SIGNAL PERCOLATION THROUGH BIOLOGICAL SYSTEMS

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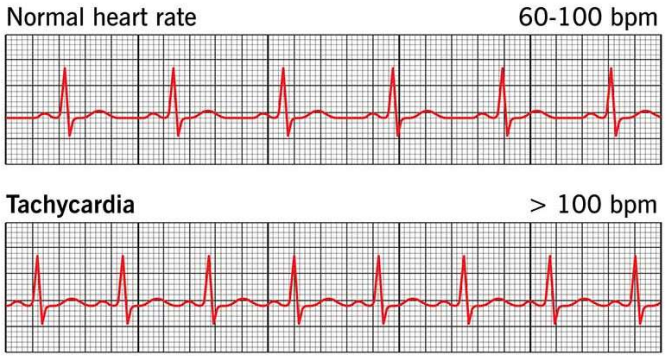
In collaboration with Md Aquib Molla

WHAT ARE WE INTERESTED AT?

- Malfunction in action potential movement through heart or brain tissues may lead to diseases like tachycardia (heart) and in connection similar disease in brain.
- Transport and delay of arrival of action potential through fibrotic tissues.
- “Tortuosity" in the heart tissue is referred to as zig zag movement of the action potential.
- For Heart there is only excitatory cells. For Brain, existence of two kinds of cells, excitatory and inhibitory ones.



Vigmond, E., Pashaei, A., Amraoui, S., Cochet, H. & Hassaguerre, M. Percolation as a mechanism to explain atrial fractionated electrograms and reentry in a fibrosis model based on imaging data. *Heart Rhythm* **13**, 1536 (2016).
Niederer, S. A., Lumens, J. & Trayanova, N. A. Computational models in cardiology. *Nat. Rev. Cardiol.* **16**, 100 (2019).

PERCOLATION

Directed Percolation

Single Forward Direction, Backward movement prohibited.

Ex. Forest Fire, electrical and thermal passage through media

Semi Directed Percolation

Movement in both direction allowed keeping in mind the Refractory Period.

Ex. Electrical movement in neurons, in the heart and brain tissues

Drossel, B. & Schwabl, F. Self-organized critical forest-fire model. *Phys. Rev. Lett.* **69**, 1629 (1992).
Moβner, W. K., Drossel, B. & Schwabl, F. Computer simulations of the forest-fire model. *Phys. A Stat. Mech. Appl.* **190**, 205 (1992).
Langlois, V., Trinh, V. H. & Perrot, C. Electrical conductivity and tortuosity of solid foam: effect of pore connections. *Phys. Rev. E* **100**, 013115 (2019).

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- Waiting = 0, Active = 1, Inactive = 2
- p_{switch} = probability of an Inactive (2) cell to become a Waiting (0) one to receive the Action Potential. Somewhat related to Refractory Period [2→0].
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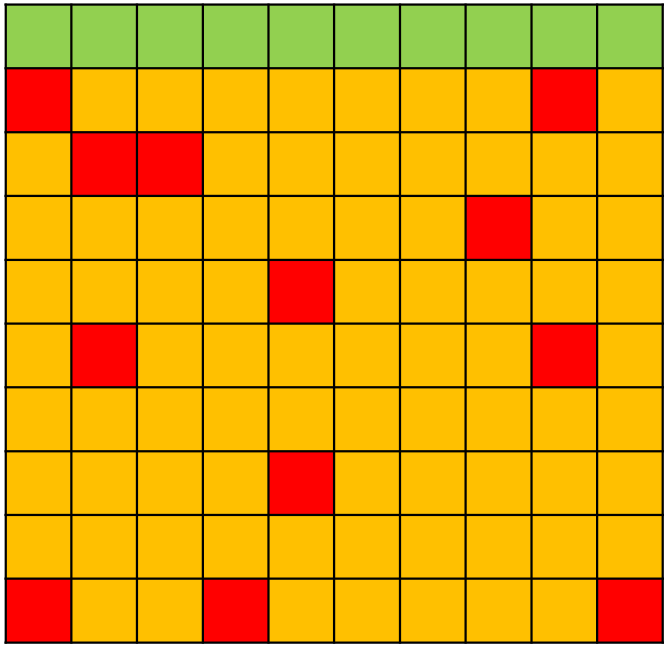
- Percolation throughput or transport : Fraction of the 1s initiated from one end that reaches the other end of the percolating system.
- Tortuosity : average time of arrival.

Hunt, A. G. & Sahimi, M. Flow, transport, and reaction in porous media: percolation scaling, critical-path analysis, and effective medium approximation. *Rev. Geophys.* **55**, 993 (2017).
Xu, W., Jia, M. & Gong, Z. Thermal conductivity and tortuosity of porous composites considering percolation of porous network: from spherical to polyhedral pores. *Compos. Sci. Technol.* **167**, 134 (2018).

MODEL DESCRIPTION

- 2D square grid of n × n cells
- Initially the cells may be "Waiting" (0) [with probability p] or "Inactive" (2) [with probability (1-p)].
- The action potential is initiated from one end.
- An "Waiting" (0) cell can be activated with an action potential and then the cell will be an "Active" (1).
- Rule for activation : if one or more of its "nearest cell neighbors" are Active.
- After Activation it becomes Inactive in the next step.
- The transformation rule 0→1→2→0. [when 2→0 is not allowed p_{switch}=0].



