Self-Organized Criticality :

A conceptual prelude to avalanche models of solar flares

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General Definition

- Aim to describe **systems that breed complexity** – phenomena as diverse as sandpiles, landscape formation, **solar flares**, biological life and evolution, social phenomena (economics, traffic jams, ...)
- The **critical point** of an SOC system is an **attractor of its internal dynamics**.
- Three key elements: **power laws & scale invariance, avalanche phenomena and pink noise**.

1 – Power Laws & Scale invariance

- **Many distributions in nature follow a power law** – the energy distribution of earthquakes or **solar flares**, pulsar's velocity changes, fluctuations in the economics system, etc. – such as $N(s) = s^{-\tau}$ where e.g. N could be the number of earthquakes with energy s.

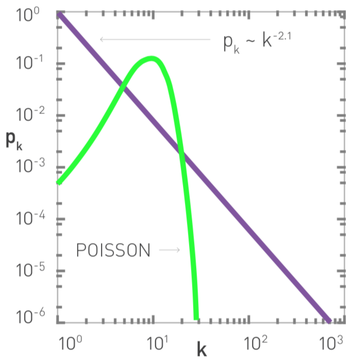


Figure 1: Degree distribution of a scale-free network. Taken from [3].

- We also say that those phenomena show ***scale invariance* - i.e. no particular feature stand out at any scale** and all the individual events follow the same logic, no matter their size. There is no "typical size" for those events.

2 – Avalanche Phenomena

- By definition, SOC systems evolve to critical states by themselves through a long transient period, and then further changes in those systems proceed by **large, catastrophic events** - i.e. avalanches.
- Back to the previous box, the size distribution of those events is given by a power law.

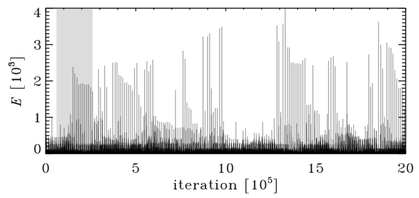


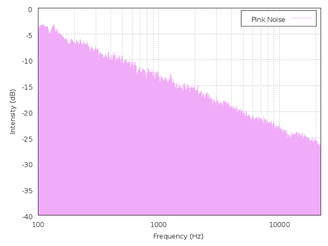
Figure 2: Distribution of earthquake energy when simulated with the Olami-Feder Christensen model. Taken from [2].

- What's so special about earthquakes or fluctuations of the economic system is that **we still can't predict individual events**.

3 – Pink Noise

- Pink noise - or, as Bak puts it, "$1/f$ noise" - is ubiquitous in nature; it's been observed in the light from quasars to highway traffic.
- It is actually a *multiperiodic signal* where there is superposition of a multitude of frequency bands, each with an **intensity related to the inverse of its frequency**.

Figure 3: Pink noise power spectrum. Taken from [6].



From SOC to Solar Flares...

- **Parker's Nanoflare Hypothesis**: coronal loops and magnetic fields are entangled by the convective motions of their photospheric footpoints – this stress is then released via localized magnetic reconnection. Understood this way, **a large flare is simply an "avalanche" phenomenon composed of multiple nanoflares**.

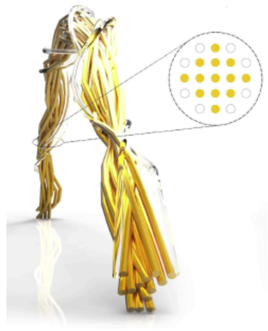


Figure 4: Schematics of a flux tube including magnetic strands. Picture taken from [4].

- Moreover, this hypothesis thus explains the **scale invariance of the distribution of flare energy release**. **More about this on my colleague Christian Thibeault's poster right beside!**

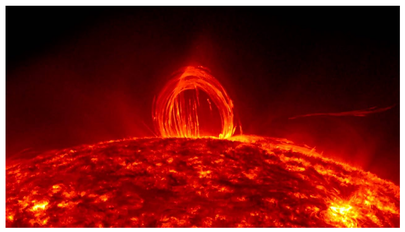


Figure 5: Eruption of July 19th, 2012. Picture taken from [5].

Take-Home

- The SOC theory **challenges our assumption that in natural systems large events only come from large shocks** (mass extinctions come from a meteorite, the downfall of the economic system comes from demande or supply shocks, etc.)
- In those systems, **slow and gradual energy accumulation** leads to **quick, intermittent and aperiodic discharges**.
- Moreover, attemps to *control or regulate* the occurrence of large events in SOC systems simply do not work (e.g. traffic jams)
- **The critical state, with events of all sizes, could be the most efficient state achieved dynamically - i.e. nature's response to the energy flow problem**.

References & Acknowledgements

[1] Bak, P. *How nature works: the science of self-organized criticality.* (Copernicus, 1999).

[2] Charbonneau, P. *Natural Complexity: A Modeling Handbook.* (Princeton University Press, 2017).

[3] Barabasi, A.-L. & Posfai, M. *Network Science.* (Cambridge University Press, 2016).

[4] Farhang, N. et al. *Principle of Minimum Energy in Magnetic Reconnection in a Self-organized Critical Model for Solar Flares. ApJ 859, 41 (2018).*

[5] Solar flare picture taken from NASA's Goddard Space Flight Center Video/courtesy of NASA/GSFC/SDO

[6] https://en.wikipedia.org/wiki/Pink_noise

GRPS

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