The Institute of Mathematical Sciences, Chennai

Complex Systems: The Organizing Principles of Nature & Society

CELEBRATING 50 years of CREATIVE SCIENCE 1962 – 2012

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What is Complex ?

Everything that the theoretician wishes weren't there!

The Grad student's prayer:

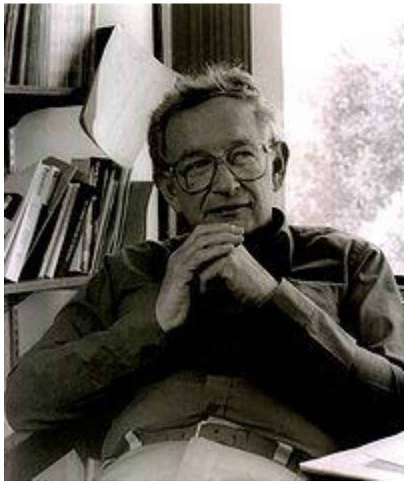
"God, please make the universe linear, stationary and Gaussian" (and we can also add "at equilibrium")

So most complex systems are

- NON-linear
- NON-stationary
- NON-Gaussian
- FAR-FROM-equilibrium

A key aspect of complex systems is the EMERGENCE of qualitatively different properties at the system-level

Emergence: “More is Different”



Philip W Anderson

P W Anderson, *Science* 1972

The elementary entities of science X obey the laws of science Y.

X	Y
solid state or many-body physics	elementary particle physics
chemistry	many-body physics
molecular biology	chemistry
cell biology	molecular biology
•	•
•	•
•	•
psychology	physiology
social sciences	psychology

But this hierarchy does not imply that science X is “just applied Y.”

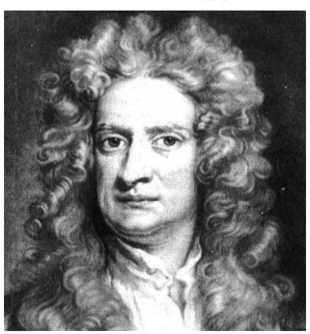
At each stage entirely new laws, concepts, and generalizations are necessary, requiring inspiration and creativity to just as great a degree as the previous one. Psychology is not applied biology, nor is biology applied chemistry.

Example: Why statistical mechanics ?

Classical Mechanics
N = 1 particle

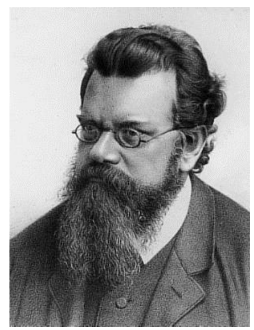
Relevant variables:
x, p

Phenomenology: Kepler's laws



Foundation: Newton's laws

Statistical Mechanics

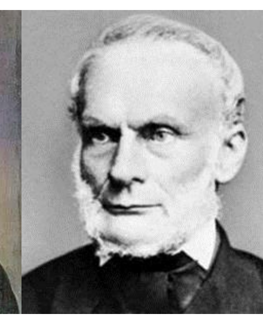


Ludwig Botzmann

Thermodynamics
N = 10^{23} particles

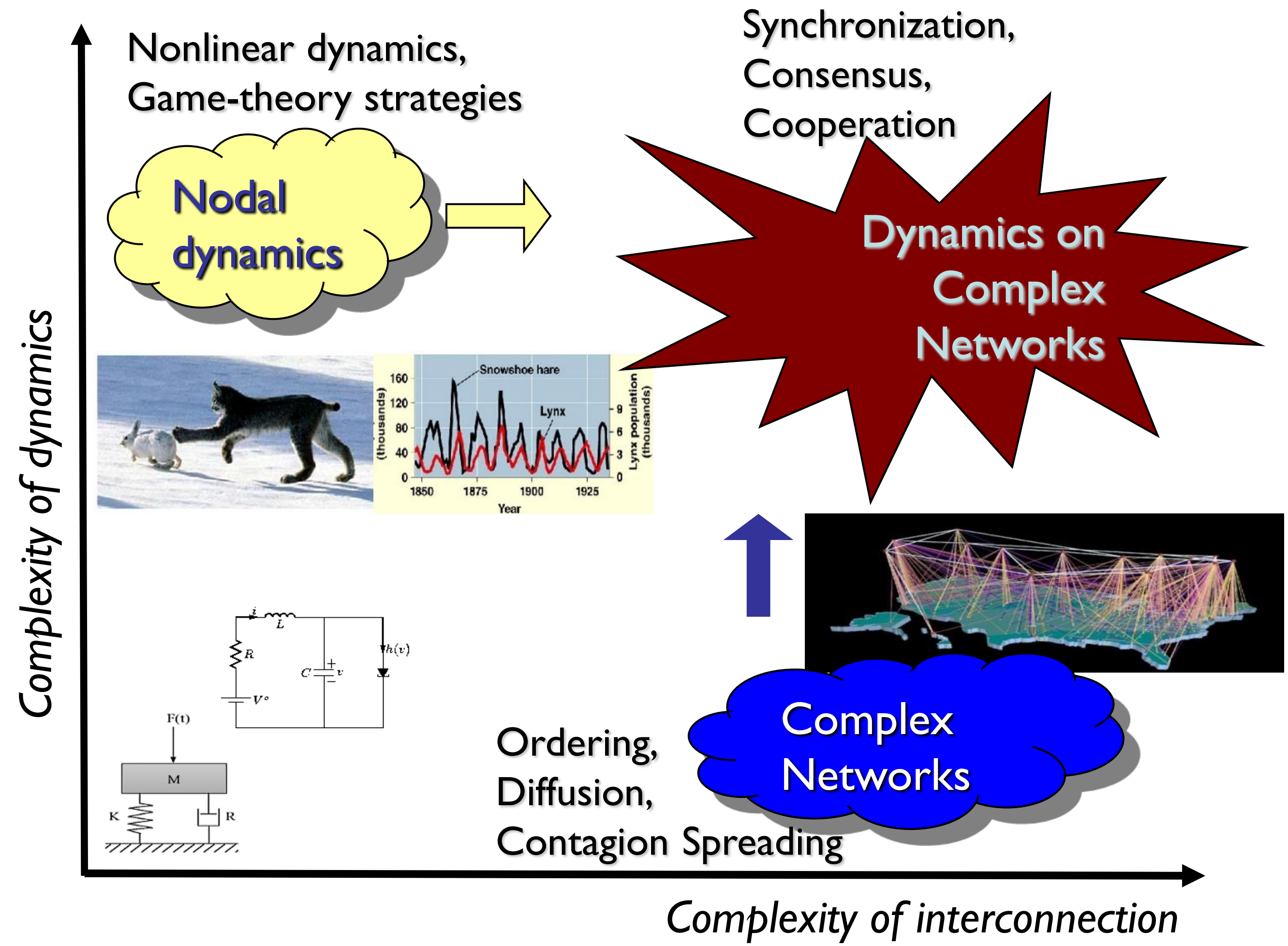
Relevant variables:
P,V,T

Phenomenology: Boyle's law etc



Foundation: The laws of thermodynamics (Carnot, Clausisus)

Problem: The components of complex systems are much more complicated than the simple particles of conventional statistical mechanics



So, do we need a new “statistical mechanics” for complex systems ?

