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Advanced School on Understanding and Prediction of Earthquakes and other Extreme Events in Complex Systems

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Extreme Events in Nature and Society: Predictive Understanding: Disaster Preparedness; the Wealth of yet Untapped Possibilities

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The problem

- **Extreme events,** also known as *critical transitions, disasters, catastrophes, and crises*, are rare point events with a low probability of occurring but a high impact on their environment. They persistently reoccur in *chaotic/complex systems* formed separately or jointly by nature and society.

- **The goal** is to predict *when and where* an extreme event will occur. Prediction makes sense only if its *accuracy* is estimated**.**

- **The problem is urgent.** Our vulnerability to extreme events is rapidly escalating due to proliferation of *high-risk objects* and *growing volatility* of the global village. Predicting extreme events is commonly recognized as:
  - The Holy Grail of modern basic science;
  - The key to survival and sustainability of our civilization.

(Decisions of G8 – 2006; G8 – UNESCO Forum, 2007. http://g8forum.ictp.it/)

Extreme events considered are generated by hierarchical dissipative complex systems

An example of such system: the lithosphere of the Earth, with strong earthquakes as the extreme events.

Structure: *hierarchy of volumes (blocks)* which move relative to each other. The largest blocks are about 10 tectonic plates; each is consecutively divided into smaller and smaller blocks, down to about 10^{25} grains of rocks.

Dynamics: *a stockpile of instability*, caused by a multitude of interacting mechanisms acting on a wide range of scales, from astronomical to molecular. None is always dominant: even a grain of rock acts as: a visco-elastic element; an aggregate of crystals; a source/absorber of fluid, volume, heat, and so on.

An earthquake may be a critical phenomenon in a certain part of fault network, <u>and</u> an element of the background seismicity in a larger volume

Another example: The American society, with an electoral change of the governing party as an extreme event

The traditional concept of American elections focuses on the division of voters into interest and attitudinal groups. By this concept the goal of the contestants is to attract maximum number of voting blocks with minimal antagonism from other blocks. Electoral choice depends strongly on the factors irrelevant to the essence of the electoral dilemma (e.g. on the campaign tactics). The work on Presidential elections shows the drawbacks of this concept and suggests the following new ways of understanding American politics and perhaps the politics of other societies as well:

- fundamental shifts in the composition of the electorate, the technology of campaigning, the prevailing economic and social conditions, and the key issues of campaigns *do not necessarily change* the pragmatic basis on which voters choose their leaders;
- it is governing not campaigning that counts in the outcomes of Presidential elections;
- different factors may decide the outcome of executive as compared to legislative elections;
- conventional campaigning will not improve the prospects for candidates faced with an unfavorable combination of fundamental historical factors; disadvantaged candidates have an incentive to adopt innovative campaigns that break the pattern of conventional politics;
- all candidates would benefit from using campaigns to build a foundation for governing in the future.

The need for a holistic approach

Holistic approach is from the *whole to details*, as opposed to the reductionism approach which is from the *details to the whole*.

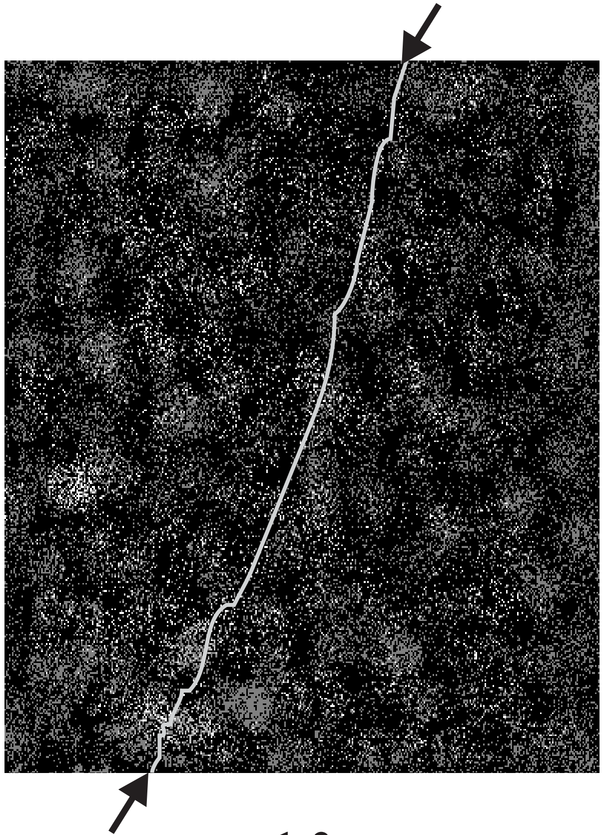
There is no fundamental "predictive" equation combining all the individual interacting mechanisms. We have to use a holistic approach, rather than deriving a prediction algorithm from first principles.

> **"*It became clear for me that it is unrealistic to have a hope for the creation of a pure theory [of the turbulent flows of fluids and gases] closed in itself. Due to the absence of such a theory we have to rely upon the hypotheses obtained by processing of the experimental data…* "**
>
> -- **A. Kolmogorov, 1943**

“It is not possible to understand chaotic system by breaking it apart”

However, a holistic approach, from the ***whole to details,*** opens up the possibility of overcoming complexity itself as well as the chronic imperfection of data.

