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Prediction of Critical Phenomena in Economy and Politics

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ON PREDICTABILITY OF CRITICAL PHENOMENA

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INTRODUCTION

Nature and Society, separately or jointly, create many non-linear systems, which selforganise themselves from time to time into abrupt overall changes, called phase transitions or critical phenomena; in applications they are often referred to as crises, catastrophes, or disasters.

I will present non-mathematical, qualitative, discussion of the new possibilities to understand and predict critical phenomena in non-linear systems, which are yet least understood: hierarchical ones, with intermediate number of degrees of freedom (neither a non-linear pendulum, nor a statistical physics case). These possibilities are rooted in the choice of scaling and in mathematical modelling of transition to a critical phenomenon. I will demonstrate how, with luck, this approach may break the current stalemate in containing some well recognised threats to mankind's survival.

Let me first remind the basic concepts. Natural science of the past two centuries regarded the Universe, as a completely predictable machine. As Pierre Simon de Laplace put it, "*if we new exactly the laws of nature and the situation of the universe at the initial moment, we could predict exactly the situation of the same universe at a succeeding moment*" (1776). However, at the turn of this century Jules Henry Poincare discovered, that "*... this is not always so. It may happen, that small differences in the initial conditions will produce very great ones in the final phenomena ... Prediction becomes impossible*" (1903).

The simple example of such an instability is a billiard game

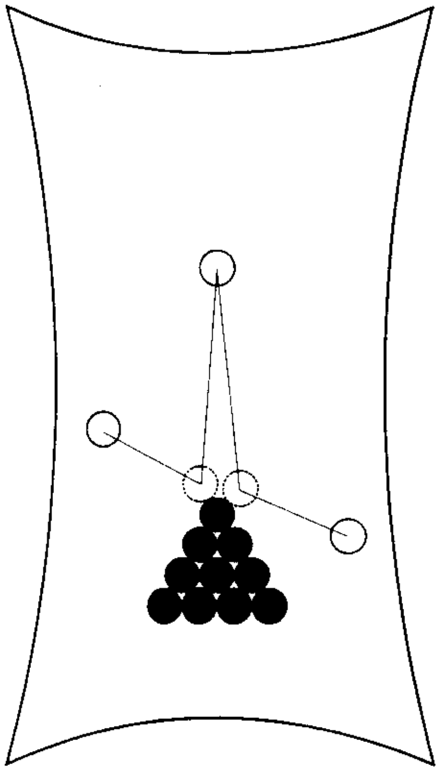

Fig. 1. Development of deterministic chaos: the impact of a perturbation does not attenuate, but exponentially grows in time.

(fig. 1). Newton's laws do determine the trajectory of each ball. However a slightest deviation in the direction of initial push will change the whole subsequent history. With concave boards the same instability will take place for a single ball, reduced to a material point ("Sinai billiard").

Deterministic chaos was regarded as an abstract concept until 1963, when Edward Lorenz has found it in a quite common, unexotic, natural process — thermal convection in the atmosphere. This triggered its recognition in one system after another — ocean, Galaxy, burning fuel, brain, stock market, the Earth's core, seismicity, with usuall advantages and drawbacks of a bandwagon.

Quoting Shakespeare, "Though this be madness, there is method

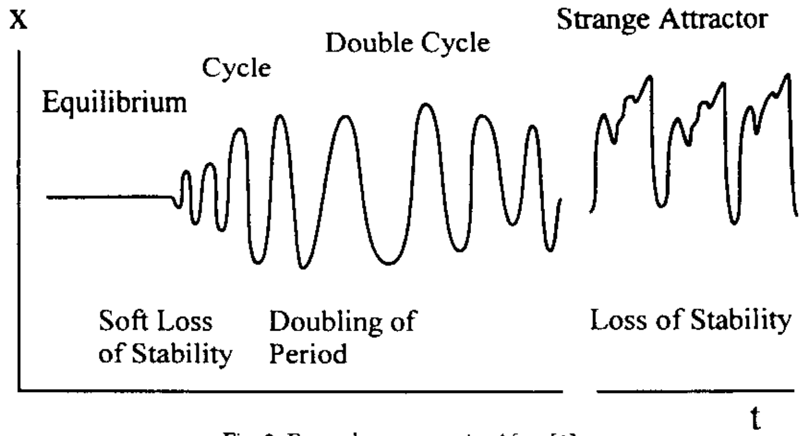

Fig. 2. Feugenbaum scenario. After [1].

in't". Chaotic systems can be made *partly* predictable in two ways. First, they transform the incoming energy or information in such a fashion, that specific spacio-temporal structures, scenarios of behaviour, emerge; examples are shown in figs. 2, 3. Recognising the beginning of a scenario, one may foresee the future behaviour, up to a limit; among examples are proverbial straws in the wind. Many such scenarios happen to be common for exceedingly diverse systems.

Second, chaotic systems may become predictable in a not too detailed scale, that is after the averaging; it may change the underlying equations, so that premonitory phenomena will emerge. This approach is used in the examples below.