Rabinovitch, R., Biton, Y., Braunstein, D. *et al.* Percolation and tortuosity in heart-like cells. *Sci Rep* **11**, 11441 (2021).

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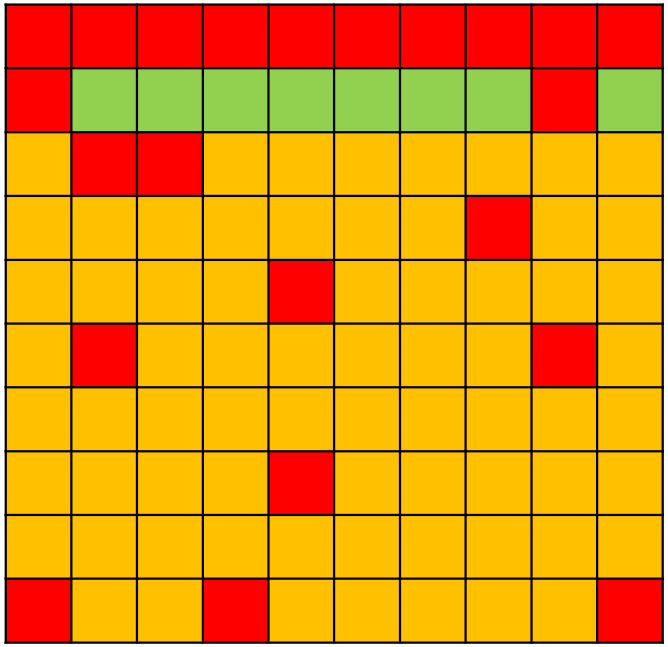

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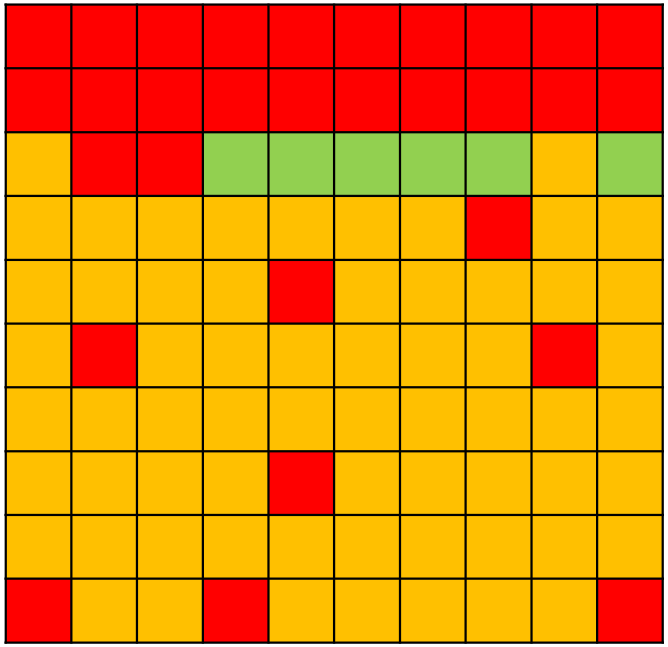

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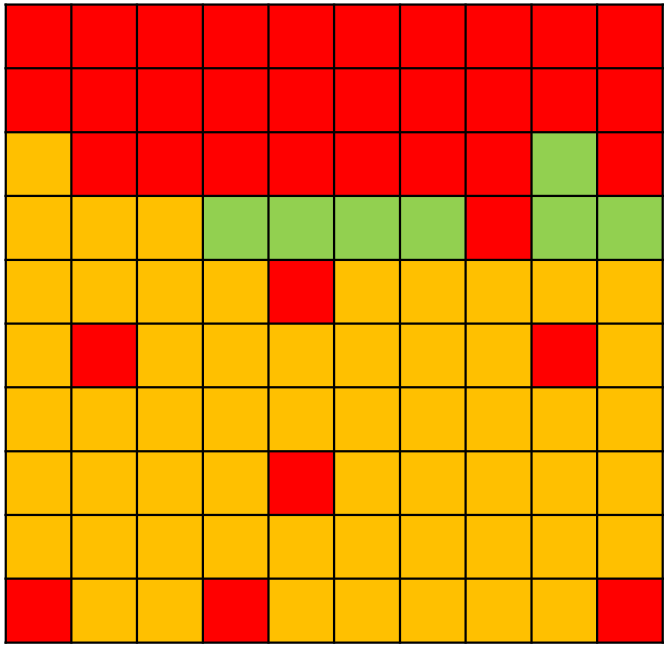