20:1



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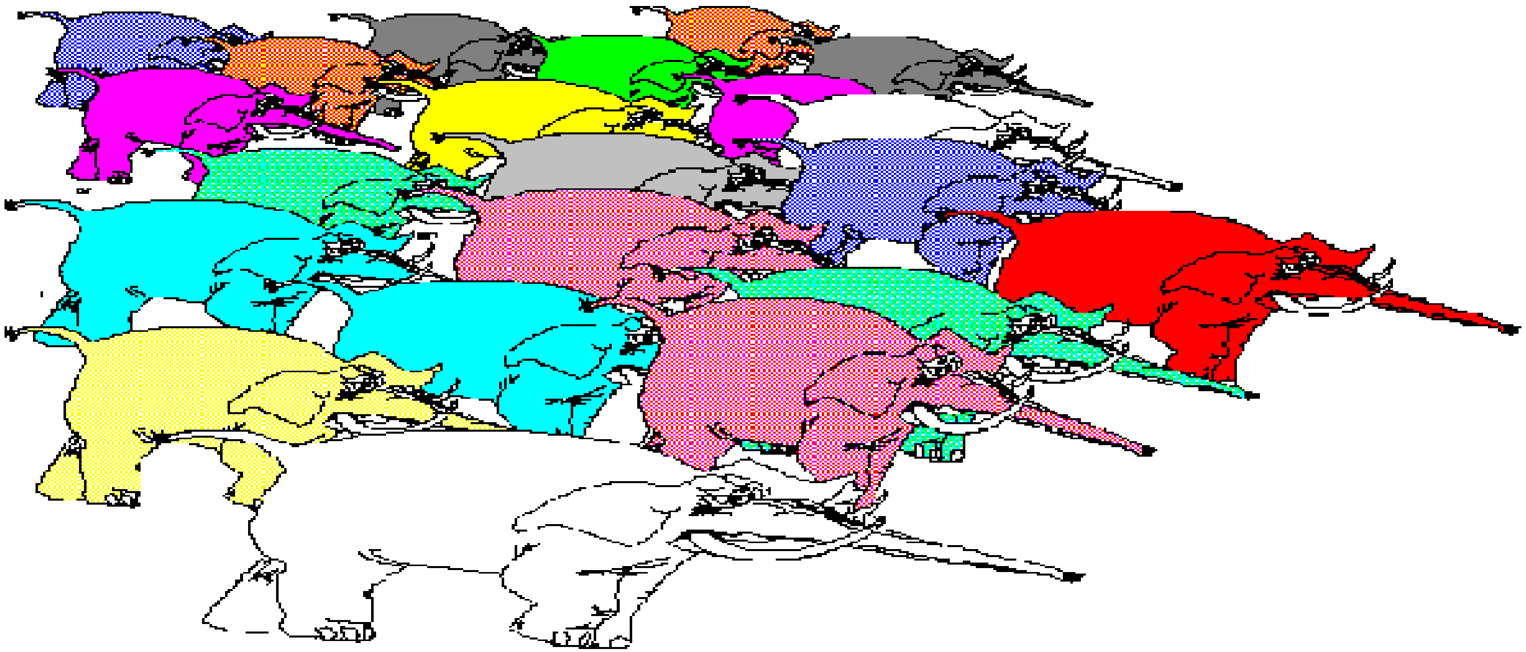
(Courtesy of Prof. Johnson, Purdue University, USA)

The need for a holistic approach, cont.



M. Gell-Mann: "If the parts of a complex system or the various aspects of a complex situation, all defined in advance, are studied carefully by experts on those parts or aspects, and the results of their work are pooled, an adequate description of the whole system or situation does not usually emerge. The reason, of course, is that these parts or aspects are typically entangled with one another. We have to supplement the partial studies with a **transdisciplinary crude look at the whole**"

After coarse-graining (smoothing), extreme events became predictable, albeit with limited precision, and premonitory patterns emerge

Premonitory patterns are deviations of the system's background activity from the long-term average. Premonitory patterns emerge much more frequently as an extreme event draws near.

Premonitory patterns might be *perpetrators* (contributing to the formation of the event) or *witnesses* (a proverbial witness is straws swirling in the wind preceding a hurricane).

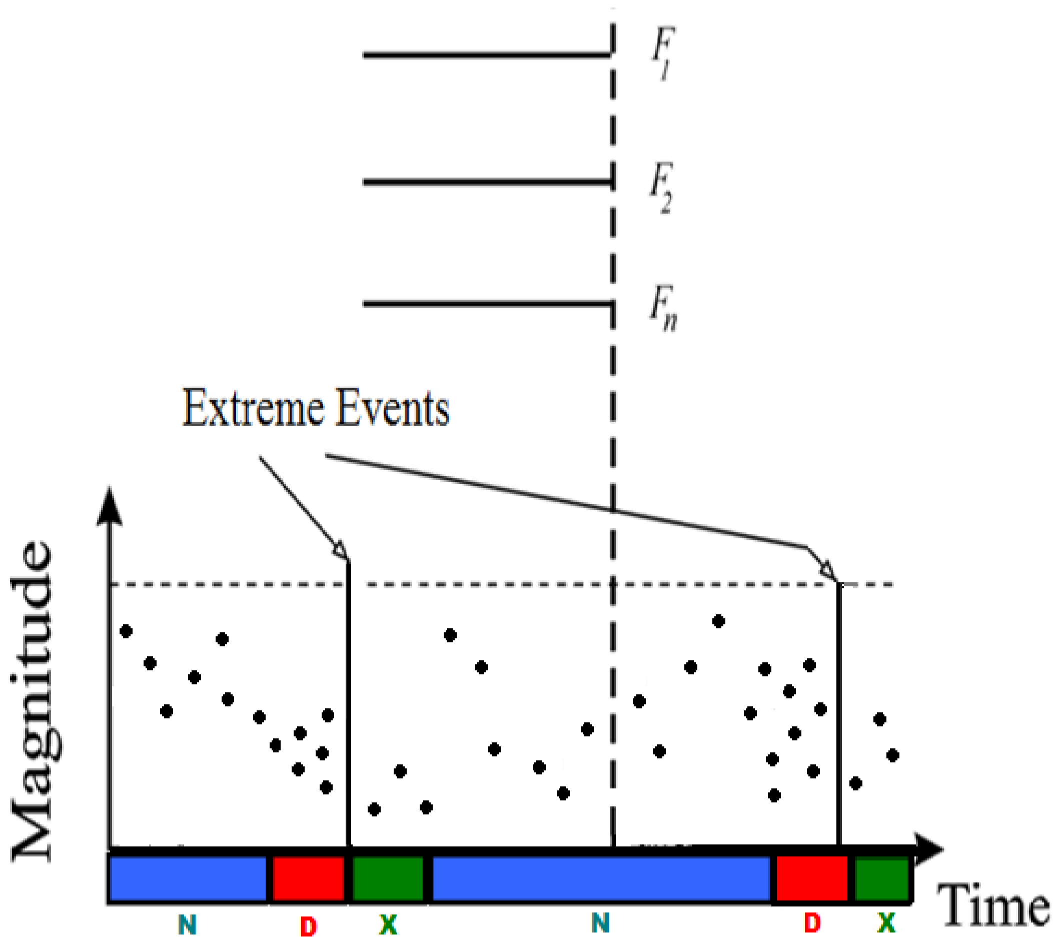
A premonitory pattern might predict not an extreme event *per se* but the destabilization of the system, which makes it *ripe* for an extreme event.

Methodology for prediction integrates numerical modeling, exploratory data analysis, theory and practical experience, even if it is intuitive.

Detection of premonitory patterns

Premonitory patterns are looked for in different processes that might signal the approach of an extreme event.

Each process is robustly described by the functions *Fk*(*t*), capturing a premonitory pattern.



KEY PROBLEM: choosing F_k

We compare $F_k(t)$ in the periods of three kinds:
D - preceding an extreme event; X - following it; N – other periods
Their difference indicates premonitory patterns.