The Quest:

Are there universal organizing principles for complex systems arising in different domains ?

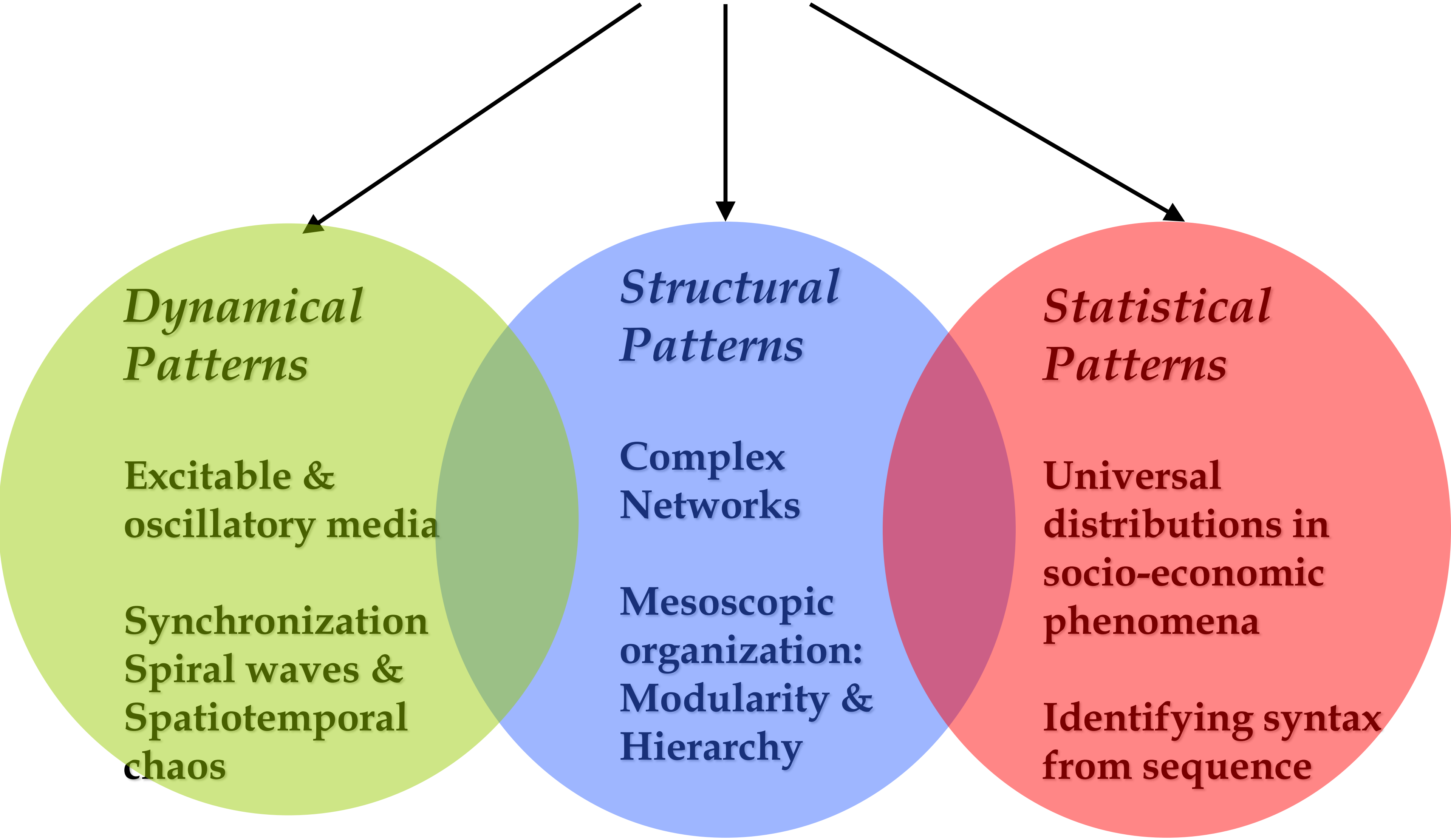
For example,

- can similar principles be at work behind the design of signaling machinery inside the cell and the design of networks of neurons in the brain ? Why networks rather than pathways ?