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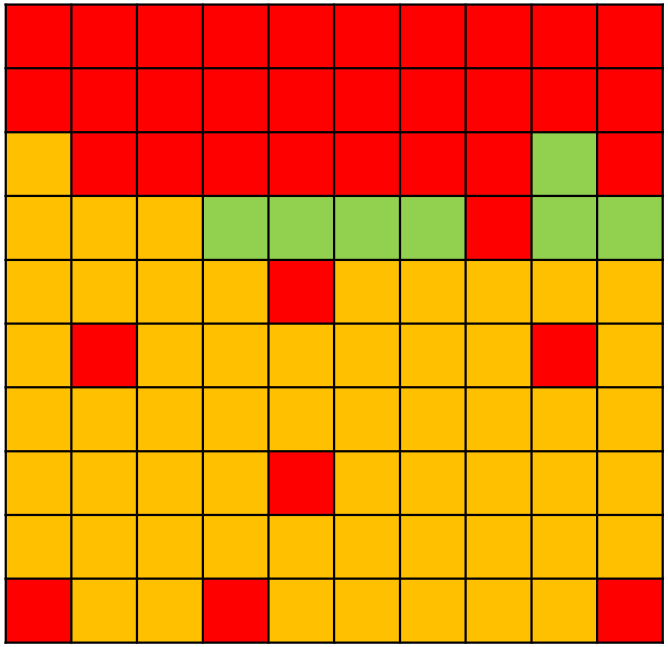
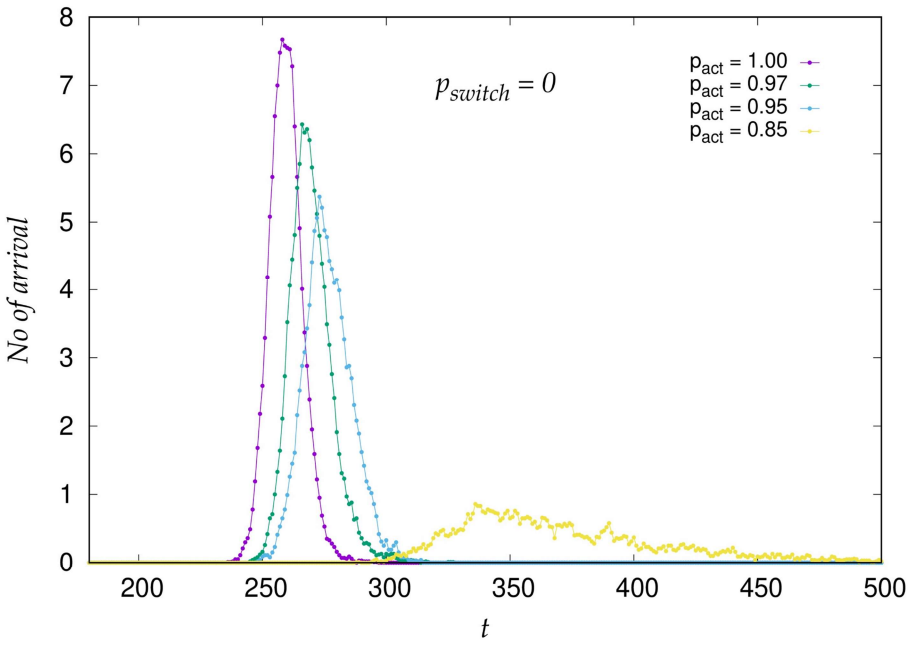
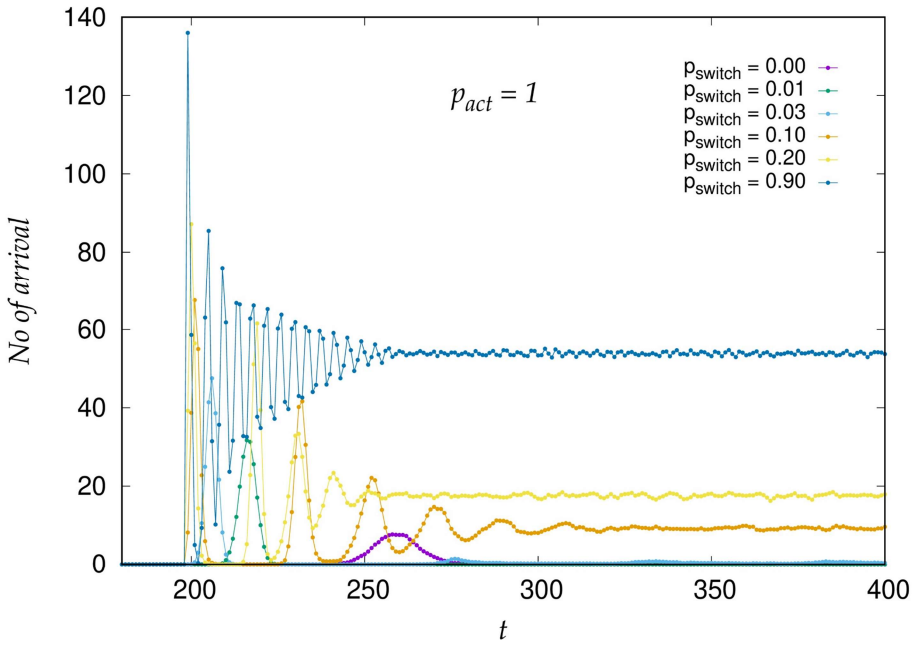
We also considered cases $p_{switch} \neq 0$ and $p_{act} \neq 1$



