STATISTICAL MECHANICS FOR COMPLEXITY RÍO DE JANEIRO 6-10 NOVEMBER 2023 Happy Birthday Constantino



MUTABILITY AND ENTROPY: APPROACHES TO COMPLEX SYSTEMS.

- Eugenio E. Vogel (a,b,c), Gonzalo Saravia (d), Denisse Pastén (e), Antonio Posadas (f,g), Patricio Vargas (b,h), Francisco Peña (h)
- (a) Department of Physical Sciences, Universidad de La Frontera, Temuco, Chile.
- (b) Center for the Development of Nanoscience and Nanotechnologie, Santiago, Chile.
- (c) School of Engineering, Central University of Chile, 8330601 Santiago, Chile.
- (d) Los Eucaliptus 1189, 4812537 Temuco, Chile.
- (e) Department of Physics, Universidad de Chile, Las Palmeras 3425, Santiago, Chile.
- (f) Departamento de Química y Fisica, Universidad de Almeria, 04120 Almeria, Spain.
- (g) Instituto Andaluz de Geofisica, Campus Universitario de Cartuja, Universidad de Granada, 18071 Granada, Spain.
- (h) Department of Physics, Universidad Santa María, Valparaíso, Chile.

BASC DEFINITIONS; CLASSICAL ISING SYSTEM; SMULATION

Total internal energy: $U(T) = \sum_{i=1}^{n} e_i p(e_i(T))$ Specific heat: $C_V(T) = \frac{dU(T)}{dT}$ Entropy $S(T) = \int_{0}^{T} \frac{dC_{V}(T')}{dT'} dT'$; S(0) = 0 $M(T) = \sum_{i=1}^{N} S_i$ Magnetization: Susceptibility: $k_B = 1$ $\chi(T) = \frac{1}{k_B T} (\langle M^2 \rangle - \langle M \rangle^2)$

 $H = -J \sum_{k,l=1}^{L^2} S_k S_l$

- Random initial pick
- One MC step= L^2 attemps
- If $U(l+1) \leq U(l)$ accept
- If U(l+1)>U(l), then if exp{ [U(l+1)-U(l)]/T} >random,
 - accept (Metropolis)
- 120,000 MC steps



ISING: ENERGY, SPECIFIC HEAT, ENTROPY



ISNG: MAGNETIZATION, MAGNETIC SUSCEPTIBILITY



SHANNON ENTROPY

- The same series of *R*=120,000 registers can be recognized by other methods.
- A histogram can be constructed at each T to get the frequency f_i for each U_i .
- Within such sampling the probability p_i of reaching the i-th state is given by $p_i = f_i/R$.
- Leading to the Shannon entropy h(T) summing over the microstates (*i*) or the levels (*j*):

$$h(T) = -\sum_{i}^{microstates} p_i \ln(p_i) = -\sum_{j}^{levels} f_j p_j \ln(p_j) \quad ; \qquad p_i = p_j \quad ; \quad \sum_{i}^{levels} f_i = R$$

MUTABILITY (NEW FORM OF ENTROPY?)

- A vector file stores the records of a measurement or simulation M(i)
- The weight of this file is *w* bytes
- We can compress this file, generating a new file of weight w*
- Mutability ζ can be now defined as the ratio w^*/w
- Any compressor could be used here, but not all give the same results. Optimization!!

$$(\mu = \vartheta =) \zeta = \frac{w^*}{w}$$

Mutability can give different results depending on the data compressor

3D ISNG MODEL (TC=4.507...)



COMPARING WLZIPWITH OTHER COMPRESSORS



wizip is a state oriented information recognizer avoinding accidental coincidences

RESULTSFOR 2D, L=128 BASED ON ENERGY SEQUENCES, WLZIPFROM NOW ON





ISNG 2D; L=128, BASED ON MAGNETIZATION SEQUENCES



CONCLUDING REMARKS; FIRST PART

- Mutability complemented by an appropriate information recognizer can give information similar to an entropy for a series representing a property of the system.
- Different properties of the same system can be evaluated one at a time.
- Compression of the sorted file renders a minimal mutability

APPLICATION TO REAL DATA SEQUENCES (WITH THE COLLABORATION OF GONZALO SARAVIA)

- Q-clock model: Characterization of two or three magnetic phases depending on the Q orientations of the spins and the temperature (Entropy 23 (2021) 1019) (P. Vargas, F. Peña; UTFSM)
- Rod deposition on square lattices: ζ recognizes two or three phases according to the rod length and concentration (Phys. Rev. E 101 (2020) 022104, (A.J.Ramirez-Pastor, M. Pasinetti; UNSLAR) ... experiment under way at UNAV, Pamplona, Diego Maza).
- Metric to characterize blood pressure (J of the American Soc. of Hypertension 10 (2016) 217-223).
- Characterization of grain flowing/clogging in a 2d vertical silo (manuscript in preparation, 2023) (R. Caitano BR, A.J.Ramirez-Pastor AR)
- Optimization of wind energy productivity (Wind Energy 126 (2018) 724-735; and submitted with S Kobe and R. Schuster; TU Dresden DE).
- Earthquake comparative characterization by means of 3 entropies: (a) Entropy 25 (2023) 1947; b) Natural Hazards and Earth Systems Science 23 (2023) 1911-1920; c) Chaos, Solitons and Fractals 165 (2022) 112874, with Denisse Pastén UCH; Antonio Posadas U. Almería ES.
- And more