Possible outcomes of prediction

Prediction is formulated as a discrete sequence of alarms.

Each alarm indicates time and space where the extreme event is predicted to occur.

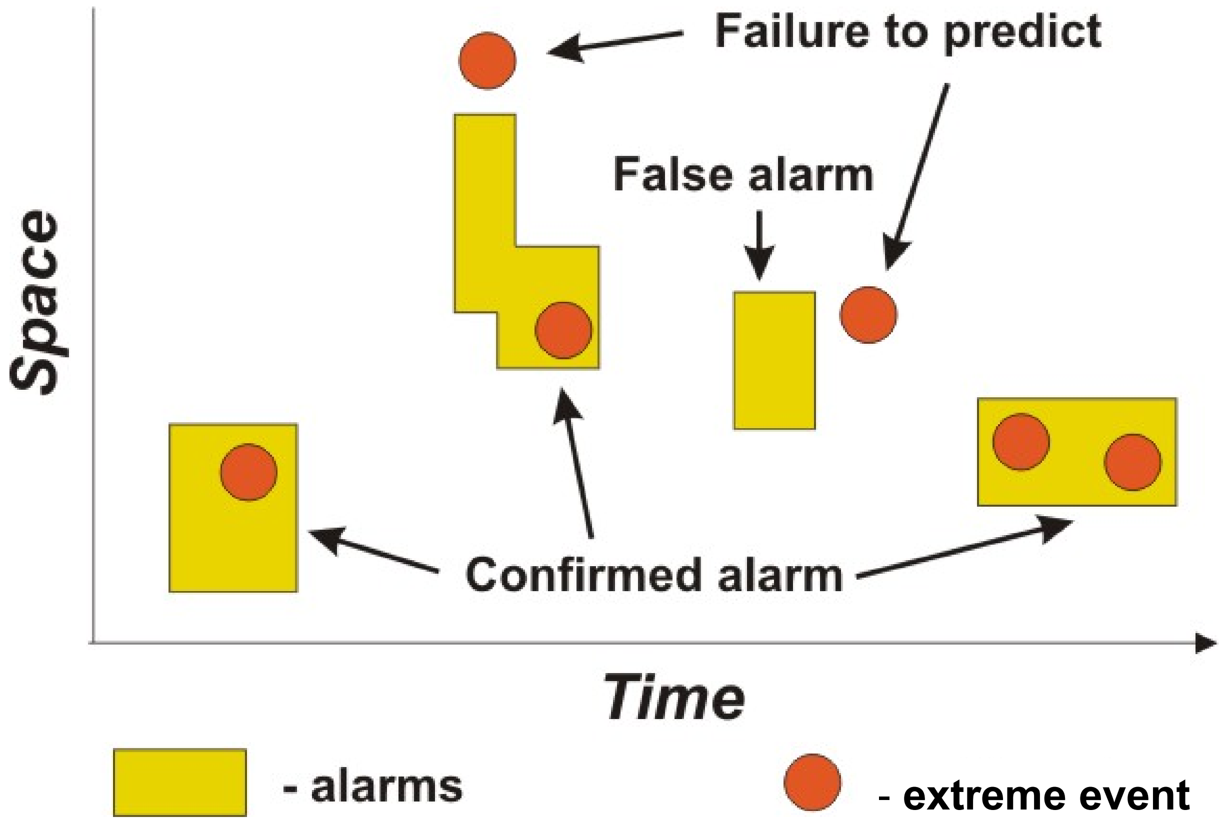
Quality of prediction is represented by:

--rate of false alarms;

--rate of failures to predict;

--total duration of alarms.

(Molchan, 2003, 2008)



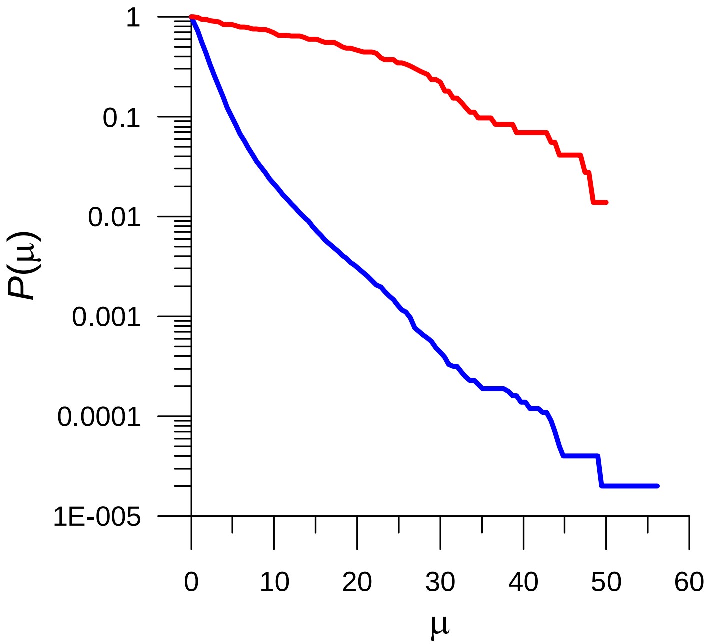
Example of universality: Premonitory transformation of scaling

1. Magnetic Storms and Earthquakes

Event is the change of the trend of a monthly indicator considered.
Size distribution P(m) is the probability that the size of an event is ≥ ***m*.**