RESULTS : NUMBER ARRIVING AT THE OTHER END

System size 200, p=0.7





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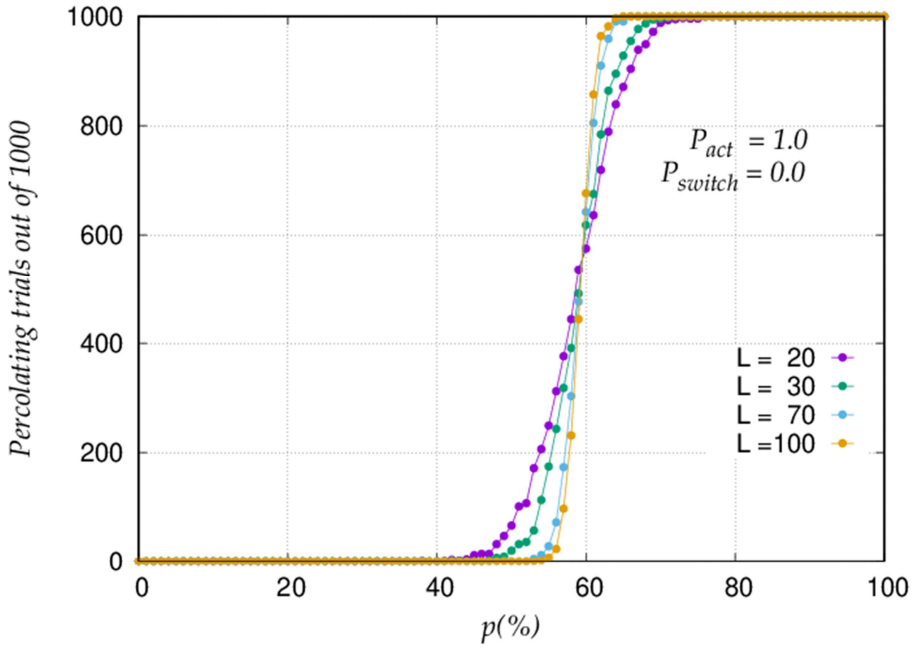
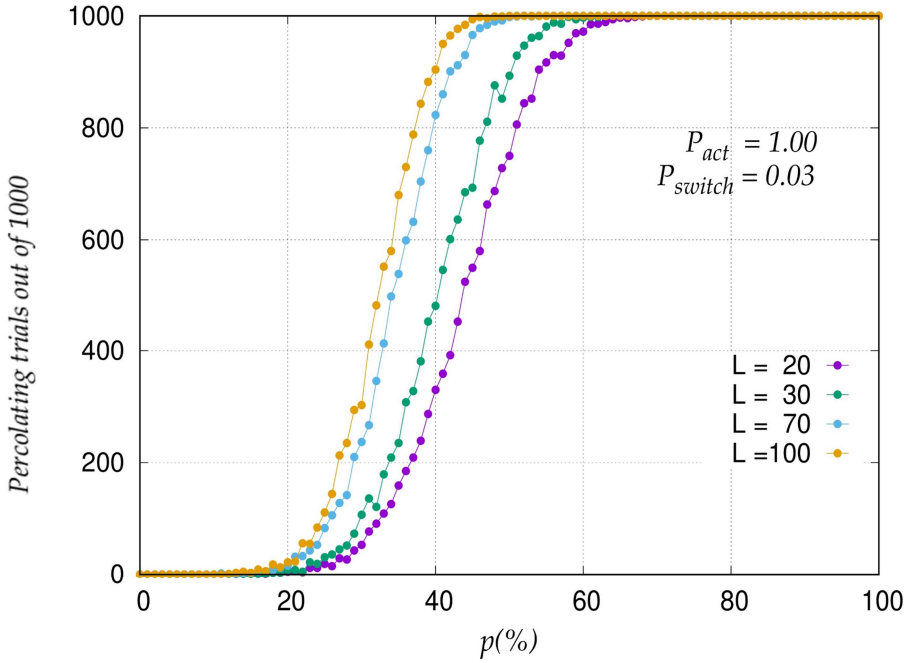
RESULTS : PERCOLATION THRESHOLD