And the 100% certain way *not* to predict a chaotic process is the opposite approach: to try to reconstruct it from too tiny details.

Now I am coming to specific examples. Please, keep in mind, that they illustrate more general principles. You will see no dynamic elegance of the previously discussed strudies: ours is the challenging situation, when no fundamental equations are yet known; Kepler was at a similar stage, preparing the way to Newton.

Earthquake prediction

Earthquakes generating part of the Earth is composed of about 10^{25} grains of rocks, which are consecutively merged into the blocks

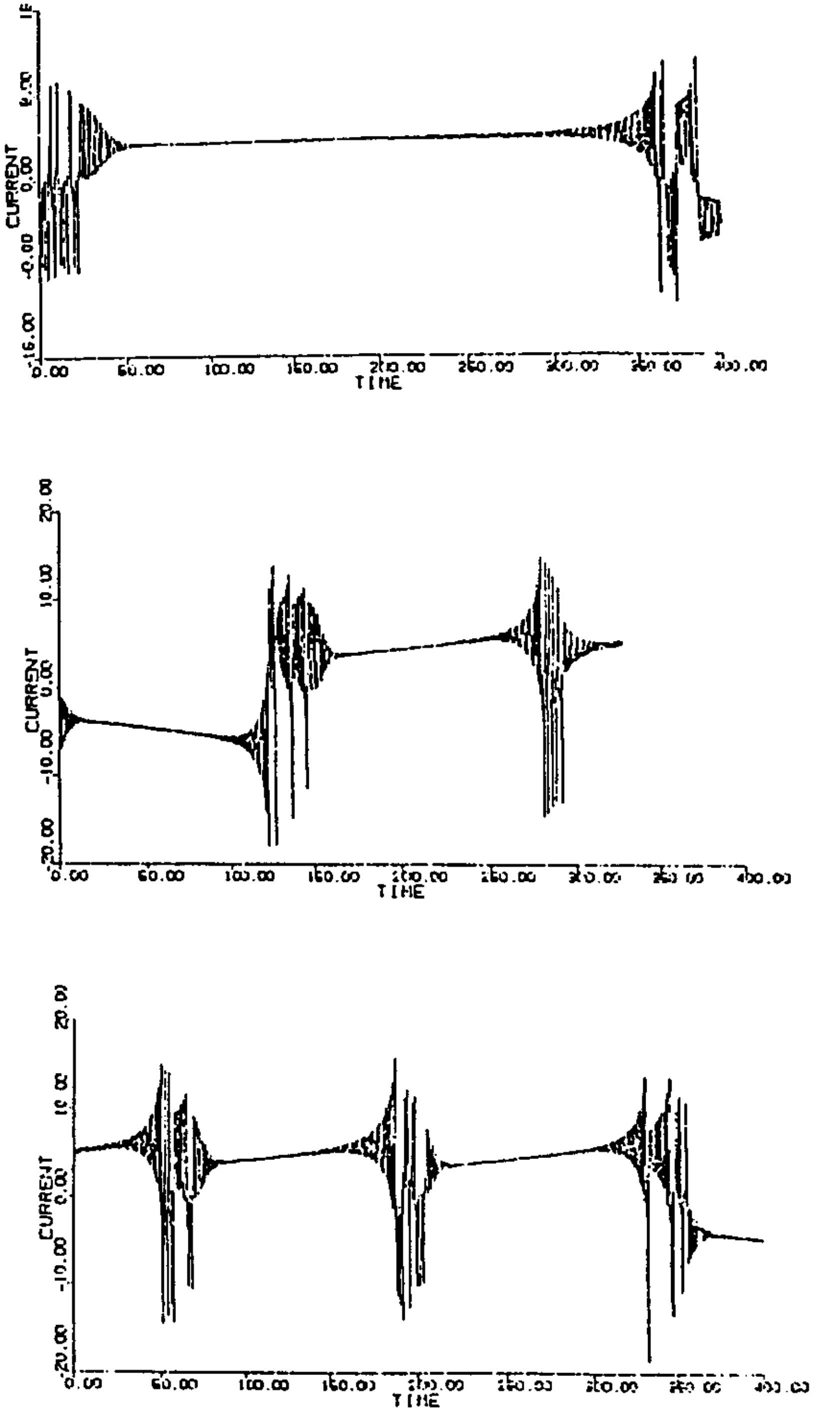

Fig. 3. Intermittence. After [1].

of higher and higher rank, until after 15 to 20 stages few continental-size tectonic plates are formed. These blocks, from grains to plates, interact along and across the hierarchy and move relatively each other under control of exceedingly diverse and unstable mechanisms. Large part of the movements is realised through formation and subsequent healing of *failures*, i.e. surfaces, where displacements are discontinuous; those of smallest size are called defects, slips, or fractures, larger ones — the earthquake sources.

About a million of earthquakes (with magnitude 2 or more) are registered each year; about 1000 of them are strong enough to be felt, about a 100 cause a considerable damage, and once in a decade or two a super catastrophic one occurs. I shall describe here how a strong earthquake can be predicted by analysis of earthquake flow in a lower magnitude range. Few more explanations first.

