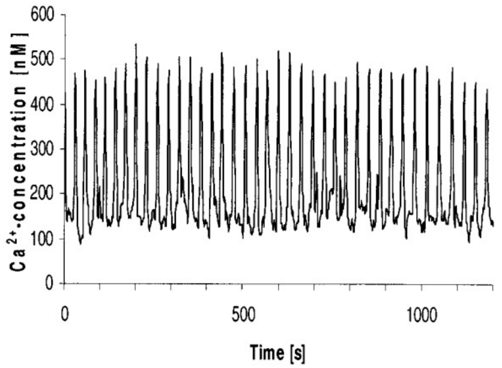
Complexity, Fluctuations and Dissipation in Nonlinear, Non-equilibrium models

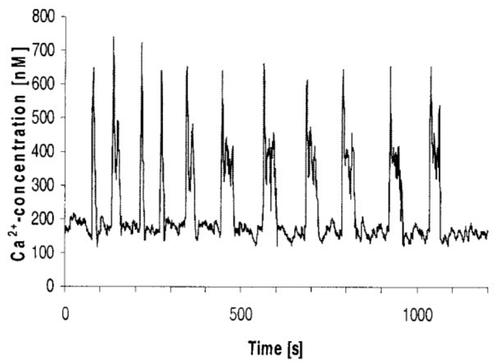
ATHOKPAM Langlen Chanu

Asia Pacific Center for Theoretical Physics, Pohang, South Korea

(A) Simple oscillations (spiking)



(B) Complex oscillations (bursting)

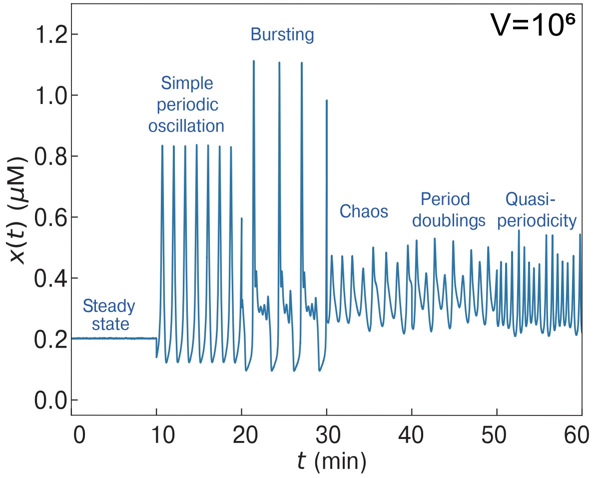


Rat hepatocytes stimulated with (A) 2μM phenylephrine, (B) 1.2 μM ATP

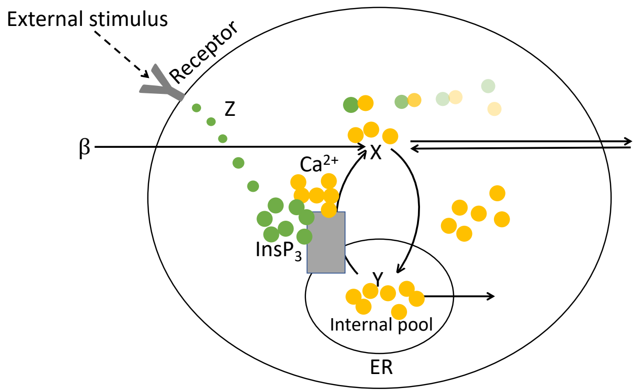
Stochastic modelling with Chemical Langevin Equation:

System size (V)

Intrinsic fluctuation $\sim \dfrac{1}{\sqrt{V}}$



Intracellular Calcium (Ca^{2+}) dynamics



Coupled, non-linear ODEs

$$\frac{dx}{dt} = V_0 + V_1\beta - V_2 + V_3 + k_f y - kx$$

$$\frac{dy}{dt} = V_2 - V_3 - k_f y$$

$$\frac{dz}{dt} = \beta V_4 - V_5 - \epsilon z$$

$$V_2 = V_{M2}\frac{x^2}{K_2^2 + x^2}$$

$$V_3 = V_{M3}\frac{x^m}{K_x^m + x^m}\frac{y^2}{K_y^2 + y^2}\frac{z^4}{K_z^4 + z^4}$$

$$V_5 = V_{M5}\frac{z^p}{K_5^p + z^p}\frac{x^n}{K_d^n + x^n}$$

How do intrinsic fluctuations interact with the “complexity” of intracellular Ca^{2+} dynamics?

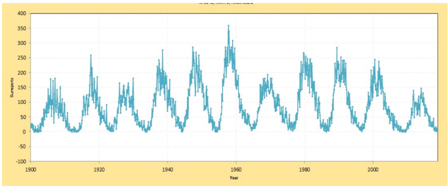
- ➢ Permutation Entropy
- ➢ Statistical Complexity

Kummer, U., *et al.* (2000). *Biophysical journal*, ***79***(3), 1188-1195.

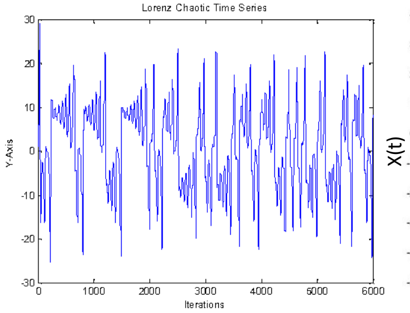
Houart, G., Dupont, G., & Goldbeter, A. (1999). *Bulletin of mathematical biology*, ***61***(3), 507-530.