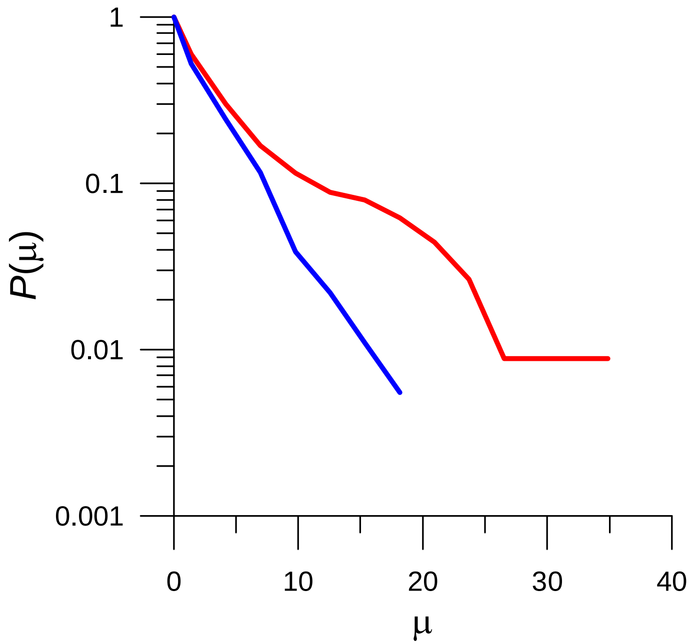
Prediction targets

Magnetic storms



Indicator – Disturbance Storm Time (DST) index

Strong (M ≥ 6.4) earthquakes in California



Indicator – the total source area (∑) of earthquakes occurred during a month

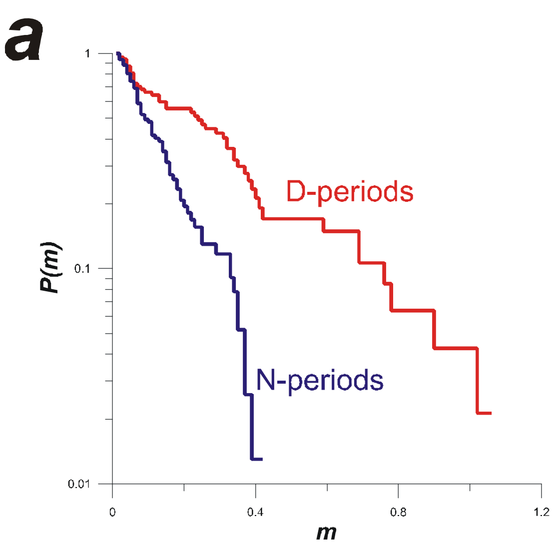
Example of universality: Premonitory transformation of scaling

2. Socio-Economic Crises

Prediction target is the starting points of a crisis.
Event is the change of the trend of a monthly indicator considered.
Size distribution P(m) is the probability that the size of an event is **≥ *m*.**

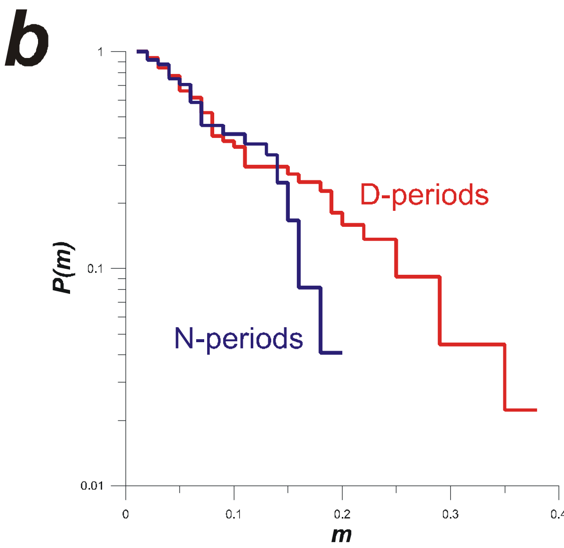
In the case of ***a*** (recessions, US, 1961-2002) and ***b*** (unemployment surges, US, 1961-2005) scaling of industrial production is shown. In the case of ***c*** (homicide surges in Los Angeles, 1975-1993) scaling of assaults with firearms is shown.

RECESSIONS, US, 1961-2002



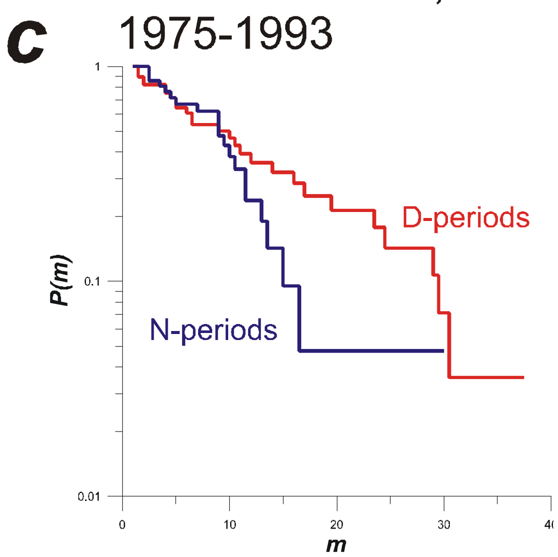
http://www.igpp.ucla.edu/prediction/ref/Pre-recession.pdf

UNEMPLOYMENT SURGES, US, 1961-2005



[http:// www.igpp.ucla.edu/prediction/ref/Unemployment.pdf](http://www.igpp.ucla.edu/prediction/ref/Unemployment.pdf)

HOMICIDE SURGES, LOS ANGELES, 1975-1993



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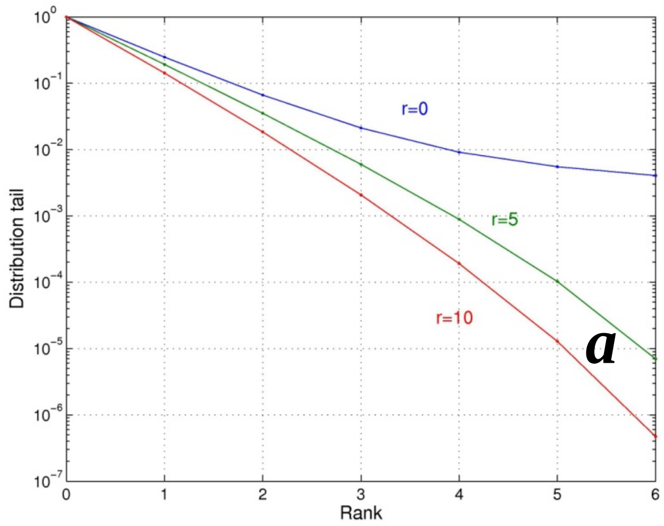
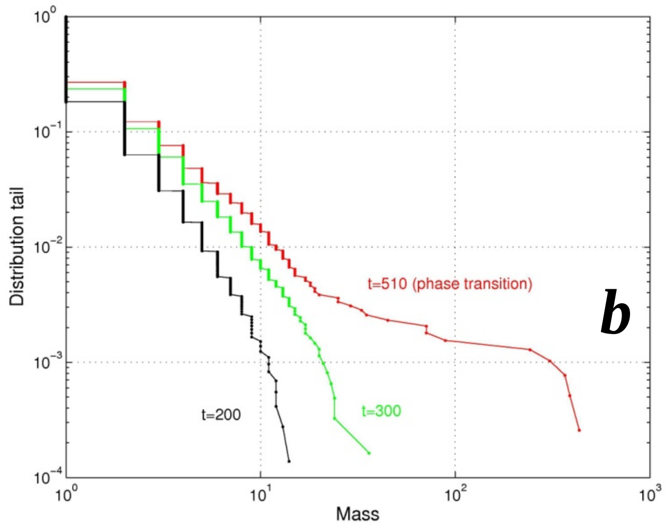
Example of universality: Premonitory transformation of scaling