Earthquakes. Fig 4 shows the crude image of the non-linear system, which generates the earthquakes. The circles are the epicenters of major earthquakes, with magnitude 6 or more, that is the energy release above 10^{21} ergs. The chains of epicenters outline the fault zones — boundary layers, separating tectonic plates; they have a similar hierarchical structure. Altogether this system may be compared with a fractured ice shield, driven by oceanic currents. Tectonic plates are driven mainly by convection currents in the underlying Earth's mantle. Under the impact of convection the blocks of each rank, from tectonic plates to the grains of rocks, move relatively each other against the forces of friction and cohesion. In seismically active regions large part of this motion is realised in a stick -slip fashion:

slow deformations and stress accumulation→
failure and fast stress release→healing→
slow deformations and stress accumulation→ ...

Chaos. The friction and cohesion between the blocks and therefore the earthquake occurrence are controlled by a multitude of mechanisms: non-linear filtration of fluids, reducing friction by lubrication; stress corrosion, caused by interaction of rocks with chemically active fluids; phase transformation of minerals, causing abrupt change of density; plastic flow, etc.

Each mechanism may abruptly — in seconds to days — change the effective strength of the blocks system by factor up to 10^5, if not more; none can be singled out as a major one, so that the others may

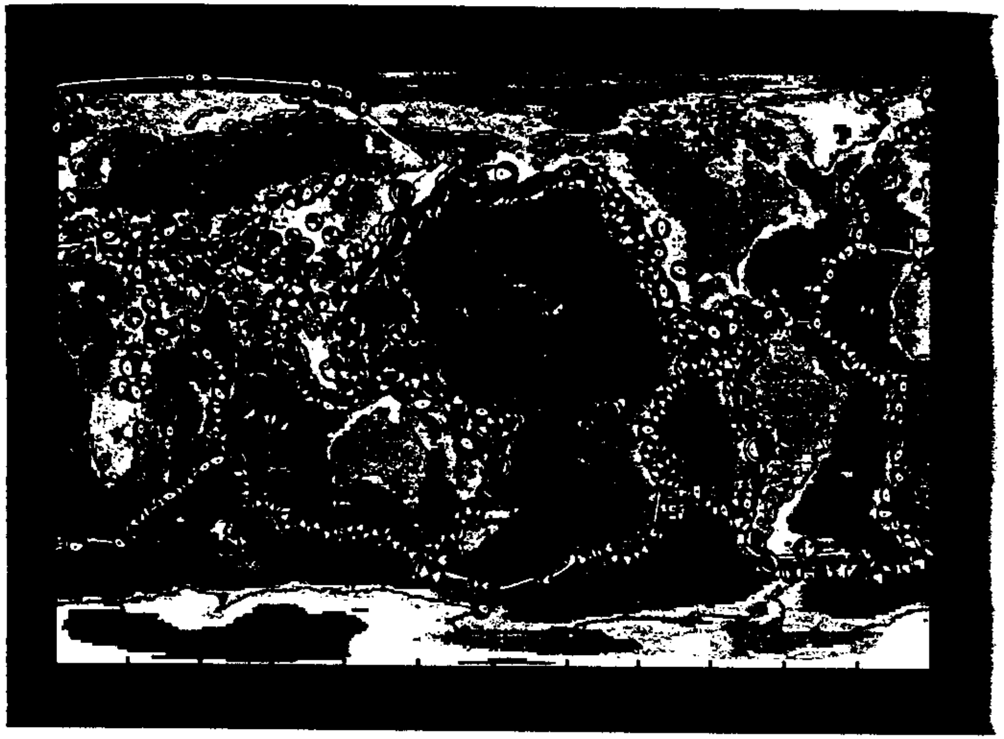

Fig. 4. Tectonic plates, separated by seismic belts. Courtesy of A. Dziewonsky, U. Salganik.

be neglected. Even the primary element, a grain of rocks, may act simultaneously as a material point, a visco-elastic element, an aggregate of crystals, a source or absorber of volume, fluids, energy, with its body and surface involved in quite different processes. In the time scale, relevant to earthquake prediction, years or less, these mechanisms turn this mosaics of the blocks into a non-linear system. This is what brought "pure" mathematicians and theoretical physicists into earthquake research (see reference in Appendix).

Prediction. To analyse or just to assemble a system of equations for these mechanisms, in the Laplacean spirit, would be, as we learned from Poincare, *in principle* futile, not speaking on technical difficulties which would be much larger, than in statistical physics; moreover, for many mechanisms the adequate equations are not found yet. So, we

have to explore the integral effect of these mechanisms, (i.e. the behaviour of the system as a whole), starting with a coarse scaling, and step by step proceeding to details, while possible. G. Puppi and A. Speranza [13] give precise and romantic description of these alternatives: "*The reactions and attitudes in respect to such complexity are linked between two extremes: on the one end is he, who identifies as the sole possible solution to the problem a meticulous treatment of every process, operating on a ... system; on the other end is he, who considers as the only hope that of 'guessing' the right equations*".