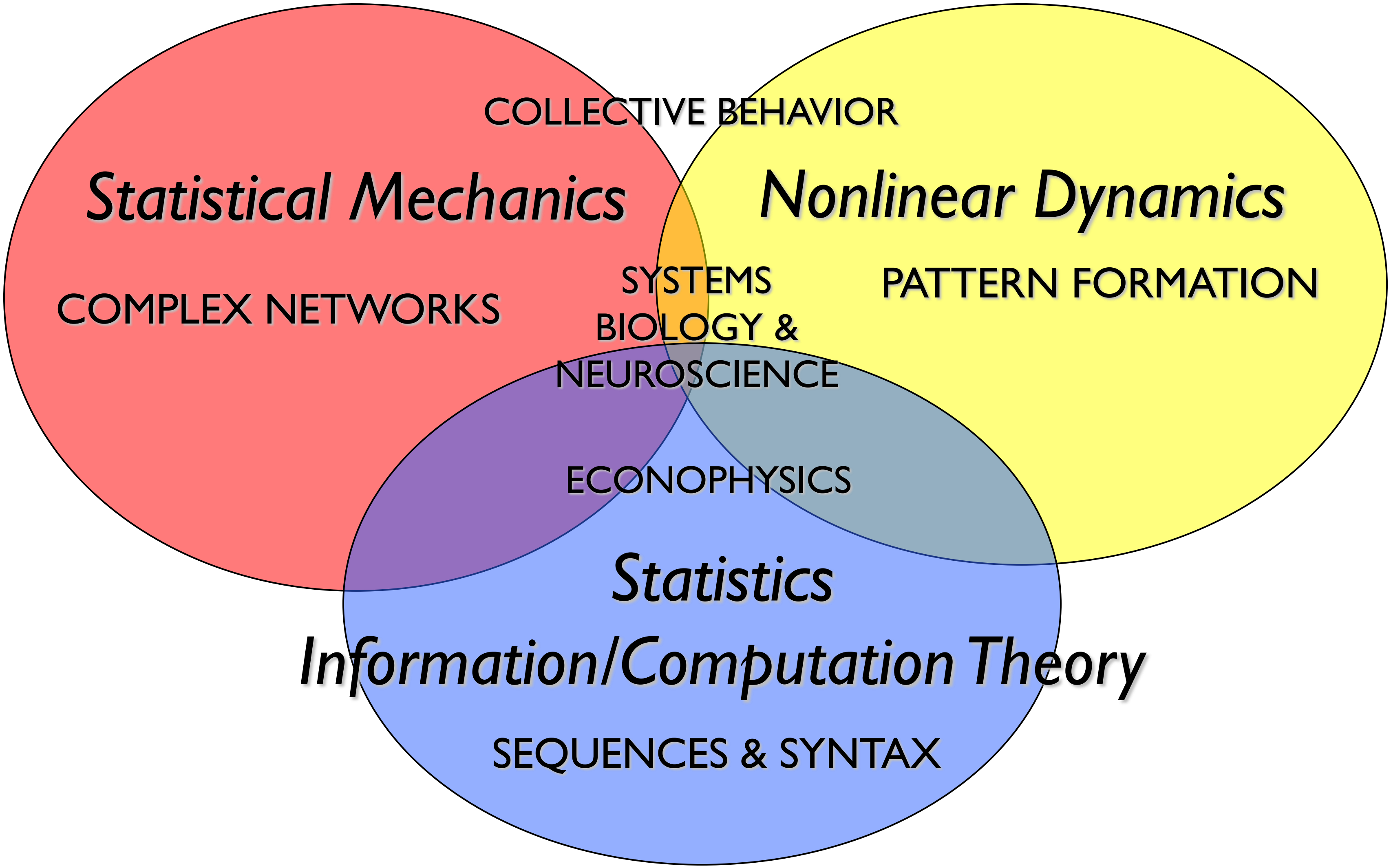
- can the process of cascading extinctions leading to ecosystem collapse be used to explain the large-scale failure of man-made systems such as electrical power grid ? What are the conditions that increase the probability of network-wide crashes, as in the recent banking system collapse ?

The Theme

Analyzing patterns in complex systems



The Tools


COLLECTIVE BEHAVIOR
Statistical Mechanics
Nonlinear Dynamics
COMPLEX NETWORKS
SYSTEMS
BIOLOGY &
NEUROSCIENCE
PATTERN FORMATION
ECONOPHYSICS
Statistics
Information/Computation Theory
SEQUENCES & SYNTAX

What can Complex Systems give back to Physics ?

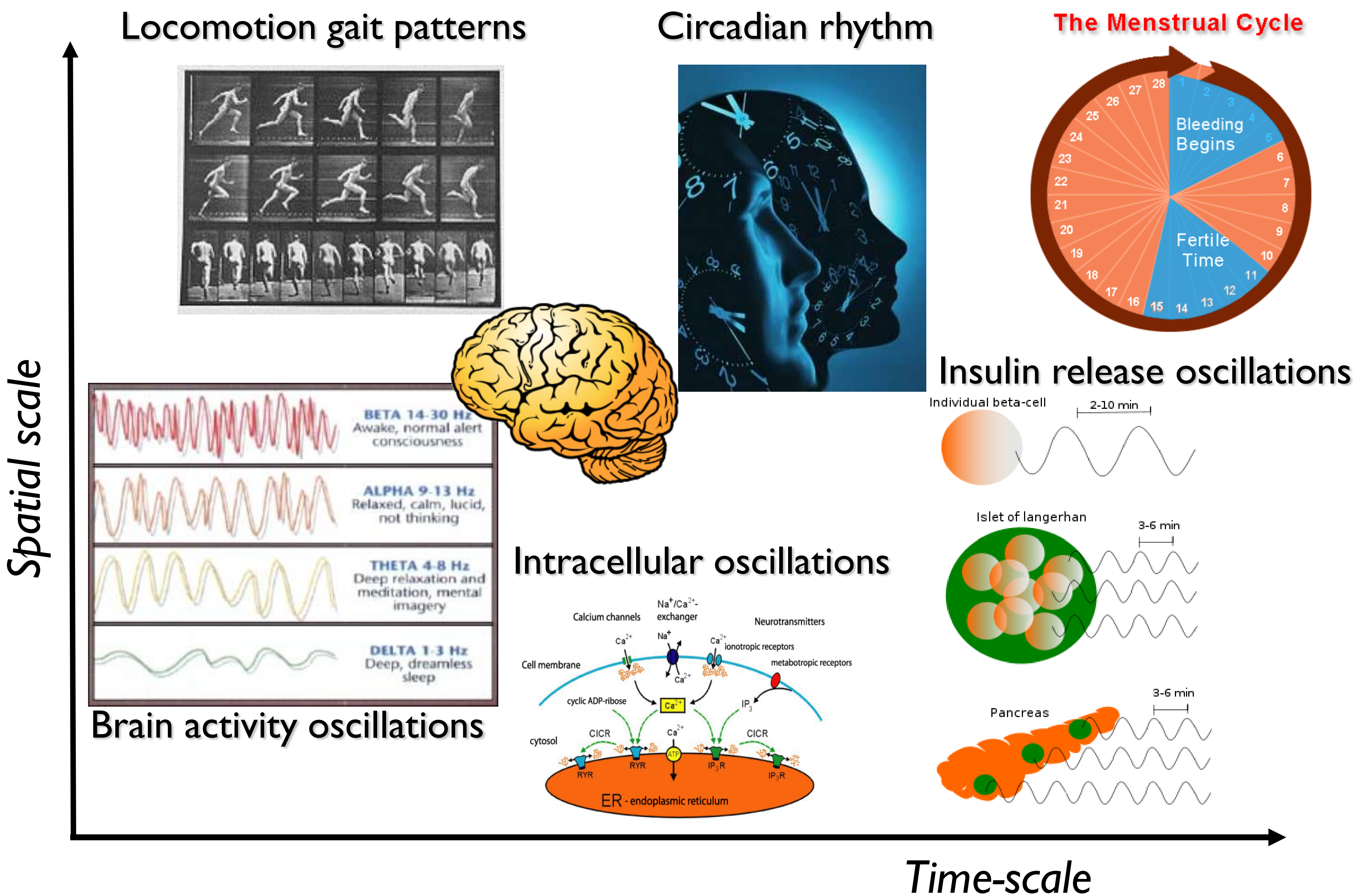
Is there a complexity transition ? If you add together enough number of interacting elements will you always eventually end up with emergence of complexity ("BOOM") ??!!