DEFINITION OF THE SEISMIC SYSTEM

- Seisms related to the Mw 8.1 Iquique earthquake, on April 1, 2014.
- Use the Integrated Plate Boundary Observatory Chile (IPOC) catalog, which sets dates: from 2007.01.01 up to 2014.12.31 (Filter #1).
- Filter # 2: Seisms within rectangle 18-24S and 68-72W.
- List of seisms Mw6.3 and larger, within these conditions:

Year	Month	Day	Magni	tude	Latitude	Longitude	Depth
2014	3	16	\bigstar	6.6	-19.95476	-70.85965	17.86
2014	3	17		6.4	-19.97812	-70.95194	21.09
2014	3	22		6.3	-19.74193	-71.03003	46.32
2014	4	1		8.1	-19.58927	-70.94021	19.91
2014	4	3		6.4	-20.23952	-70.68120	24.34
2014	4	3	$\overrightarrow{\mathbf{x}}$	7.6	-20.59462	-70.58543	21.96
2014	4	4		6.3	-20.59444	-70.70383	22.50
2014	4	11		6.3	-20.70646	-70.72461	20.72



MAGNITUDE, TIME (2014) AND GUTENBERG-RICHTER



Filter # 3: Seisms with magnitude Mw over 2.2.

DEPTH BY IPOC (LEFT) ; SUBDUCTION PLING LATITUDE (RIGHT)



Filter #4: Seisms with depth up to 70 km are left for the analisis

The total number of seisms after the 4 filters is 10640.

HANDLING OF DATA

- Data will be handled as a discrete sequence of magnitudes and time intervals.
- Statistic analysis techniques will be used
- Distributions by different physical observables will be used

TSALLISENTROPY AND EARTHQUAKES

(POSADAS, A. AND SOTOLONGO-COSTA, O.: NON-EXTENSIVE ENTROPY AND FRAGMENT-ASPERITY INTERACTION MODEL FOR EARTHQUAKES, COMMUN. NONLINEAR SCI., 117, 106906, HTTPS://DOI.ORG/10.1016/JCNSNS2022.106906, 2023.)

Tsallis entropy has been expressed as
$$S_T = \frac{1}{q-1} \left[1 - \sum_{i}^{\Omega} p_i^q \right]$$
,

where q has to be evaluated for each system. For our seismic distribution we can assign a probability $p(M_i)$ to each magnitude according to the distribution for the 10640 entries. Then we can make use of direct relationships from statistical physics:

$$S(T) = -\sum_{M_0}^{M_{Max}} p(M_i) \ Log(p(M_i));$$

$$\sum_{M_0}^{M_{Max}} p(M_i) = 1;$$

$$\overline{M} = \sum_{M_0}^{M_{Max}} M_i \, p(M_i)$$

The combination of these three conditions by means of Lagrange multipliers and the physical conditions imposed by the Gutenberg Richter method can lead to get the value of q

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SUMMARY OF SOME PROPOSED Q VALUES

Autores	Región	q
Sotolongo y Posadas 2004	Sur Península Ibérica (Andalucía)	1,6
	Península Ibérica	1,64
	California	1,65
Silva et al. 2006	Samambaia - Brazil	1,6
	New Madrid - USA	1,63
	Anatolian - Turkey	1,71
Darooneh y Mehri, 2010	Irán	1,78
	California	1,81
Telesca 2010	L'Aquila Italia (Periodo 1)	1,48
	L'Aquila Italia (Periodo 2)	1,74
	L'Aquila Italia (Periodo 3)	1,7
Telesca 2011	California	1,54
Valverde-Esparza et al. 2012	Jalisco (México)	1,7
	Michoacan (México)	1,69
	Oaxaca (México)	1,63
	Guerrero (México)	1,64

SHANNON ENTROPY

- The probabilities p_i are obtained directly from the distribution of values characterizing the observable chosen to represent the system.
- A system can be characterized by several observables and its choice can be important to establish its properties.
- In the case of earthquakes we can deal with the succession of magnitudes or the succession of intervals between consecutive events.

WLZIPAND MUTABILITY

The vector file to the left corresponds to the R=50 seisms beginning on February 01,2014, covering a few days before the 6.6 triggering Iquique earthquake.