The second approach (not reaching the equations yet) is illustrated in fig. 5. The territory of California is scanned by 8 overlapping circles (fig. 5A). Within each circle a sequence of earthquakes is analysed. It is coarsely described by seven functionals, defined in a sliding time-window. N is the number of earthquakes, L its deviation from a long-term trend, Z - concentration of sources in space, B - clustering of eartquakes in space-time; indexes 1 and 2 indicate two different magnitude ranges. Dots indicate "large" values, exceeding certain percentile. An alarm is declared, when sufficient number of the functionals became "large" within a narrow time-interval. Black polygon shows the reduced area of alarm, determined in second approximation on the basis of additional data. (This description is oversimplified, of course; actually the analysis is based on pattern recognition of infrequent events, developed by Gelfand school. It is among few methods of artificial intelligence, which outperform the humans in the cases, when complexity of a process considered is too high for a statistical analysis).

Several prediction algorithms of such kind were developed and are being tested now by advance prediction in about 20 regions world-wide, Italy included. They are based on premonitory phenomena, which are briefly summarised below (fig. 7). The accuracy of these algorithms is limited, so that they would allow to prevent only a part of the damage from earthquakes. On the other hand, only a small fraction of the relevant models and data has been made use of so far in non-linear dynamics approach. It seems realistic to increase fivefold the accuracy of prediction by further development of models and incorporation into analysis the faults' geometry, satellite geodesy data, and fluids migration. These possibilities are being explored now.

Universality (a conjecture). According to B. Spinosa "*love is not the passion, but understanding*". Similarly, what prediction is about is

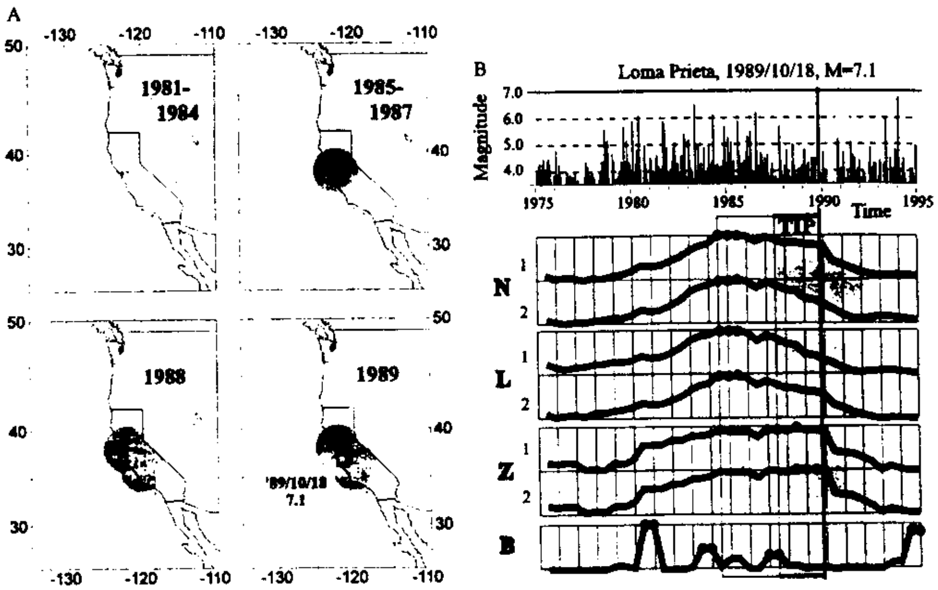

Fig. 5. Intermediate-term prediction of Loma Prieta earthquake in California, 1989. A. Areas of alarms. B. Diagnosis of alarm. Explanations are given in the text. After [7].

understanding of the process considered, as well, as the damage reduction. So, the next problem is a physical explanation: why these precursors, and not some others? And here we have a lucky break: premonitory phenomena, depicted by the above algorithms, are reproduced on the models of rather general type, e.g. cellular automata. Moreover, some precursors were found on such models first, and then confirmed on observations.

Two out of several such models are shown in fig. 6. In the hierarchical model on the top the time is divided into finite intervals; at each interval an element of the lowest level becomes "a failure" with a probability p and then heals after some time. When a group has two failures simultaneously, the corresponding element of higher level becomes a failure and then heals etc.

Model at the bottom of fig. 6 is similar to the "life game" known in biology; it consists of elastic discs, pressed together in a box with steadily moving borders. The discs move relatively each other in a stick-slip fashion, selforganising themselves into transient chains.