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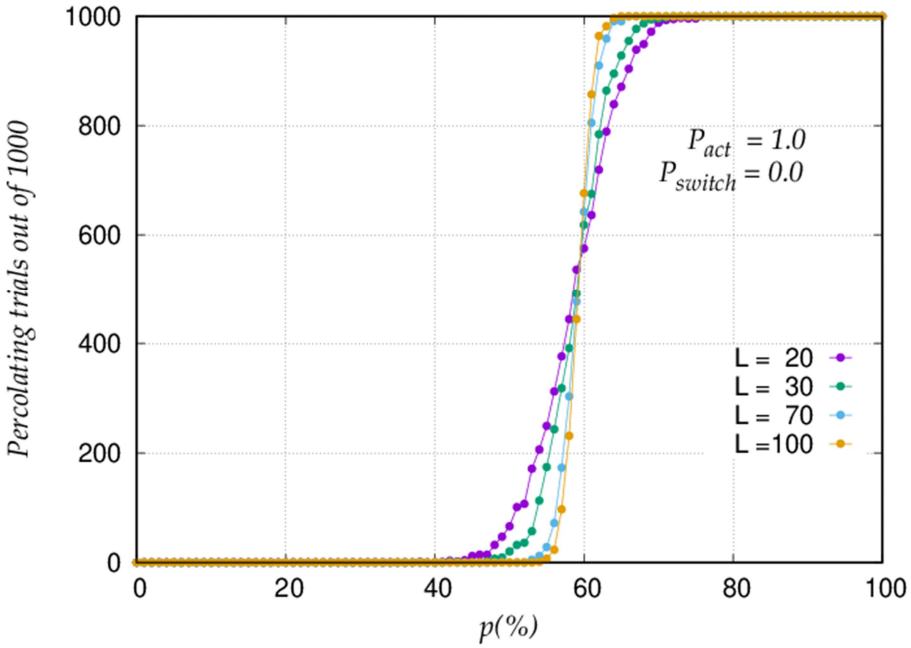

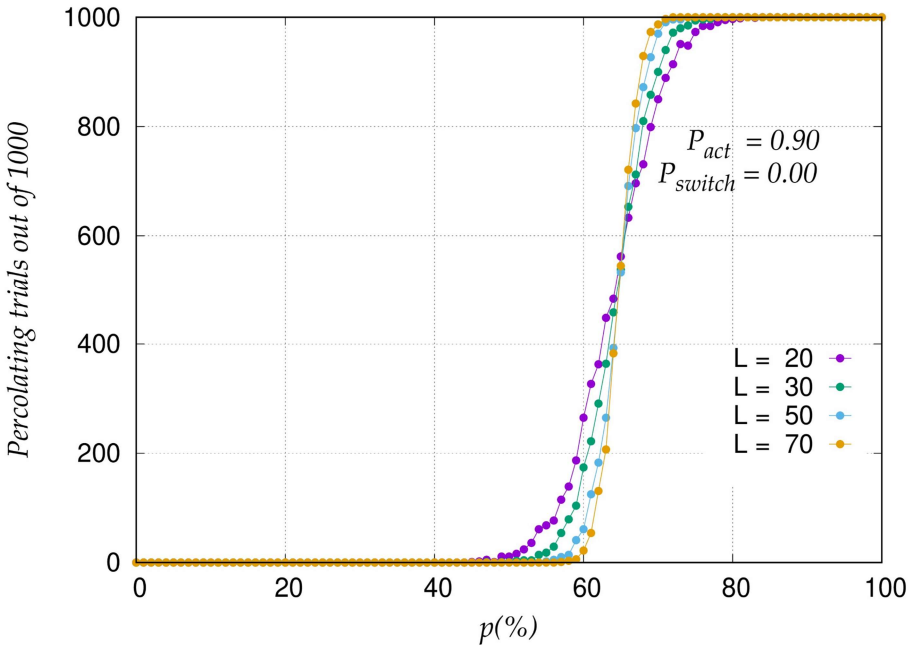

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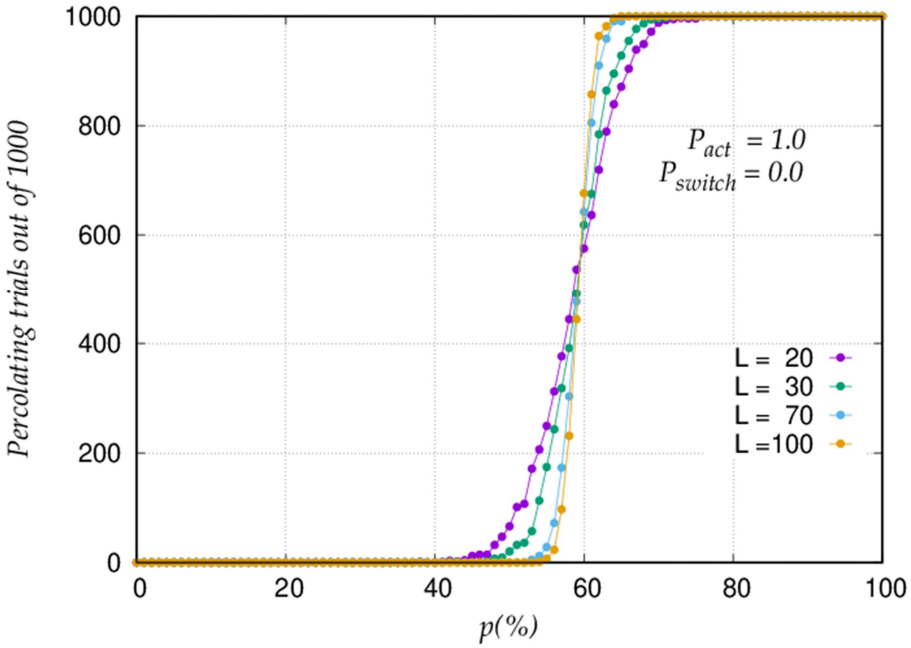