 ${\mathcal W}$

W*

$$h(T) = -\sum_{j=1}^{beans} p_j(T) f_j \log\left(p_j(T)\right)$$

Shannon, a byproduct of mutability

WLZIPAFTER SORTING

The same vector of magnitudes for the R=50 seisms beginning on February 01,2014, are now orders in increasing order of magnitude and then compresses by WLZIP:

j	М	Map	f_j	$p_j = f_j/R$
1	2.2	$0,\!6$	6	0.1200
2	2.3	$6,\!3$	3	0.0600
3	2.4	$9,\!5$	5	0.1000
4	2.5	$14,\! 6$	6	0.1200
5	2.6	20,2	2	0.0400
6	2.7	22	1	0.0200
7	2.8	$23,\!3$	3	0.0600
8	2.9	$26,\!3$	3	0.0600
9	3.0	29	1	0.0200
10	3.1	$_{30,2}$	2	0.0400
11	3.3	32	1	0.0200
12	3.4	33	1	0.0200
13	$_{3,5}$	$34,\!3$	3	0.0600
14	3.6	37	1	0.0200
15	3.8	38,2	2	0.0400
16	4.0	$40,\!4$	4	0.0800
17	4.1	$44,\!2$	2	0.0400
18	4.3	46,2	2	0.0400
19	4.6	48	1	0.0200
20	5.5	49	1	0.0200

VARIANTSOF MUTABILITY ("DYNAMICAL ENTROPY"?)

- The original sequence can be altered to respond to special conditions. The Shannon entropy remains the same, but the mutability changes substantially.
- Suppose we want to break Markovian chains, so the original file is disordered or scrambled previous to its compression.
- For other purposes it could be interesting to inquire on the data according to their values in an ordered way, so the original file is ordered and blocks of entries for the same value are then compressed.
- In the previous example, the 3 values of mutability are $\zeta_{\text{orig}}=0.85$, $\zeta_{\text{dis}}=0.90^*$, and $\zeta_{\text{sort}}=0.78$, so history matters.

RESULTSAND DISCUSSION FOR IQUIQUE SEISMS

- Results for Tsallis entropy on magnitude
- Results for mutability on magnitude
- Results for mutability on intervals

Citation: Pasten, D.; Vogel, E.E.; Saravia, G.; Posadas, A.; Sotolongo, O. Tsallis Entropy and Mutability to Characterize Seismic Sequences: The Case of 2007–2014 Northern Chile Earthquakes. *Entropy* **2023**, *25*, 1417. https://doi.org/10.3390/e25101417

TSALLISENTROPY ON IQUIQUE (IPOC DATA)

Overlapping (one event) windows of
W consecutive events.

□ *W*=256 to 2048.

- Symbols identify the three most important earthquakes.
- Real time representation 2007-14.

□ Broad increase of S_T during the three years previous to 2014.04.01



MUTABILITY ON IQUIQUE

- Overlapping (one event) windows of W consecutive events.
- □ W=256 to 2048.
- Symbols identify the three most important earthquakes.
- Real time representation 2007-14.
- Broad decrease of ζ_{orig} during the three years previous to 2014.04.01
- □ Mutability has inverse behavior as compared to S_T : Why?
- □ *S_T* reflects the real world related to the space distribution for large structures, rocks, sand and empty spaces underground.
- Mutability deals always with the data reflecting properties of the configuration space: monotonic behavior during the energy accumulation periods.



SEARCH FOR PREMONITORY SIGNALS DYNAMIC APPROACH



ALTERNATIVE PROPERTY TO BE STUDIED

- Similarly to the magnitude analysis we can look at intervals between consecutive seisms in the sequence.
- Intervals increase previous to seism while energy is being accumulated underground.
- During the earthquake and for months or years afterwards the system accommodates shortening the intervals between successive seisms.

MUTABILITY ON CON CUTIVE IN TERVALS; W=64



CONCLUDING REMARKS, SECOND (AND LAST) PART

- Tsallis entropy grows a couple of years before a large quake (energy accumulation?)
- Mutability decreases a couple of years before a large quake (only small quakes?)
- Tsallis suddenly decreases at the time mutability suddenly increases days and hours before a large earthquake. (To be tested for other earthquakes).



Thanks Constantino! Thank you all for your presence!

CARTOON OF SUBDUCTION: EMPTY SPACE DECREASE



MAGNITUDE V/STIME DAY BEFORE AND AFTER MAIN SEISM



ISNG 2D; L=128, BASED ON MAGNETIZATION SEQUENCES



MUTABILITY ON MAGNETIZATION DATA L=64: DIFFERENT W



Mutability for magnetization data in nearly independent of the observation time window

NATURALTIME



After a great earthquake (Mw larger than 6) a great deal of seisms of all intensities follow at short intervals. In real time this hides the texture of the aftershock regime. However, displaying any entropy with respect to the natural time unfolds hidden features of this regime emerge.





MUTABILITY ON ENERGY DATA: L=128 AND L=64



SHANNON ENTROPY ON ENERGY



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