Gillespie, D. T. (2000). *The Journal of Chemical Physics*, ***113***(1), 297-306.

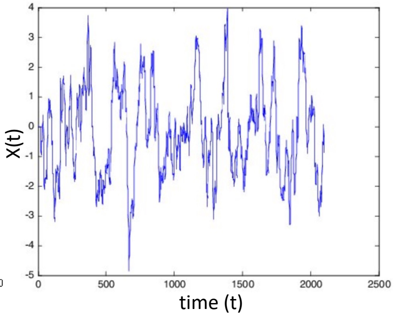
Regular (Periodic)



Chaotic

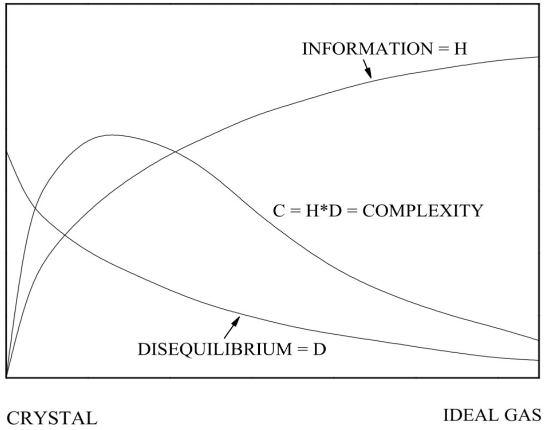


Random



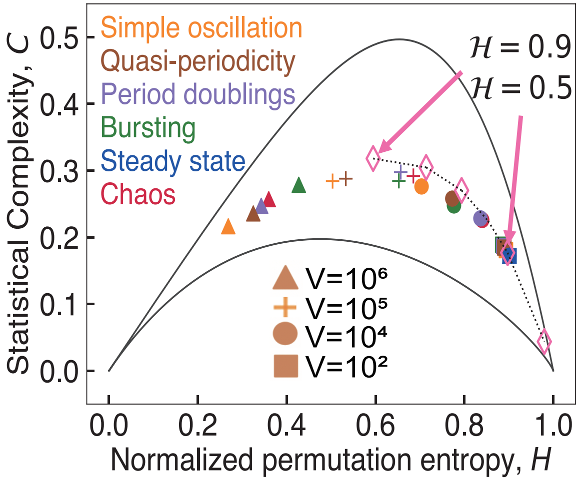
Permutation Entropy - a complexity measure for time series

$$S[P] = -\sum_{j=1}^{r!} \rho_j(\pi_j) \log \rho_j(\pi_j)$$

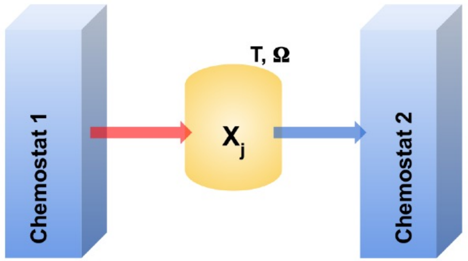


Statistical Complexity

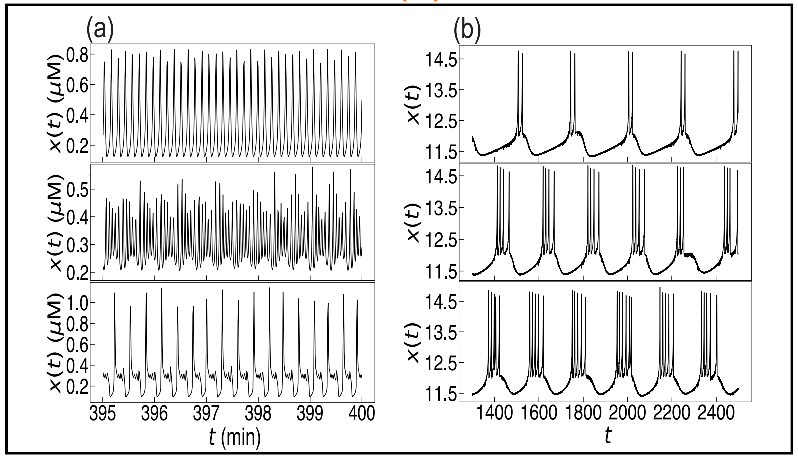
Complexity-Entropy Plane



Non-Equilibrium Chemical Reaction System



(a) Intracellular Ca^{2+} oscillation (b) Hindmarsh-Rose neuron model



Chemical Langevin Equation: $d\mathbf{x} = \boldsymbol{F}(\mathbf{x})dt + \frac{1}{\sqrt{\Omega}}\boldsymbol{G}(\mathbf{x})d\boldsymbol{W}$

Stochastic thermodynamics
- Non-Equilibrium Steady State
- Total Entropy Production Rate

Investigate dissipation in stochastic complex oscillations

Poster #3

Bandt, C., & Pompe, B. (2002) *Physical review letters*, ***88***(17), 174102.
Lopez-Ruiz, R., Mancini, H. L., & Calbet, X. (1995). *Physics letters A*, ***209***(5-6), 321-326.
Chanu, A.L., Singh, R.K.B., Jeon, & J.-H. (2024) *Chaos, Solitons & Fractals*, **185**, 115138.
Chanu, A.L., Mishra, P., Kumar, S., & Singh, R.K.B. (2024) *arXiv preprint arXiv:2406.06019*.

Dynamics Days Asia Pacific 13/YKIS2024, YITP, Kyoto University, Japan 2 July 2024