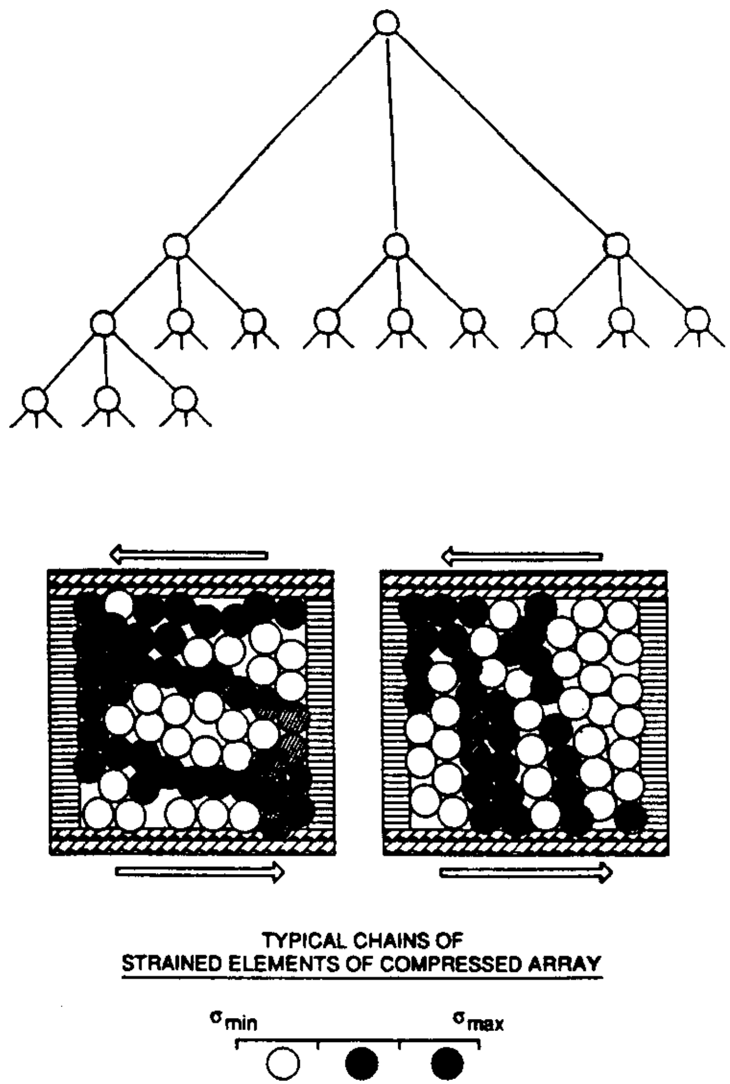

Fig. 6. Two of the lattice models, reproducing premonitory seismicity patterns. After [7].

These models, though used to reproduce dynamics of seismicity, are not particularly earth-specific: they may be related to economy, electorate, a megacity ... *It seems, that we encountered in seismicity the symptoms of near-critical state, which are not specific to any single process, but reflect some general laws of selforganisation in the lattices of interacting elements.*

A qualitative summary of these symptoms is given in fig. 7. They remain hypothetical so far and are being explored in several quite different processes.

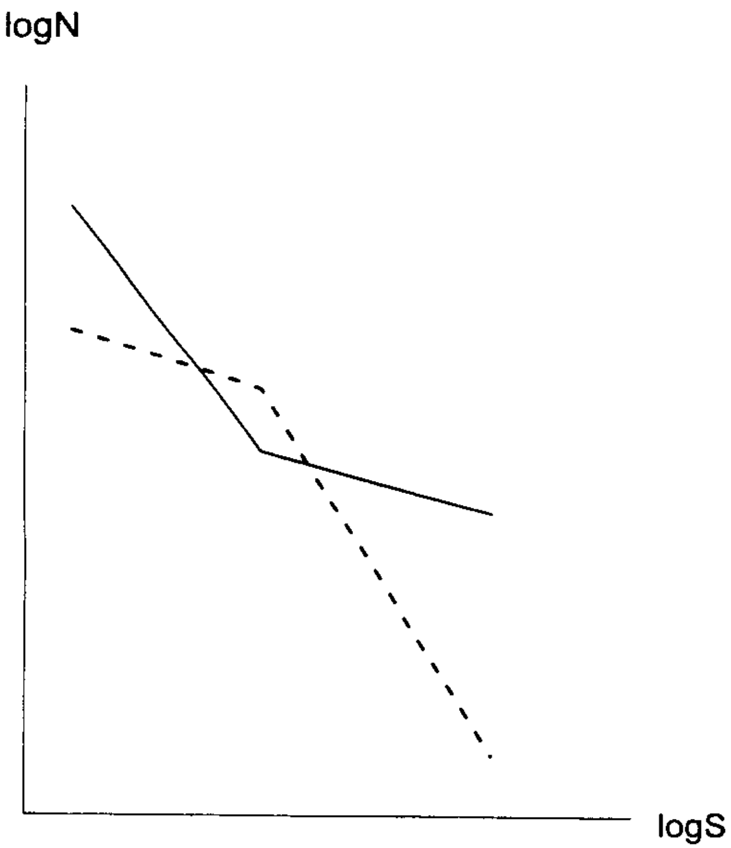

Fig. 7A. Scheme of premonitory transformation of *size S vs. occurrence rate N relation* in the static of a system. Dashed line corresponds to the time, which is far from a critical phenomenon, solid line - close to it.