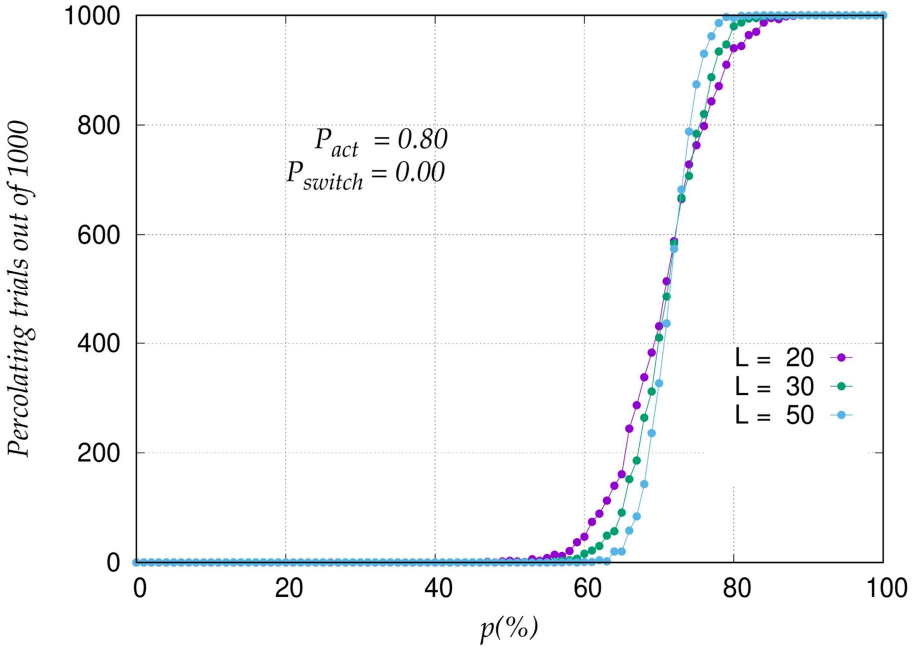

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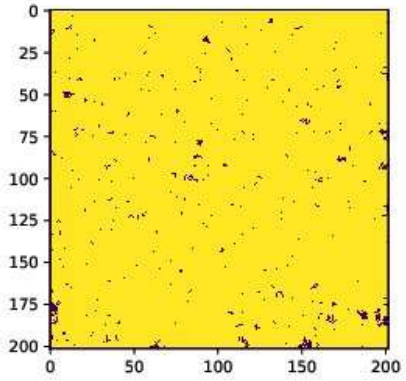
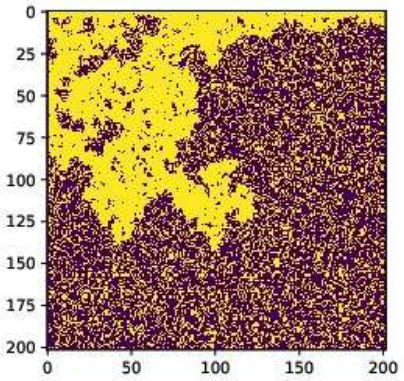
RESULTS : SNAPSHOTS

System size 200, p=0.7

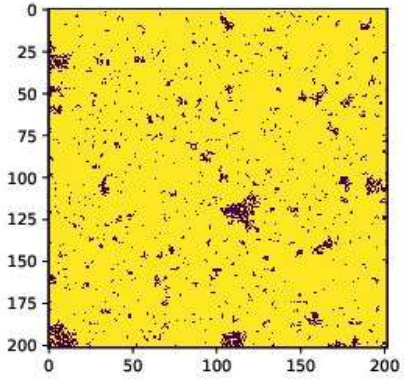


$p_{act} = 1$

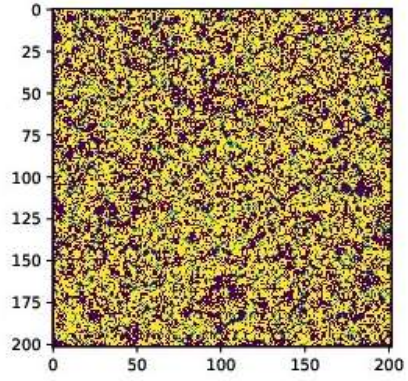


$p_{act} = 0.8$

$p_{act} = 0.9$



$p_{act} = 1$
$p_{switch} = 0.2$



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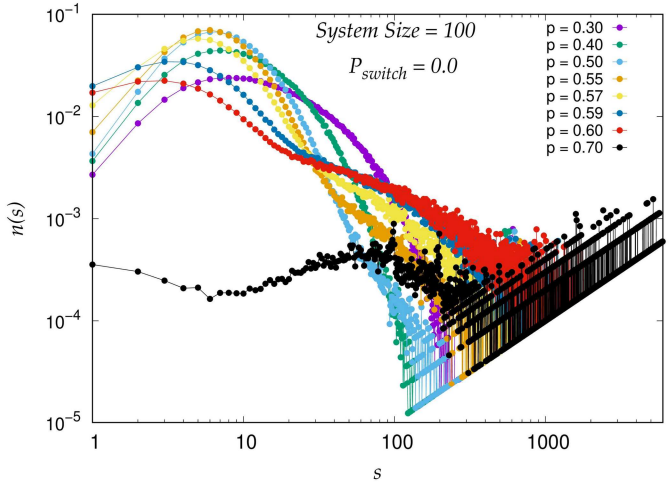
RESULTS : CLUSTER DISTRIBUTION



