approach. *Ecological Modelling*, 92:89 pp., 1996.
228. M. Tabor. *Chaos and Integrability in Nonlinear Dynamics.* John Wiley & Sons, New York, 1989.
229. F. L. Tòth. Practicing the future: implementing "the policy exercise concept". Working Paper 86-23, IIASA, Laxenburg, 1986.
230. F. L. Tòth. Practicing the future. Part 2: Lessons from the first experiments with policy exercises. Working Paper 88-12, IIASA, Laxenburg, 1988.
231. F. L. Tòth. Policy exercises. Research Report 89-2, IIASA, Laxenburg, 1989.
232. F. L. Tòth, editor. *Fairness Concerns in Climate Change*, Proceedings of the International Workshop held at PIK, Potsdam, 1997. Forthcoming.
233. F. L. Tòth, T. Bruckner, H. Füssel, M. Leimbach, G. Petschel-Held, and H. J. Schellnhuber. The tolerable windows approach to integrated assessment. In *Asia-Pacific Workshop on Integrated Assessment*, Tokyo, 1997. IPCC. Forthcoming.
234. R. P. Turco. *Earth under Siege: From Air Pollution to Global Change.* Oxford University, Oxford, 1996.
235. E. Tziperman, H. Scher, S. E. Zebiak, and M. A. Cane. Controlling spatiotemporal chaos in a realistic El Niño prediction model. *Physical Review Letters*, 79:1034 pp., 1997.
236. *United Nations Climate Change Bulletin*, Geneva, 1995. Interims Secretariat for the UN Climate Change Convention. Issue 7.
237. UNESCO. *Man Belongs to the Earth: International Co-operation in Environmental Research. UNESCO's Man and the Biosphere Programme.* UNESCO, Paris, 1988.
238. United Nations. *Indicators of Sustainable Development: Framework and Methodologies*, United Nations, New York, 1996.
239. United Nations Conference on Environment and Development (UNCED), Rio de Janeiro. *Earth Summit '92*, London, 1992. The Regency.
240. United Nations Development Programme (UNDP). *Human Development Report 1990*, Oxford University Press, New York, 1990.
241. U.S. National Committee (USNC). *The United States Man and the Biosphere Program*, U.S. MAB Secretariat, Washington, 1996.
242. D. G. Victor. The Montreal Protocol's non-compliance procedure: lessons for making other international environmental regimes more effective. In W. Lang, editor, *The Ozone Treaties and Their Influence on the Building of Environmental Regimes.* Federal Ministry of Foreign Affairs, Vienna, 1996.
243. W. von Bloh, A. Block, and H. J. Schellnhuber. Self-stabilisation of the biosphere under global change: a tutorial geophysiological approach. *Tellus*, 49B:249 pp., 1997.
244. J. von Neumann. *Theory of Games and Economic Behaviour.* Princeton University, Princeton, 1944.
245. L. Walras. *Elements d'économie politique pure ou theorie de la richesse sociale.* Lausanne, 1874.
246. A. J. Watson and J. E. Lovelock. Biological homeostasis of the global environment: the parable of daisy world. *Tellus*, 35B:286 pp., 1983.
247. World Bank (WB), editor. *Monitoring Environmental Progress*, The World Bank, Washington, 1995.
248. WELT NEWS. Malaysia, 1996. Special supplement to the newspaper Frankfurter Allgemeine Zeitung, 23.12.1996, p.2, p.14.
249. R. Weterings and J. B. Opschoor. *The Ecocapacity as a Challenge to Technological Development.* Advisory Council for Research on Nature and Environment, Rijswijk, 1992.
250. P. Williamson and P. S. Liss. Understanding the earth system. In R. E. Munn, J. W. M. La Riviére, and N. van Lookeren Campagne, editors, *Policy Making in an Era of Global Environmental Change.* Kluwer, Dordrecht, 1996.
251. J. Wisdom. Meteorites may follow a chaotic route to Earth. *Nature*, 315(6022):731 pp., 1985.
252. J. Wisdom, S. J. Peale, and F. Mignard. The chaotic rotation of Hyperion. *Icarus*, 58(2):137 pp., 1984.
253. J. Wittig. Experimentelles zur Rayleigh-Bénard-Konvektion. Skript zum Ferienkurs der KFA Jülich, 28.2-12.3.1983, "Nichtlineare Dynamik in kondensierter Materie".
254. World Climate Research Programme (WCRP). *World Climate Research Programme*, 1996. http://www.wmo.ch/web/wcrp/wcrp-home.html.
255. World Commission on Environment and Development (WCED). *Our Common Future (The Brundtland Commission)*, Oxford University, Oxford, 1989.
256. World Resources Institute (WRI). World Resources, Annual Reports 1986-1997.
257. World Resources Institute (WRI). *World Resources 1992-93*, Oxford, 1992. Oxford University Press.
258. Worldwatch Institute (WI). *State of the world: Worldwatch Institute Reports on Progress Towards a Sustainable Society.* Annual Reports 1984-1997.
259. Worldwatch Institute (WI). *State of the world 1994. A Worldwatch Institute Report on Progress Towards a Sustainable Society*, Norton, New York, 1994.

260. Z. Xia. Arnold diffusion in the elliptic restricted three body problem. *Journal of Dynamics and Differential Equations*, 5:219 pp., 1993.
261. X. Xiao, D. W. Kicklighter, J. M. Melillo, A. D. McGuire, P. H. Stone, and A. P. Sokolov. Linking a global terrestrial biogeochemical model and a 2-dimensional climate model: implications for the global carbon budget. *Tellus*, 49B(1):18 pp., 1997.
262. L. A. Zadeh. Fuzzy sets. *Information and Control*, 8(3):338 pp., 1965.
263. H.-J. Zimmermann. *Fuzzy Set Theory and its Applications*. Kluwer, Dordrecht, 1991.
264. X. Zolotas. *Economic Growth and Declining Social Welfare*. New York University, New York, 1981.