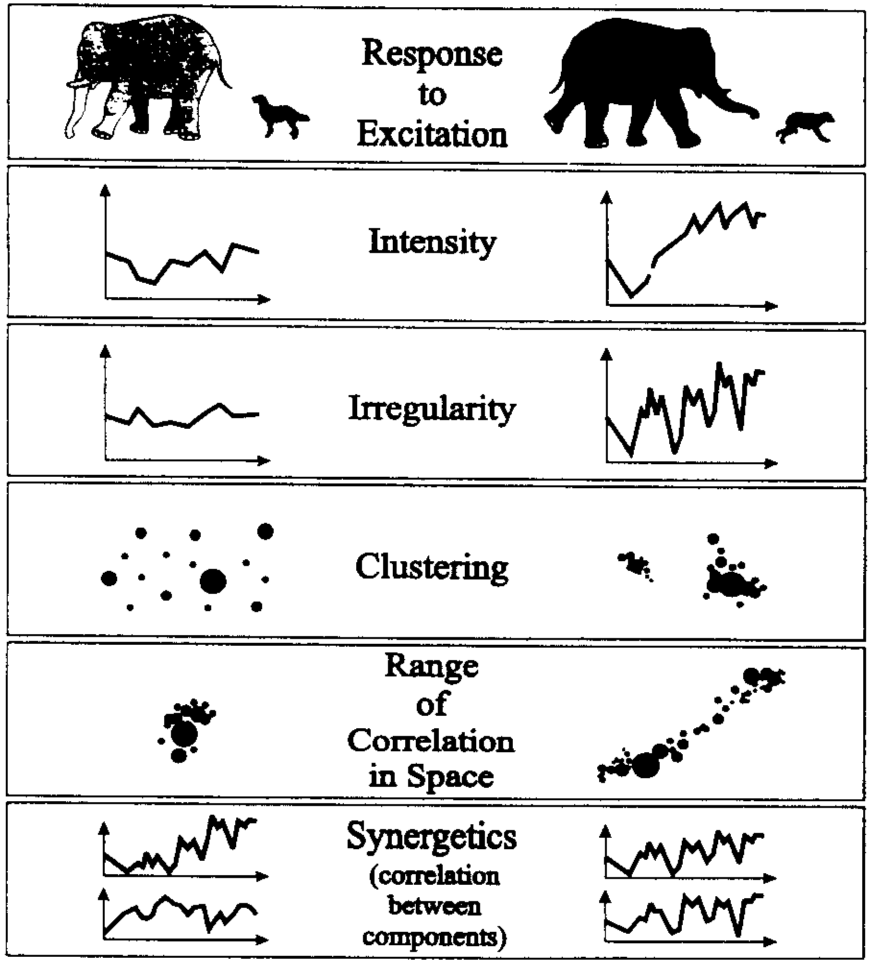

Fig. 7B. Hypothetically universal sysmptoms of near-critical state. These symptoms are extracted from a noise ("static") of a system. Note, that the systems considered have a limited selfsimilarity, so that the static itself may consist of critical phenomena of smaller scale.

The power of scaling is beyond doubt, however. This may be illustrated by the fact, that strong earthquakes occur unpredicted in the middle of the dense networks, composed of thousands of sensors, installed to find earthquake precursors. In all successful predictions these networks were never used; only the data of 10^2 times more rarefied routine networks were analysed. Why a coarse scaling often works better in many fields, may be illustrated by fig. 8.

I'll describe now few more examples.

DESTRUCTIVE MOVEMENTS IN LOW-SEISMICITY REGIONS

Several years ago an important building near Moscow collapsed without any of the usual reasons, like construction failure, landslide, ground failure etc. This happened in the middle of the European