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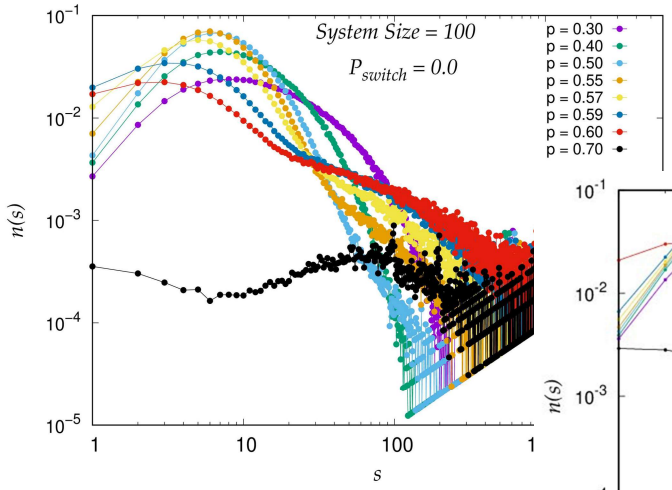

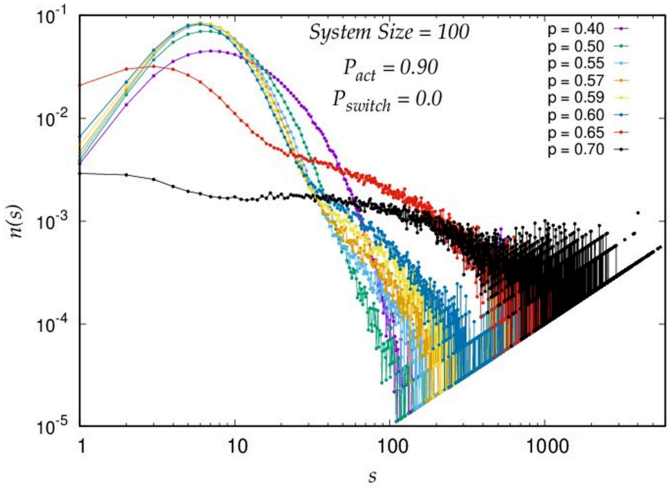

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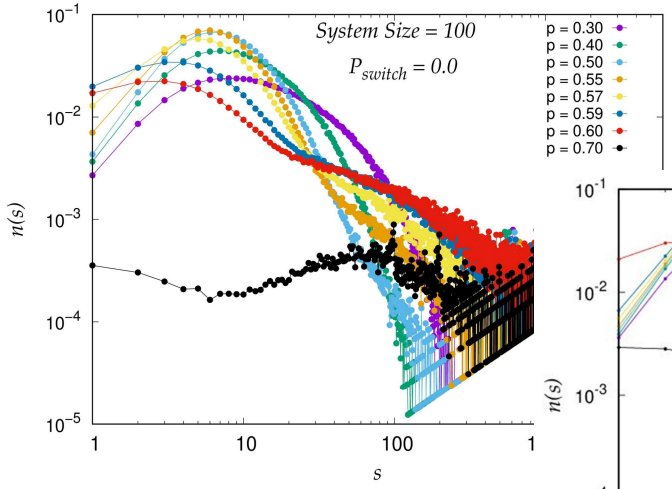