Can contribute to

- Statistical Mechanics: Non-equilibrium Systems
- Even kinetic theory throws up surprising results after a detour through complex systems
- Nonlinear Dynamics: Characterization of spatiotemporal phenomena
- While low-dimensional systems well understood, what about the bifurcations or routes to chaos of spatially extended systems ?

Dynamical Patterns

"Clocks" in nature: span many space & time scales



Synchronization of spatially distributed oscillations is ubiquitous in nature…

- Pacemaker cells in the heart
- β-cells in the pancreas
- Long-range synch across brain during perception
- Contractions in the pregnant uterus
- Menstrual cycles
- Rhythmic applause
- Pedestrians on a bridge falling in step with the swinging motion of bridge

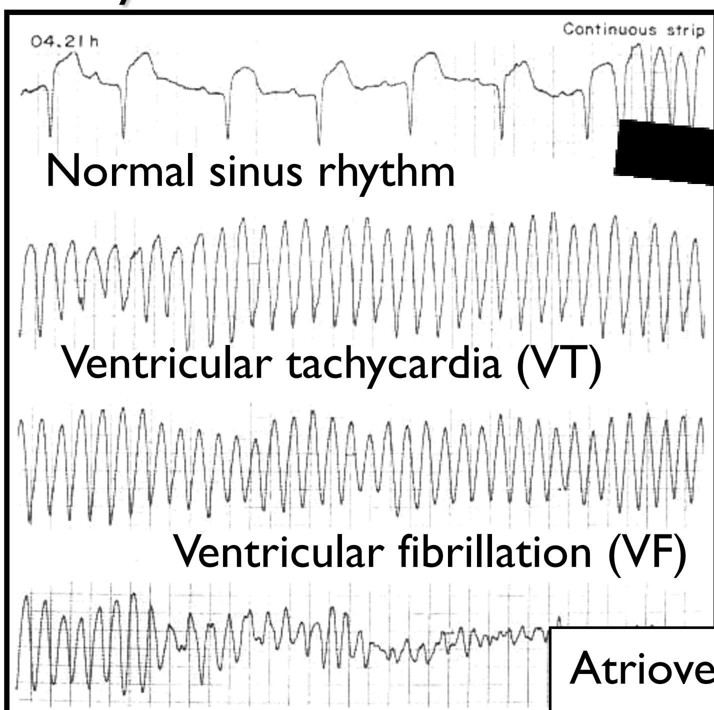
Male Fireflies flashing in unison

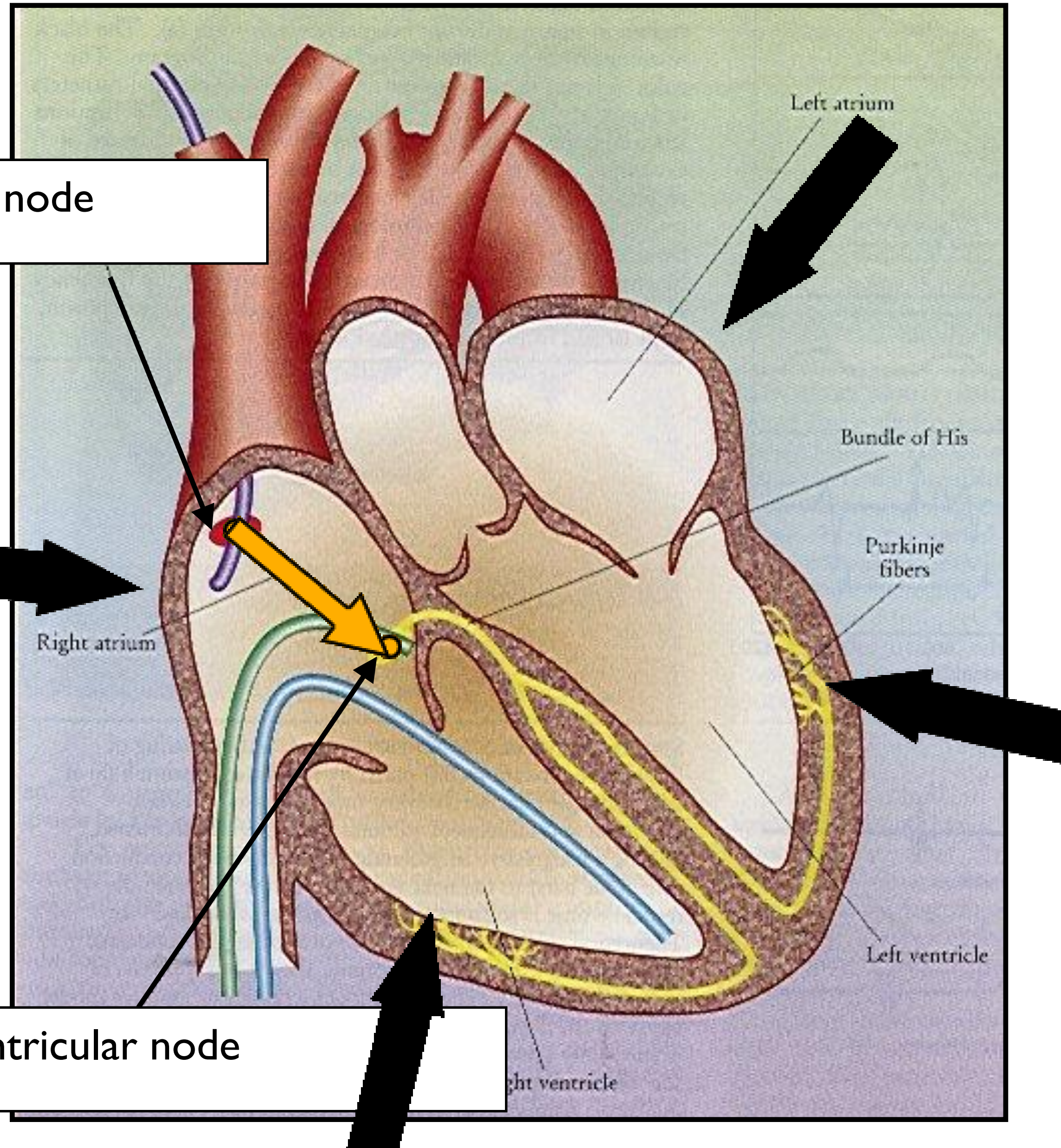
Each insect has its own rhythm – but the phase alters based on seeing its neighbors lights, bringing harmony