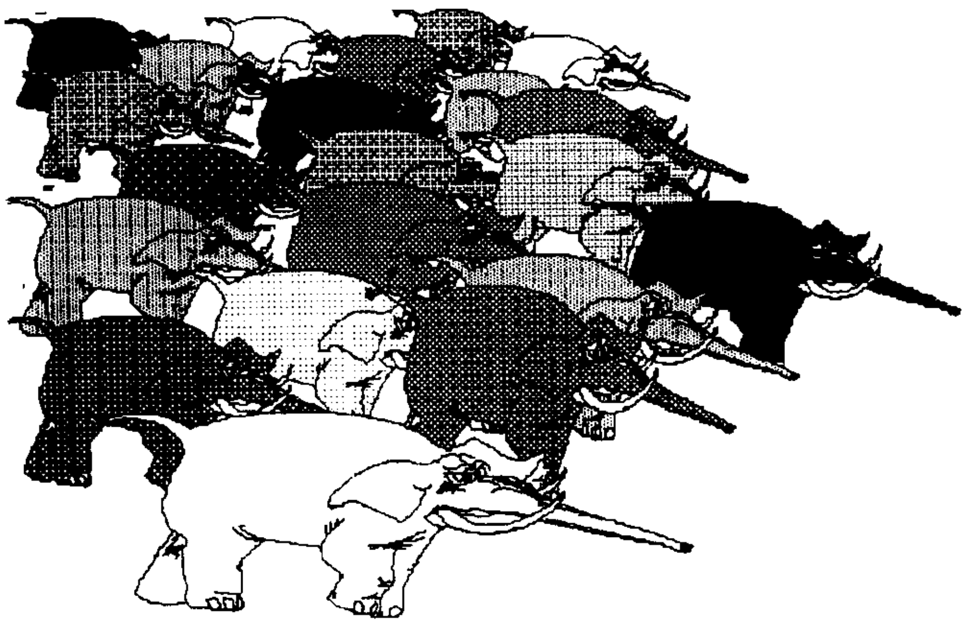

Fig. 8. A case, when prediction requires a coarse scaling: the charge of the herd is determined by collective behaviour, which can hardly be deducted from details of the individuals.

Platform — a geologically stable region with very low seismicity. A long — shot explanation was that the Earths' crust is divided here into unknown blocks, and that the faults between them harbour instead of the earthquakes the destructive slow movements, e.g. creep, which can't be registered by the existing observational system. Similarly to the earthquakes in active regions, such movements would be concentrated near intersections of faults, where the Earth's crust is particularly fractured due to geometric incompatibility of the movements of the blocks, simply saying, — due to collision of their corners.

Special analysis, with the same type of a coarse scaling, indeed revealed the faults, shown on fig. 9; only few of them were known before. It is known, that areas around fault's intersections are most unstable. The collapsed building *was* near a faults intersection. This could be a coincidence; however two years after this map was published, Russian Ministry of Civil Protection released a list of other unexplained industrial accidents, and 80% of them also happen to be near intersections, shown on the map. These faults are invisible in the detailed maps, of the 1:50,000 scale, traditionally used to evaluate the safety of construction sites. For this analysis 20 times less detailed maps, in 1:1 mln scale, were needed; however methodology of analysis is rather sophisticated. Part of it was developed for scene recognition from missiles.

Unaccounted unstable areas of this type became critically dangerous after an assortment of high-risk constructions appeared in the platforms. For example, about 15 nuclear power plants and quite a few toxic waste disposals are situated within few hundred km further west. Even more dangerous objects are scattered in other platforms worldwide.

It is realistic now to re-evaluate the safety of such objects, adapting the above methodology to global satellite — born observations and the modern data base for solid Earth.

SELF-DESTRUCTION OF MEGACITIES

Finally, I would like to bring your attention to a non-linear system, which just started to attract basic research: a megacity. Many of them, in the West and East, North and South, have developed powerful mechanisms of self-destruction. Their ground is destabilised