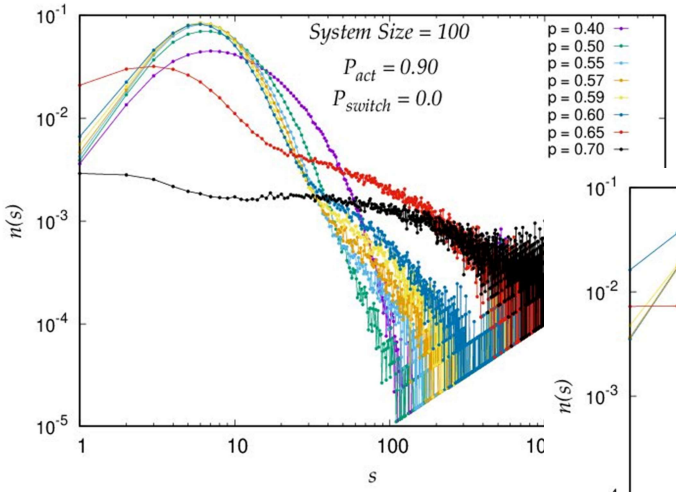

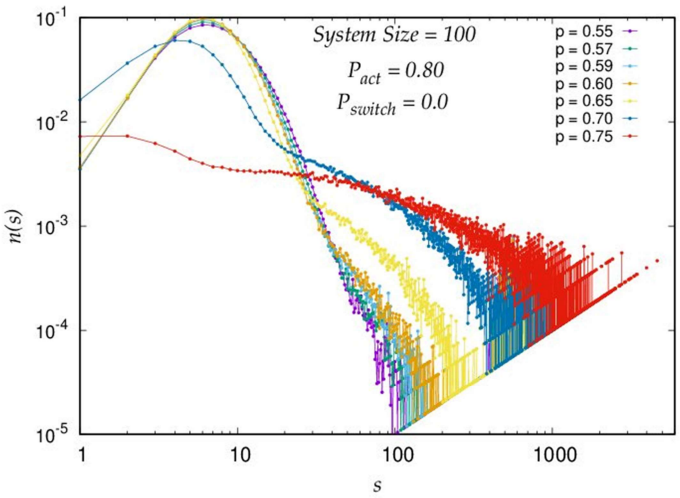

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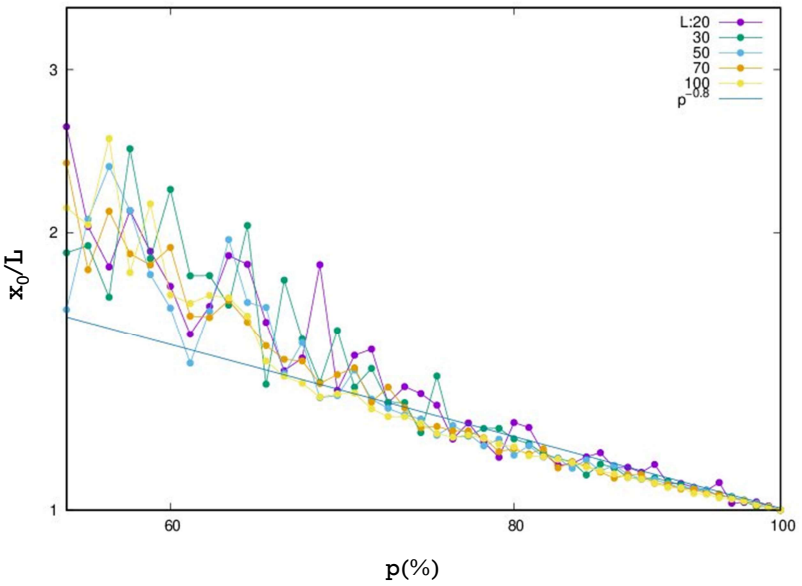
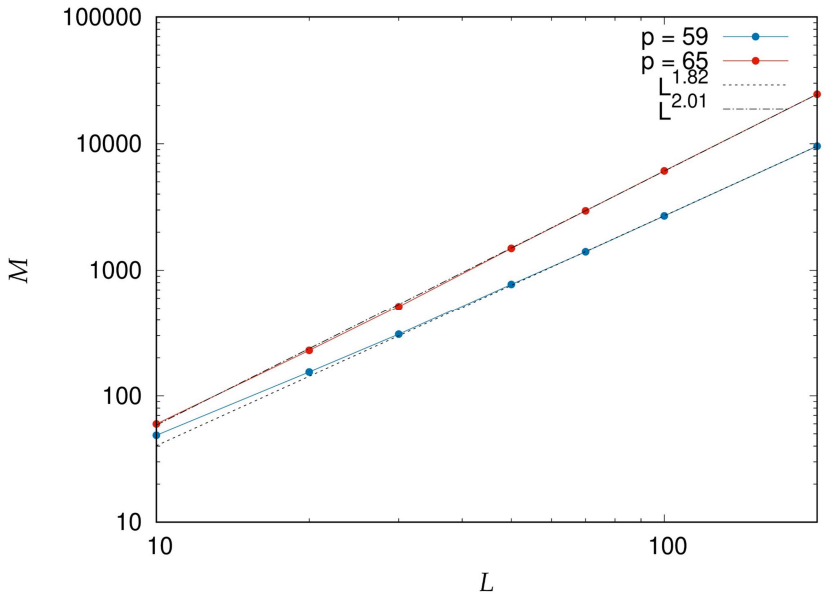
RESULTS : TORTUOSITY & LARGEST CLUSTER





$p_{act} = 1,\ p_{switch} = 0$

Manuscript under preparation

SUMMARY AND DISCUSSION

- A fibrotic tissue inside an organ is responsible for delay of signal (action potential) arrival in the system. It also reduce the quantity of active cells and introduce spreads in their arrival.

- When we consider larger refractory period, there is no active reentry path. However when $p_{switch} \neq 0$, there is always an reentry path. For this the number arriving is never zero. Therefore, even if there is a fibrotic area surrounded by healthy tissues, no active reentry mechanism can be initiated under a single stimulation when the refractory period is large. Shorter refractory period will initiate the reentry.

- The Percolation thresholds shift drastically to lower p values even for a small value of p_{switch}, equivalent to shorter refractory period. For $p_{switch} = 0$ and lower p_{act}, however the thresholds shift towards higher p values. This can be compared to higher inhibition as in brain cells.

- Cluster distribution shows a power law behaviour close to criticality.

- The data collapse for tortuosity shows for high p it is almost fitted to p^(-0.8).

- The largest cluster versus L curve shows that for $p = p_c$, it behaves as L^D, whereas for $p > p_c$ as L^d.


thank you