3. Models





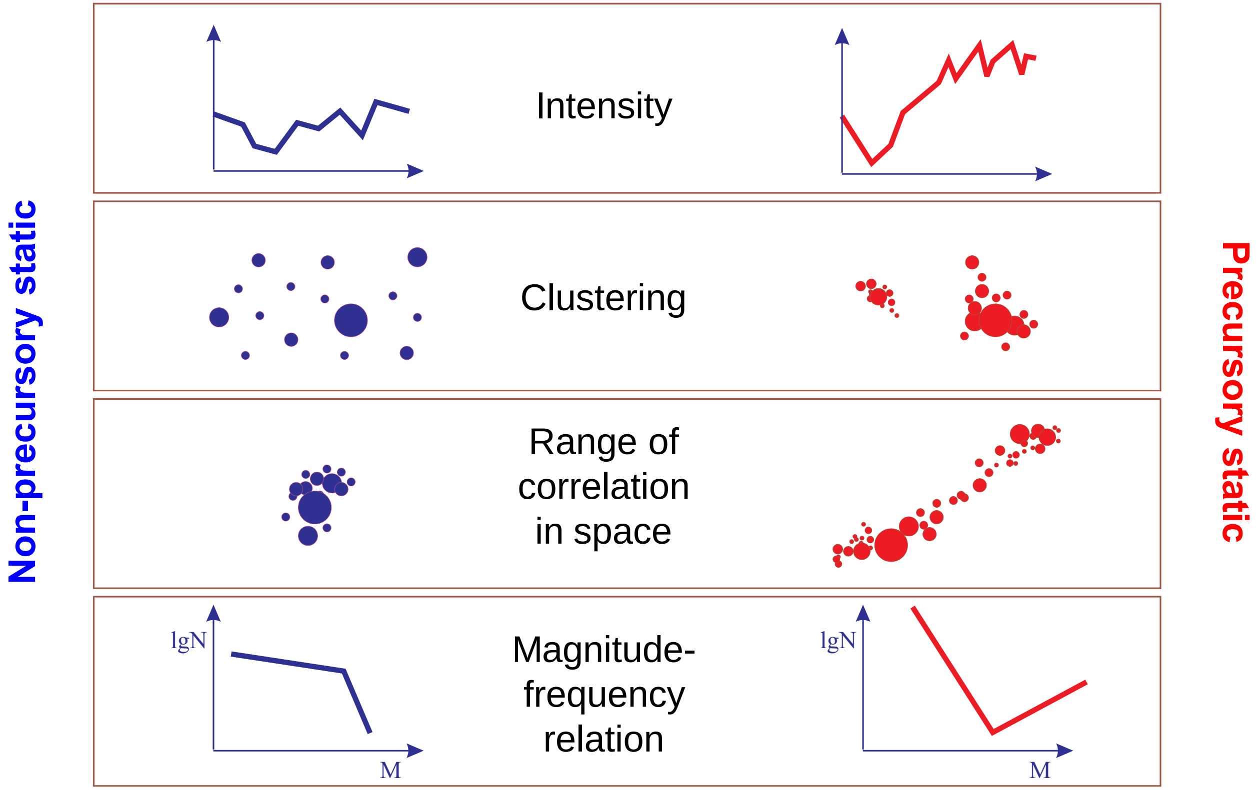
a) **Branching diffusion; control parameter *r* – distance from the origin**

Gabrielov et al. http://arxiv.org/abs/0708.1542arXiv:0708.1542v1

***b*) Cluster dynamics; control parameter *t* – time window**

Gabrielov, Sinai et al. http://wolfweb.unr.edu/homepage/zal/pubs/GKBSZ08.pdf

Other types of common premonitory patterns are established by modeling and data analysis



These phenomena are reminiscent of asymptotics of a non-linear system near the phase transition of second kind. However, we consider not the equilibrium, but the growing disequilibrium, culminated by a critical transition.

Predicting individual extreme events
1. Earthquakes

A family of prediction algorithms with characteristic duration of of alarms of years or months has been developed and put to test by prediction in advance in many regions worldwide. This will be described throughout the next two weeks.

Two examples of scoring:

•Algorithms M8 & MSc, since 1992

•13 out of 24 M8+ earthquakes were captured by M8 with alarms occupying altogether about 30% of the time-space considered.

•9 out of 24 M8+ earthquakes were captured by MSc with alarms occupying 17% of time-space.

•Algorithm SSE since 1989

•17 predictions were made in advance.

•11 were correct. Among 6 errors were:

1 failures-to-predict a second strong earthquake

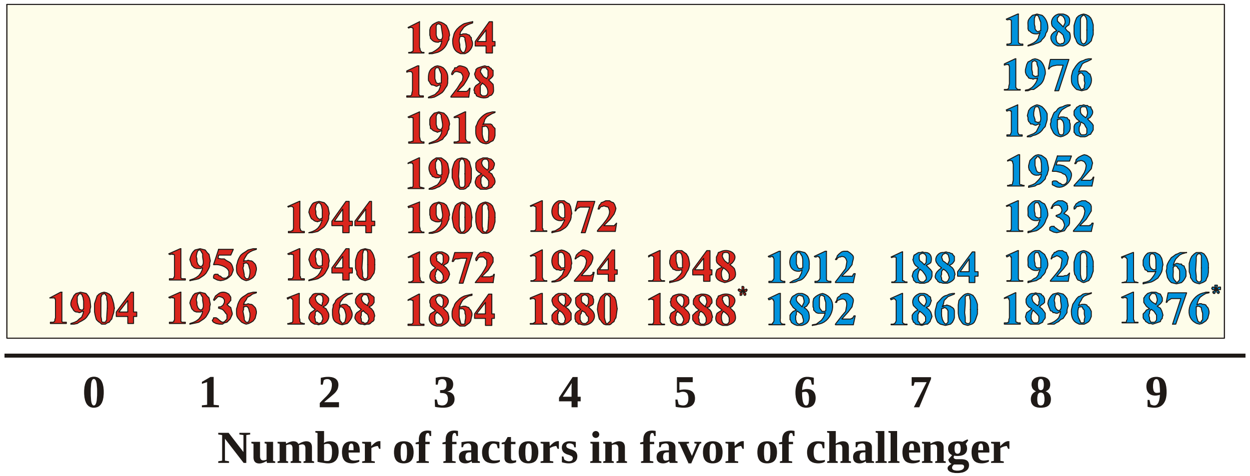
5 false alarms (two of them were near misses)

Prediction of individual extreme events
2. US Presidential elections

Prediction is based on thirteen socio-economic and political factors.
Victory of challenging party is predicted when 6 or more factors are in its favor.
Otherwise victory of incumbent party is predicted.