… and vital for the proper functioning of many biological systems

Example:

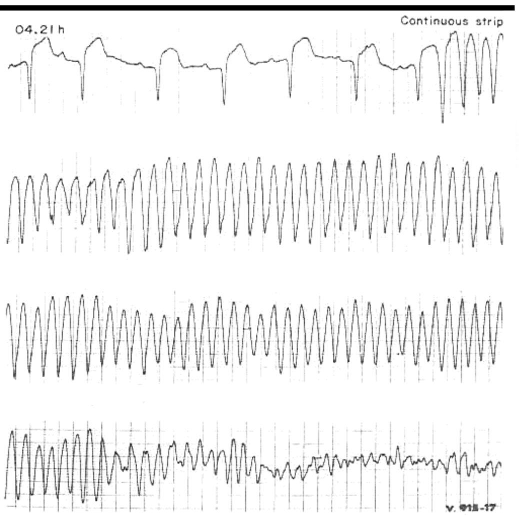
Disruption of coherent collective activity in heart can result in life-threatening arrhythmia

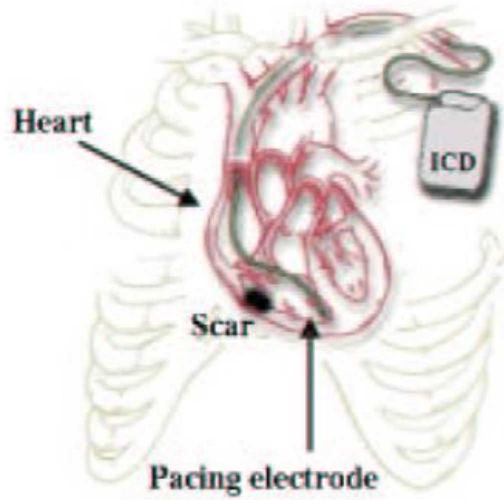


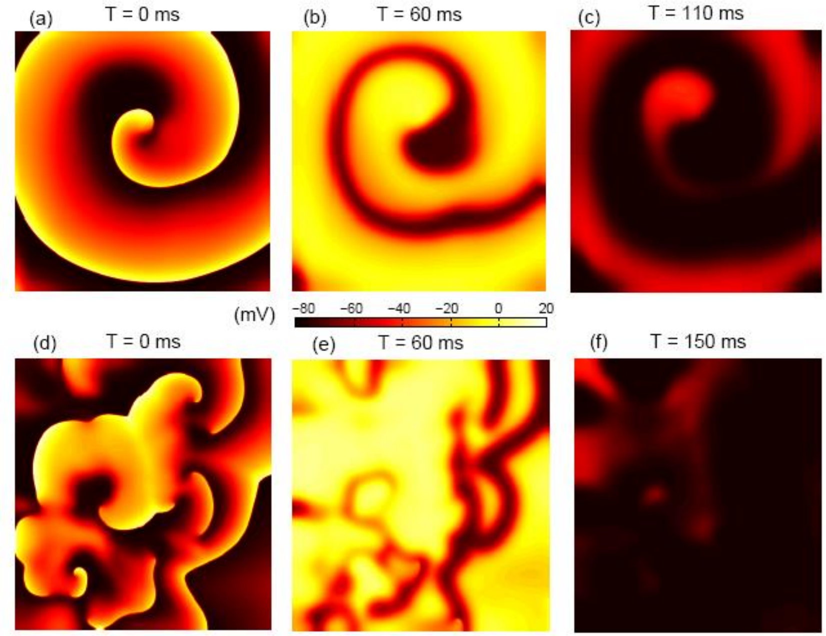


Understanding the genesis of Cardiac Arrhythmias

Arrhythmia: Life-threatening disruption in natural rhythmic functioning of the heart

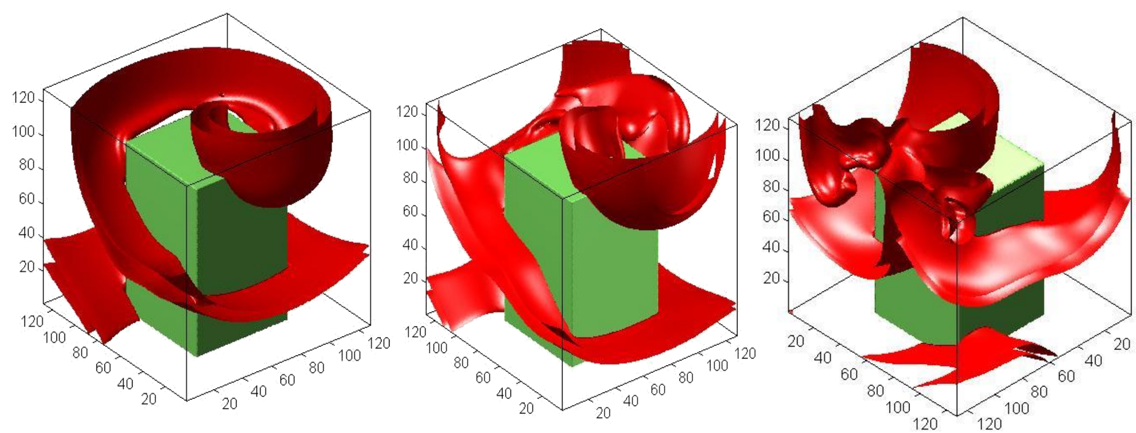






Can only be treated through application of large electrical shocks to the heart – but how much is enough ?

Are scar tissues and other inexcitable regions in the heart pro-arrhythmic or prevent the initiation of life-threatening fibrillation ?