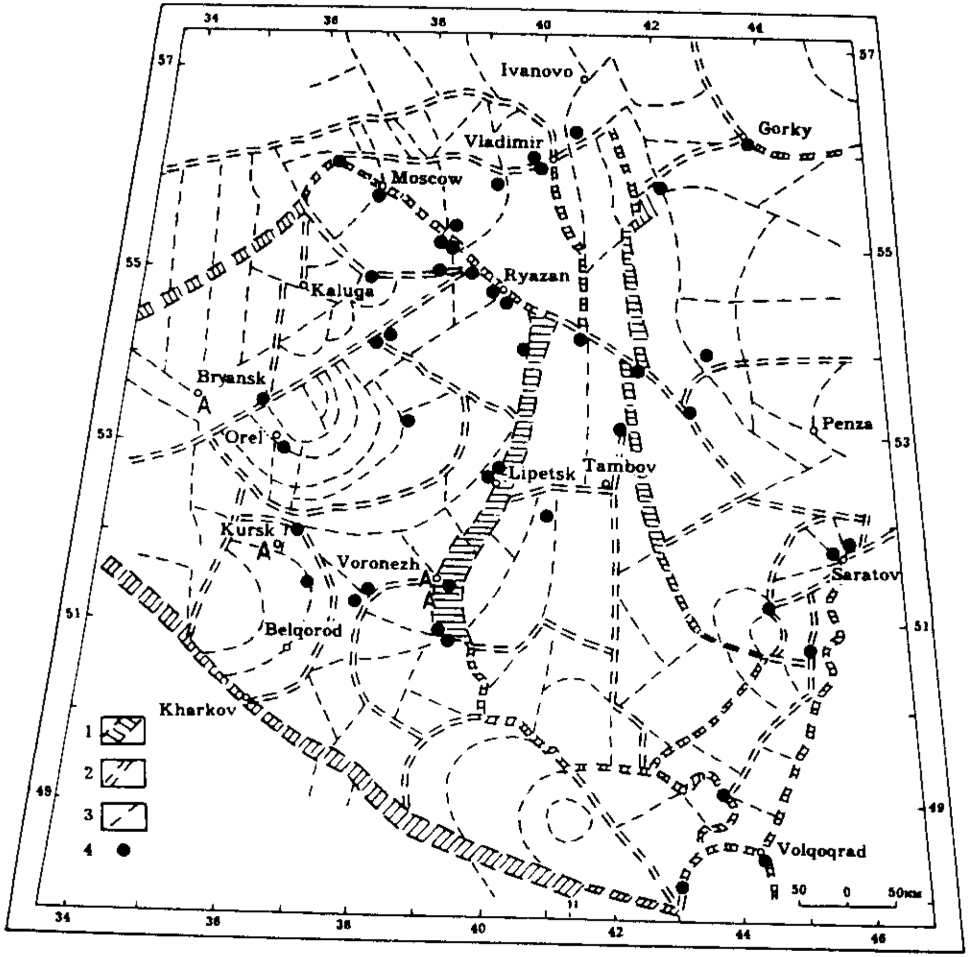

Fig. 9. Faults in the Central Russian Plain. 1, 2, 3 - faults of the first, second, and third rank respectively. 4 - industrial accidents of unknown origin. A - nuclear power plants. Areas around faults' intersections are fractured and unstable. Dots show the sites of industrial accidents of unknown origin (collapse of building, release of toxic waste, breakdown of lifelines, etc.). 80% of these accidents occurred within 25 km from the most unstable faults' intersections, with at least one fault of first of second rank. After [4].

by inhomogeneous loading, vibrations, extraction of water, injection of chemically active waste, violation of biological equilibrium etc. [12]. Cumulative effect of these factors turns the ground under the megacities into a new physical phenomenon, yet unnamed; it can't be understood, as a soil, or a rock massif.

Hardly any megacity, even a poore one, spends less than a billion dollars per year to cope with this instability; however it keeps growing, so that instead of isolated objects the geoengineering infrastructures became destabilised.

Social and economic infrastructures are in similar condition, so that four unstable systems, Earth, Life, Engineering and Society, are tied together in a megacity, to a widely spread concern (noticeably, it was the Mayor of Moscow, Ur. Yu. Luzhkov, who suggested, that Moscow became a chaotic system, which nobody understands, so that the science should help).

The integrated approach, such as described above, was hardly ever tried and obviously deserves attention here. International efforts in this directions are under discussion now.

PRACTICAL SIDE: BASIC RESEARCH FOR MANKIND'S SURVIVAL

Urgency. We all know about the dangers, which, in the words of J. Wiesener, "*are a threat to civilisation's survival, as great, as ever posed by Hitler, Stalin, or the atom bomb*". Some ofthese dangers are generated by non-linear systems of the type, which we have discussed today (hierarchical ones, with intermediate number of degrees of freedom): an earthquake — prone, or a creep — prone region, harbouring high risk objects; a megacity, on a way to self-destruction; probably also a society, generating violence, and economy, generating depressions ... These disasters keep escalating, though huge investments are made to contain them (about $\$10^{11}$ per year for geological disasters alone).

An example is the vulnerability of our world to the earthquakes. It is critically growing due to proliferation of high-risk objects, clustering of population, and destabilisation of large cities. Today a single earthquake may take up to a million lives; cause material damage up to a $\$10^{12}$, with chain reaction expanding to world-wide economic depression (if it occurs in *Tokyo*); trigger major ecological catastrophe (e.g. several Chernobil-type calamities at once); paralyse national defence (if it occurs in *Dead Sea rift*) ... Critically vulnerable became the low seismicity regions, e.g. European and Indian platforms, Eastern US etc. The other dangers, mentioned above, are at least of the same scale.

A hope. Prediction of these disasters — a crucial component of their reduction — is in obvious stalemate: they always loom at the horizon and always come as a tragic surprise. To a large extent this is due, I believe, to inadequate theoretical base of prediction research, in particular, to orientation at an unduly detailed scaling; it reflects a costly illusion, that one may understand a non-linear system by studying it piece by piece.

The approach, which we have discussed today, may break this stalemate, though this is not easy. Several international projects are aimed at such an approach. Its applications to social systems are described in [9].

Some inertia has to be overcome, however, to set up all the necessary R&D. Responsibility for dealing with disasters in question rests mainly on Governmental agencies, which are traditionally inclined, not unlike Soviet economy was, towards the *cost-plus* operations, with frontier research easily sacrificed to the applied one, if not to a bulldozer engagement of inadequate technologies; some, luckily few, behemoth industries follow suit. On the other hand part of the inertia comes from scientific community too: the cause demands initiative, comparable to that of Einstein and Szilard.

Notes

The results, reviewed here, are obtained, to a large extent jointly, in the following Institutions.

Russia: International Institute for Earthquake Prediction Theory and Mathematical Geophysics, Moscow.

Italy: International Centre for Theoretical Physics, Trieste, with associated researchers world wide; University of Trieste.

US: University of California (L-A and Santa Barbara); Cornell and American Universities; Carnegie Institution of Washington; US Geological Survey; Southern California Earthquake Centre.

France: Institute of the Physics of the Earth, Paris; Observatory of Nice (astrophysical unit).

South America: Continental Seismological Centre (CERESIS).

Israel: Geological Survey.

Theoretical problems involved (which were not discussed today) belong to the following fields: lattice models of non-linear systems; turbulent cascades; non-linear mechanics; optimal control.

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