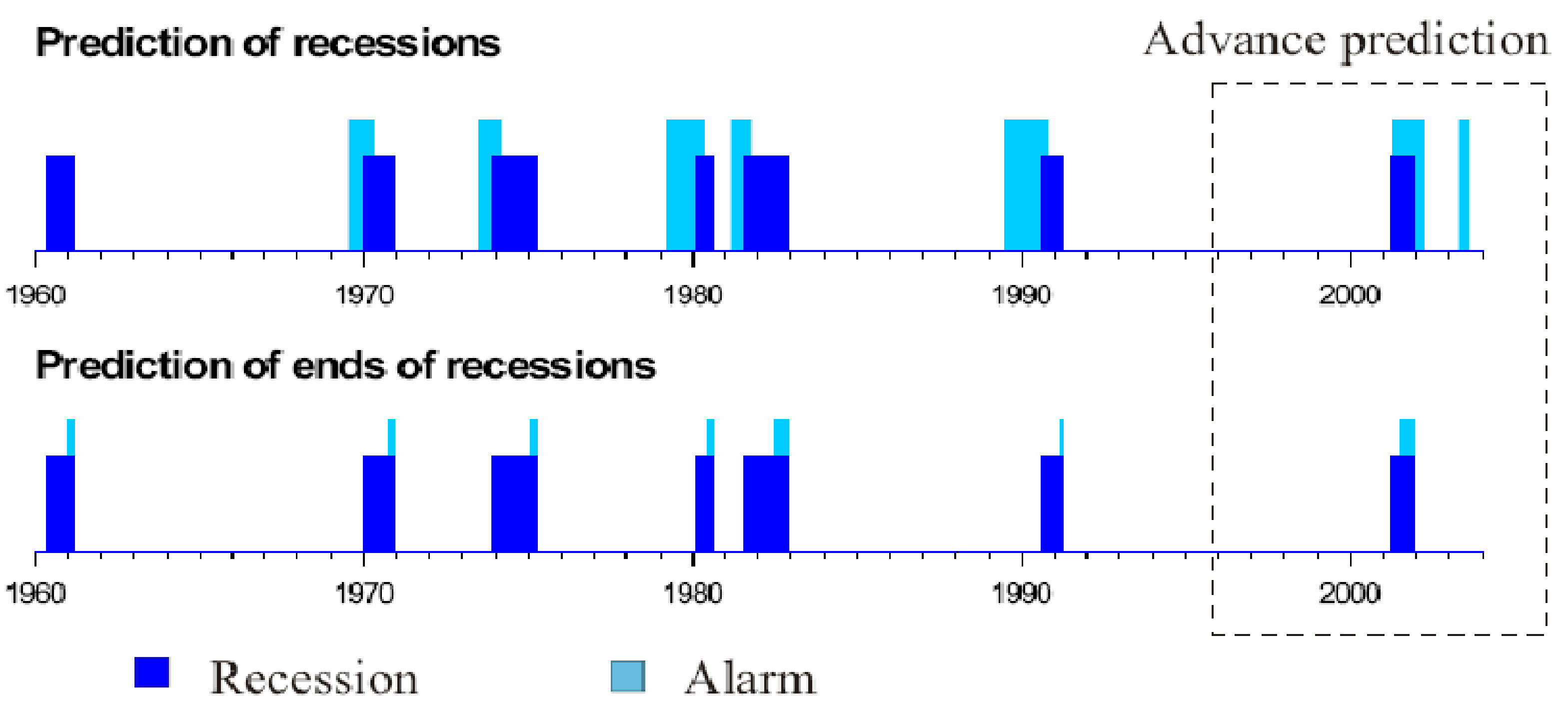
Predictions published months in advance: all 7 were correct