S Sridhar and Antina Ghosh

For many processes

No centralized coordination

agency have been identified as yet

Ordering without centralized coordination

Local interactions can lead to order without an organizing center in complex systems

Wikipedia

Wikipedia

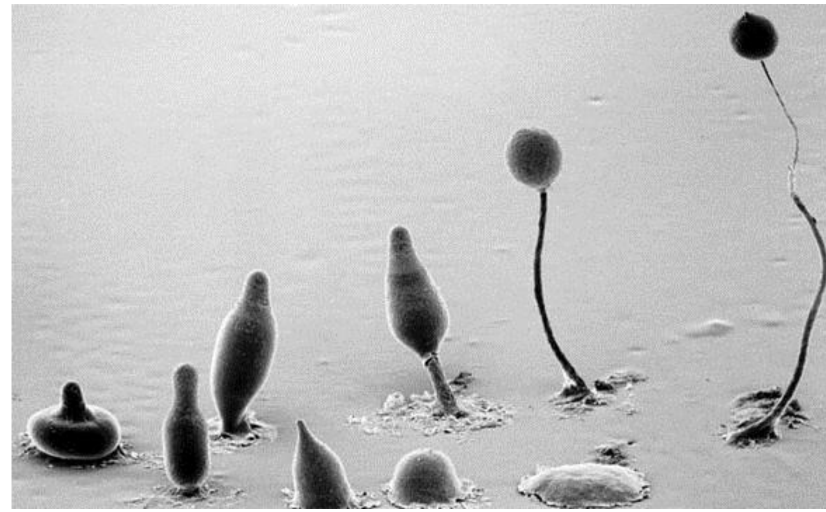
Examples:
flocking and swarming

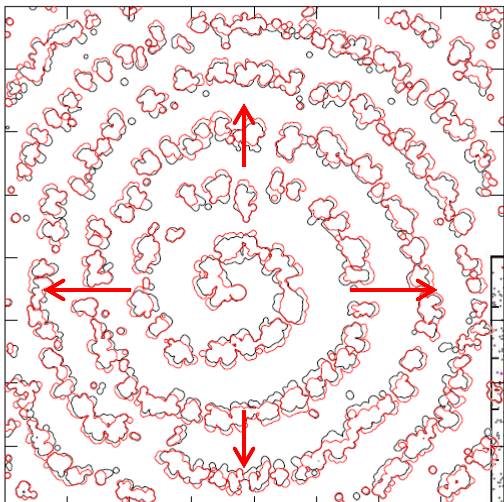
Patterns in cellular assemblies

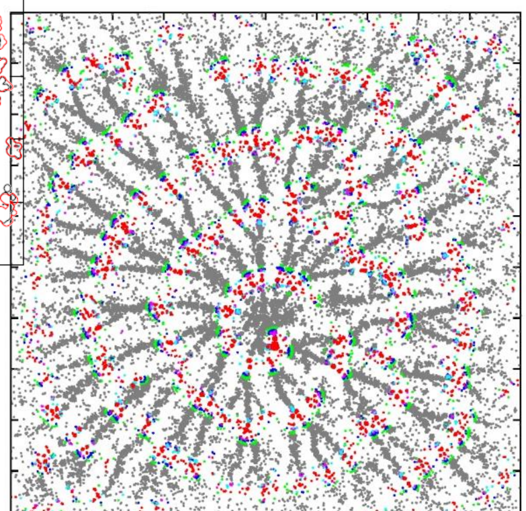
Populations of uni-cellular organisms communicate and coordinate their activities resulting in appearance of spectacular patterns

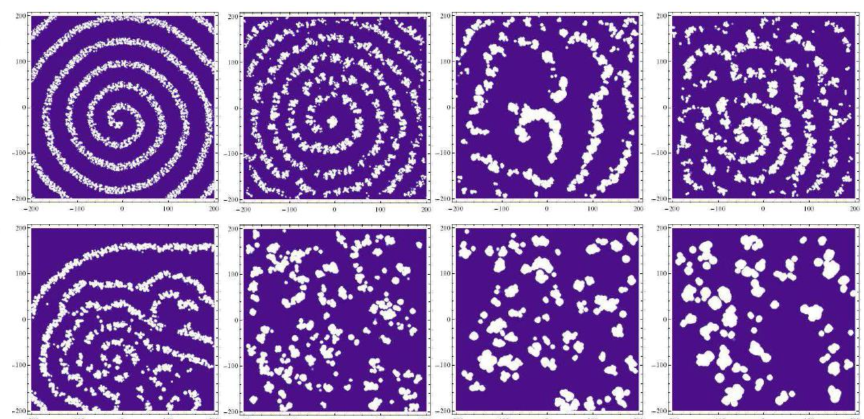
Example: Social amoebae (e.g., Dictyostelium) send out cAMP waves during starvation conditions to aggregate – resulting in spiral waves and streaming patterns

betatest.dictybase.org







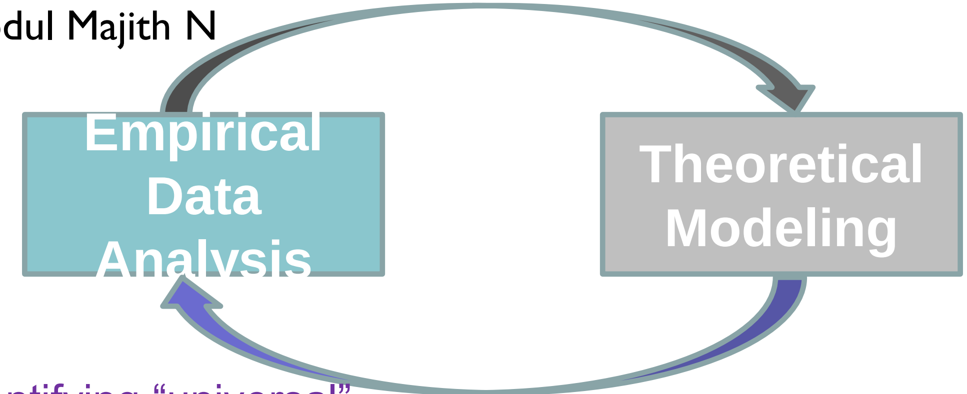


Can be understood in terms of simple excitable media models with mobile agents

Trilochan Bagarti

Example: Modeling the dynamics of Indian urban traffic

Abdul Majith N



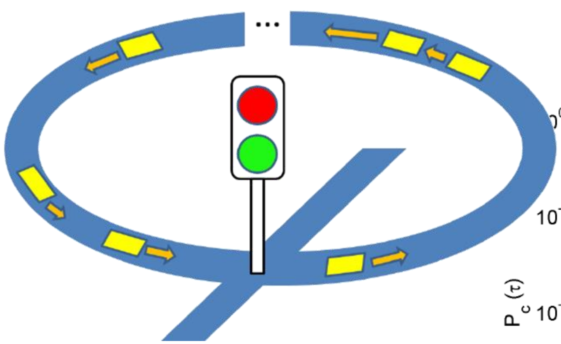
Identifying "universal" collective patterns that are independent of specific local conditions

Explaining collective patterns using "robust" models not sensitively dependent on specific details