Retrospective Analysis: 1860 - 1980

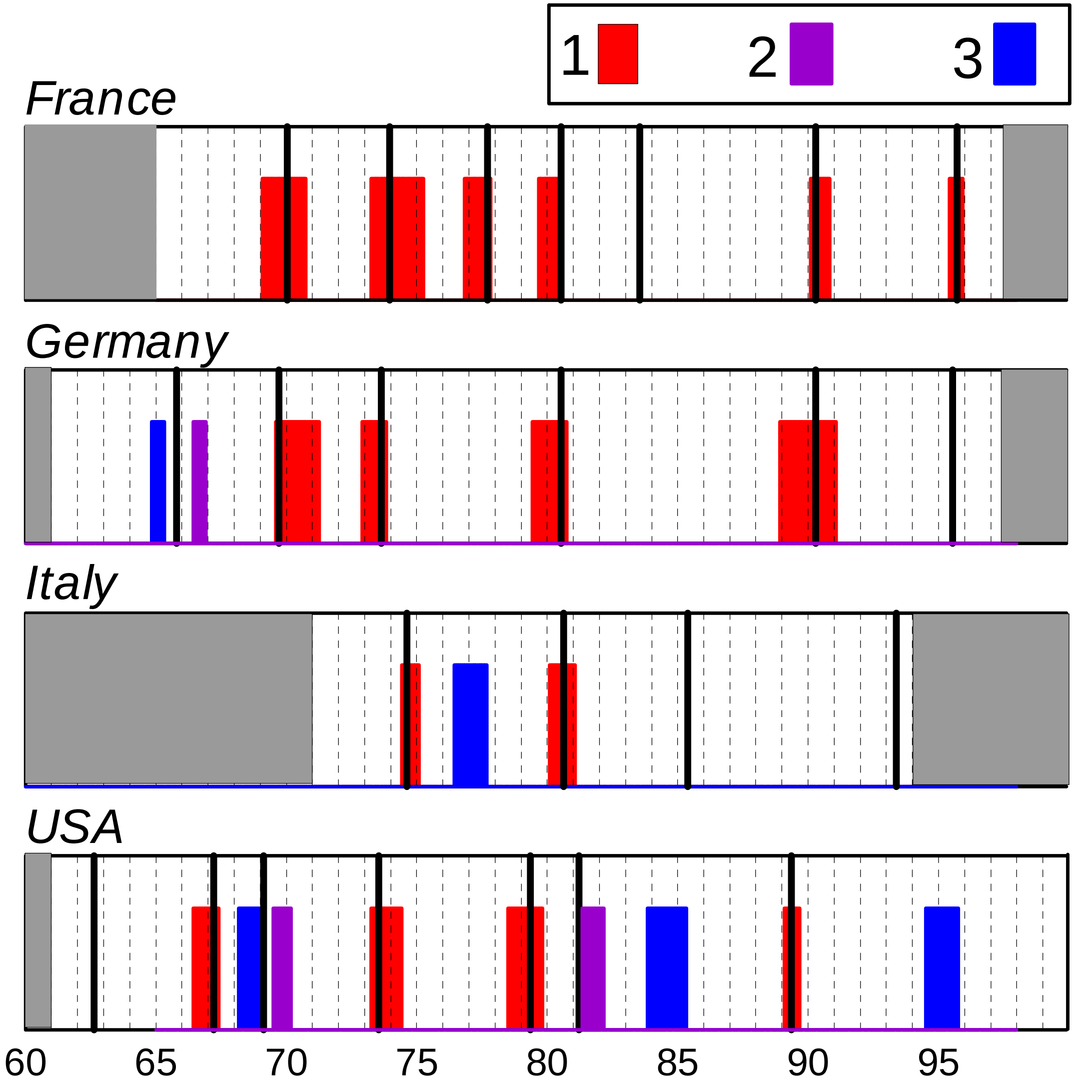


* years when popular vote was reversed by electoral vote.
Red = incumbent won; blue = challenger won.

Prediction of individual extreme events
4. US Recessions (onset and end)

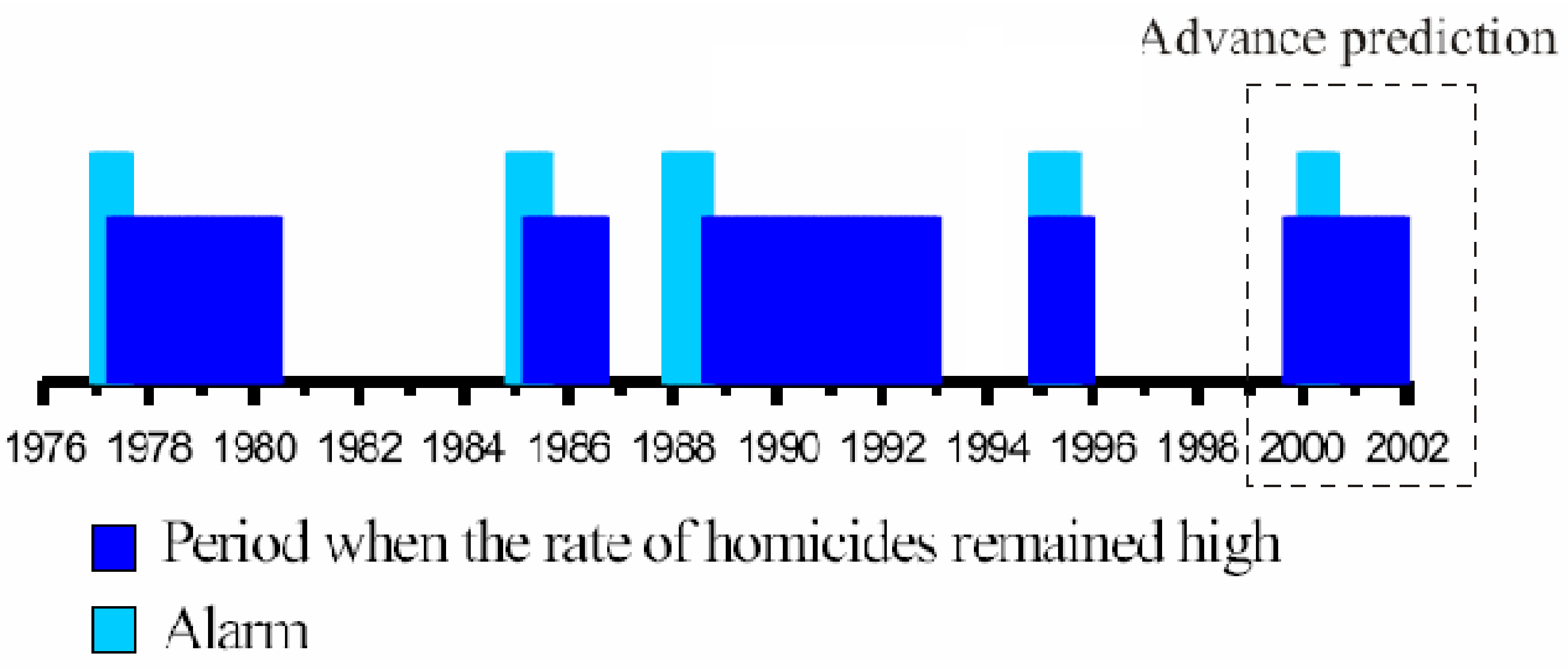


Prediction of individual extreme events
5. Surge of unemployment

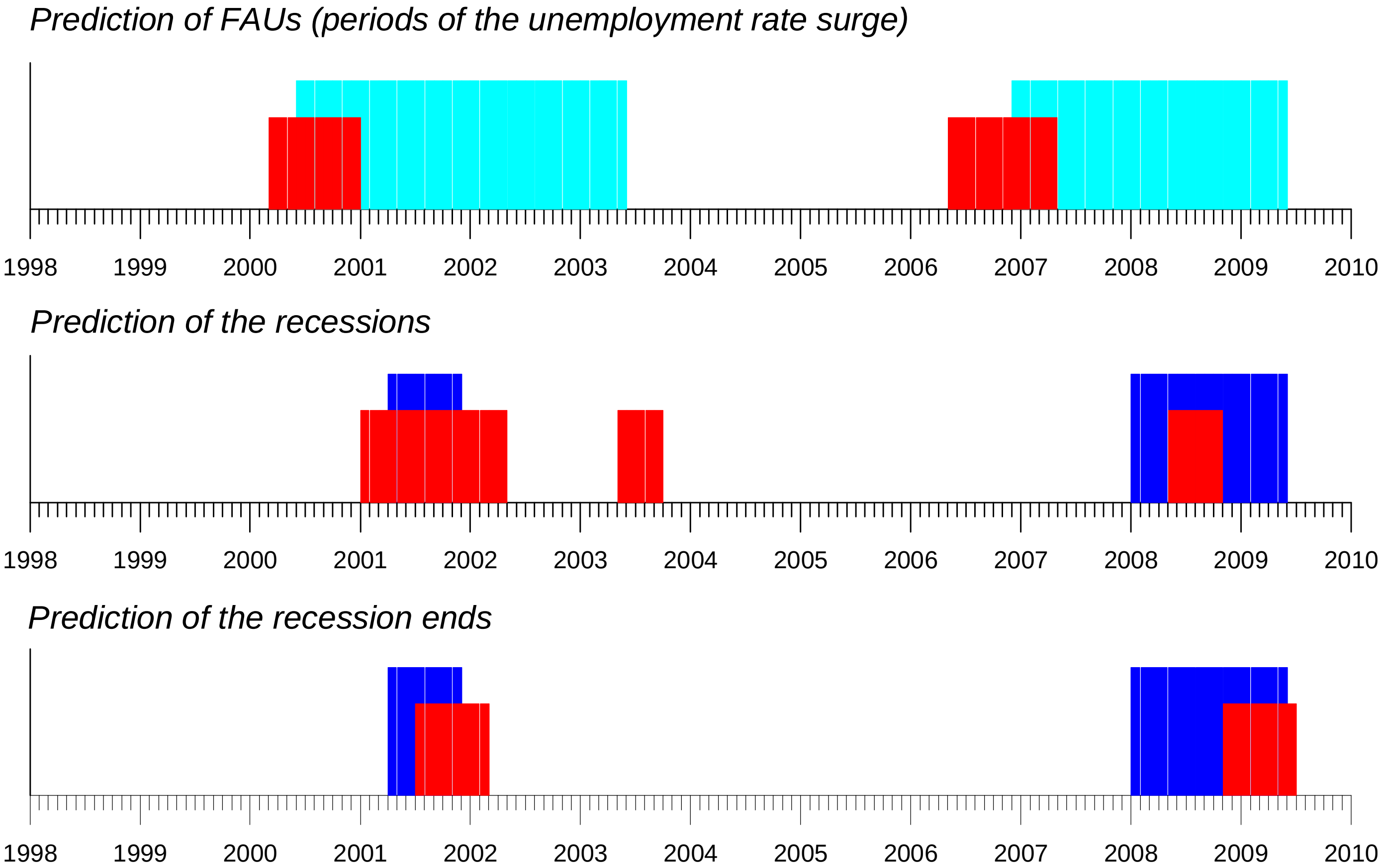


The thick vertical lines show the moments of *FAU*s in a country. Bars – the alarms with different outcome: 1 – alarms that predict *FAU*s, 2 – alarms starting shortly after *FAU*s within the periods of unemployment surge, 3 – false alarms. Shaded areas on both sides indicate the times, for which data on economic indicators were unavailable.

Prediction of individual extreme events
6. Surge of homicides in Los Angeles



Predictions made in advance for the U.S.



Cyan bars show the periods of the unemployment surge, blue bars - the periods of the recessions, red bars - the periods of the relevant alarms.

Note that the beginning of recovery from the current recession is predicted in the last panel. Prediction was made in December 2008

Keilis-Borok,V.I., et al, *J. Forecasting*, 2000, **19, 1: 65-80;** *Pattern Recognition*, 2005, **38, 3: 423-435;** *J. Pattern Recognition Res.*, 2008, **3, 1: 40-53**.

Validation of prediction algorithms

"With four exponents I can fit an elephant" (J. von Neumann).

Each algorithm inevitably includes adjustable elements such as the choice of data to the numerical parameters. In lieu of a "pure" theory of extreme events they have to be data-fitted retrospectively. This creates the danger of self-deceptive data-fitting. For that reason prediction algorithm should be validated by a series of consecutive tests:

-- *Sensitivity analysis*: Testing whether prediction is stable to variation of adjustable elements.

-- *Out of sample analysis*: applying algorithm to past data not used in its development.

-- *Predicting future events* – the only decisive test.

Powerful methodology of such tests, based on error diagrams, is developed by G. Molchan (2003, 2008).

Joint optimization of prediction and preparedness

Quality of prediction is determined by rate of failures to predict, rate of false alarms, and total time-space occupied by alarms.

There is certain freedom in choosing the tradeoff between these characteristics. What combination is optimal depends on what damage can be prevented with different combinations; in other words - on preparedness actions that might be undertaken in response to prediction. Accordingly prediction and preparedness have to be optimized jointly. *There is no "best" prediction per se. And most accurate prediction is not necessarily the optimal one* (Molchan, 2003, 2008).

MINI-PROJECT: HOW TO START?

Pour commencer il faut commencer

(*to start one should start*)

Work in progress includes prediction of many other targets: magnetic storms, surges of price of oil, armed conflicts, and others.

You are welcome to suggest your own project.

Choose:

Target: Extreme event that you want to predict

Data: Already available time series possibly containing precursors, to be considered one at a time

Premonitory patterns to be considered one at a time

A possibility:

Analyze a time series generated by a model

Our school sums up the collaboration of scientists and technical experts from:

- Int. Institute of Earthquake Prediction Theory and Mathematical Geophysics, Russian Ac. Sci., Moscow
- The Abdus Salam International Centre for Theoretical Physics, Trieste
- Moscow State University
- Institute of Mathematics & Mechanics, Russian Ac. Sci., Ekaterinburg
- Vernadsky State Geological Museum, Russian Ac. Sci., Moscow
- UCLA
- Purdue University
- University of Nevada, Reno
- American University, Washington DC
- University of Trieste
- Institut de Physique du Globe de Paris
- Ecole Normale Supérieure (Paris)
- Observatoire de la Côte d'Azur
- LA Dept of Water and Power

As well as disaster management organizations in Russia, Italy and the US.

Yet Untapped Possibilities

"The paradox of want amimist plenty" (contemporaries descriptions of the Great Depression of 1929)

Nodes

Strong earthquakes and other geological disasters nucleate in particularly unstable mosaic structures, called nodes, that are formed around fault intersections or junctions. Roughly put, they are formed due to collisions of the corners of the blocks.

Nodes interact through a fault network and control the stability of the lithosphere by the geometric incompatibility between the geometry of a fault network and its kinematics.

Strong earthquakes nucleate only in the nodes, moreover, in specific nodes that have been pattern recognized in many regions worldwide.

Nodes are textbook knowledge in structural geology and mineral prospecting but, for some incomprehensible reason, they are usually ignored in seismology with dire consequences.

More untapped possibilities for geological disasters prediction

Look for different precursors in blocks, faults, and nodes

Some immediate possibilities for socio-economic predictions

- Continuing experiments ***in advance prediction***, for which the above findings set up a base. Successes and errors are equally important.
- Incorporating ***other available data*** into the analysis.
- Predicting the same kind of extreme events ***under different conditions.***
- Predicting ***the end*** of a crisis.
- ***Multistage prediction*** with several lead times.

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Website

http://www.bol.ucla.edu/~vkborok

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