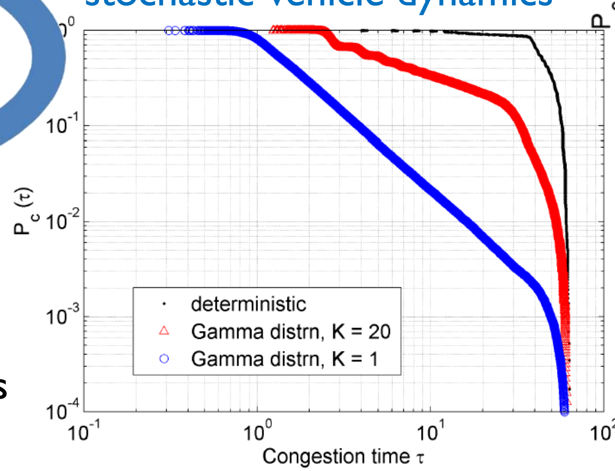
Micro-Model:

Traffic dynamics at an intersection controlled by signal

A novel kinetic Monte Carlo method for simulating stochastic vehicle dynamics



For simplicity consider a single-lane road that has an intersection where traffic is controlled by a signal

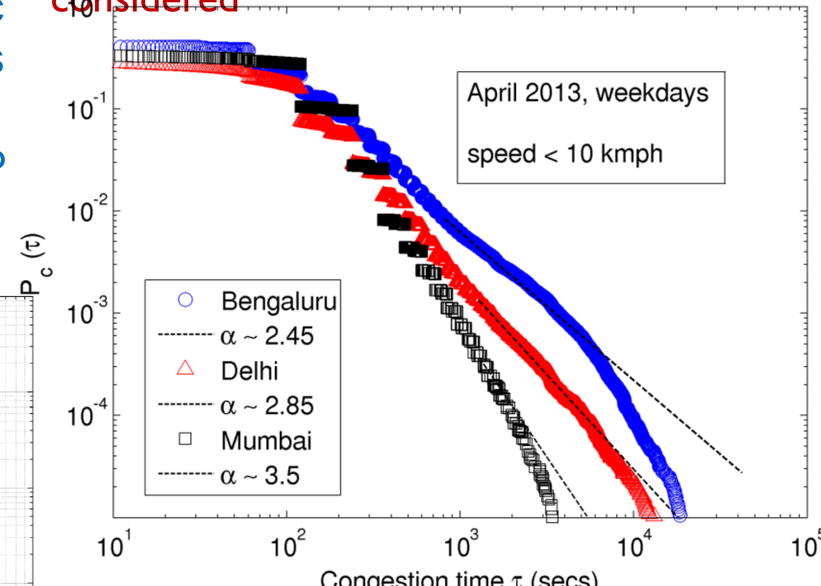


Macro-Patterns:

City wide traffic statistics inferred from "probe" vehicles

Data: GPS traces of ~1000 taxis from Bengaluru, Delhi and Mumbai for several months in 2013-14

Universality: Congestion time distributions of different cities exhibit a power law – albeit with different exponents, almost invariant over period considered



Model reproduces the power law behavior of congestion time distributions

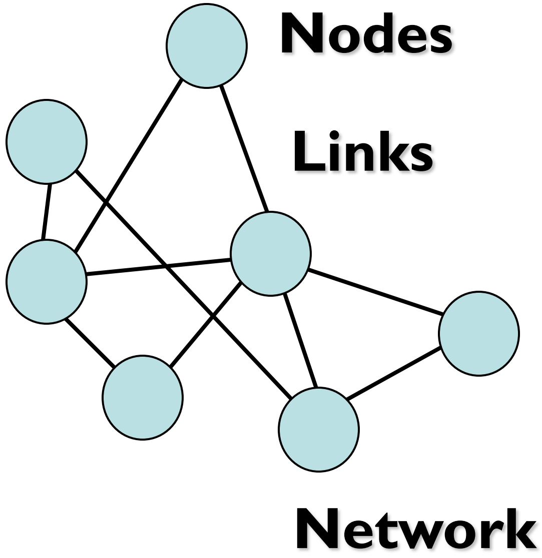
Structural Patterns

Complex Networks

Components = Nodes

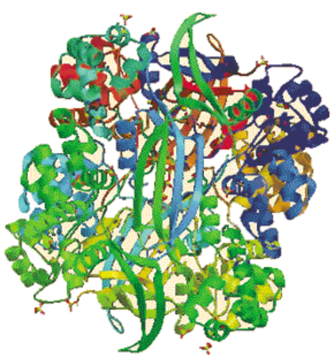
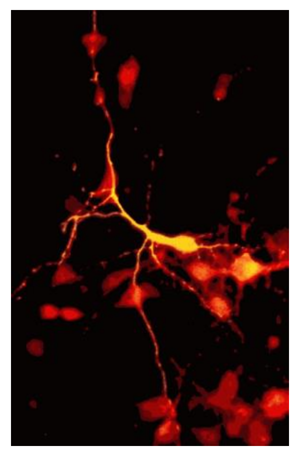
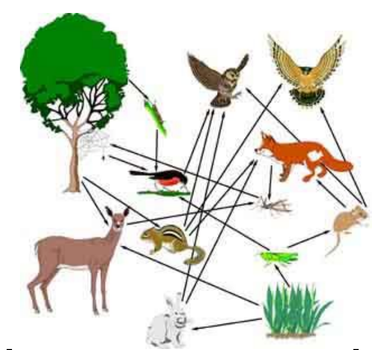
Interactions = Links

System = Network



Ubiquity of Networks

Networks appear at all scales

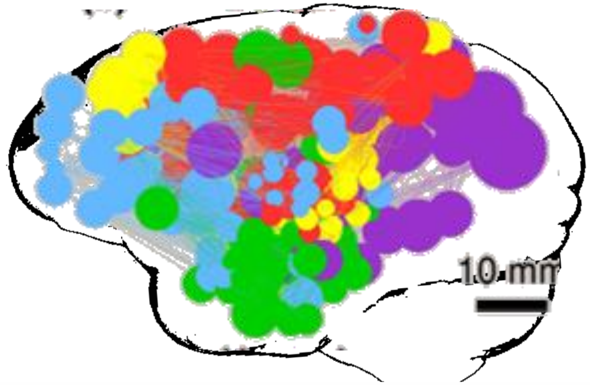
Proteins	Intra-cellular signalling	Neuronal communication	Epidemics	Food webs
				

10^{-9} m | 10^{-6} m | 10^{-3} m | 1 m | 10^{3} m | 10^{6} m

Molecules	Cells	Organisms	Populations	Ecologies

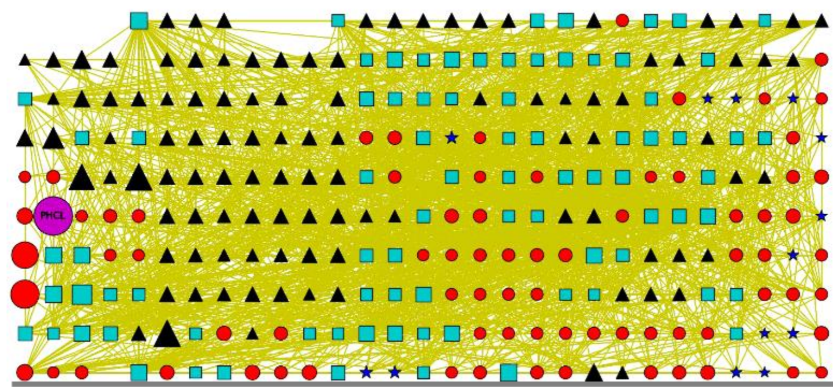
Simulating the collective activity of the Brain

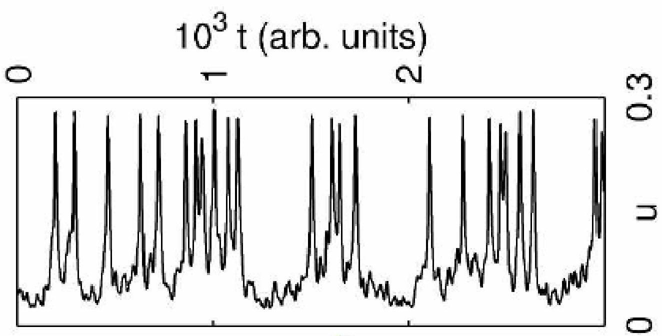
Modeling the Macaque brain as a network of brain regions



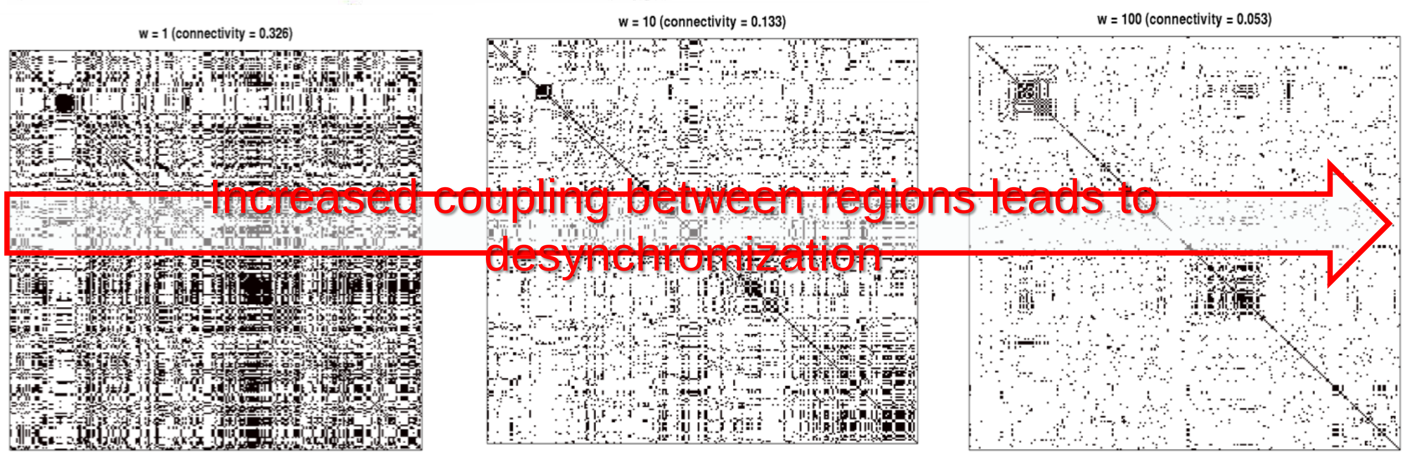
Collaborators: Anand Pathak, Shakti N Menon, Raj K Pan and Sitabhra Sinha (IMSc); Nivedita Chatterjee (SN Chennai)

A biologically realistic neural network simulator for the entire somatic nervous system of the nematode *Caenorhabditis elegans*





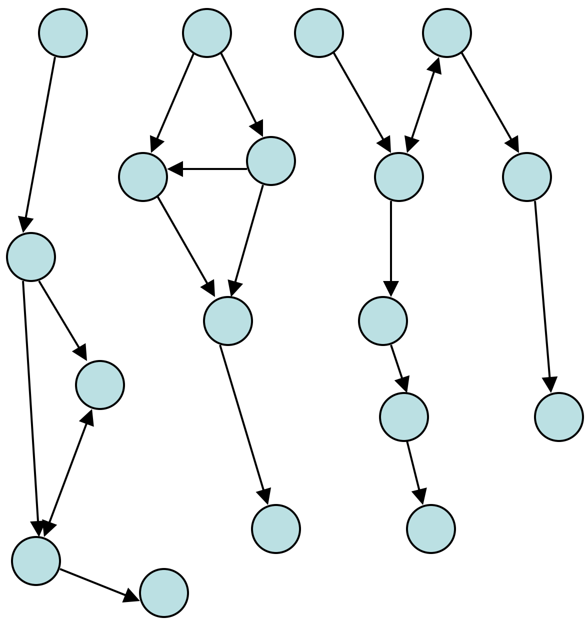
Collective dynamics yields realistic EEG-like traces

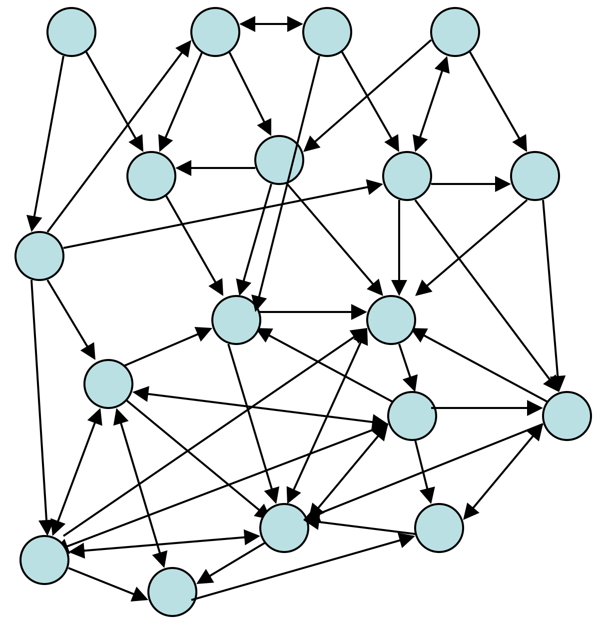


Can explain higher connectivity in functional networks reconstructed from EEG recordings of fatigued subjects

Pathways vs Networks

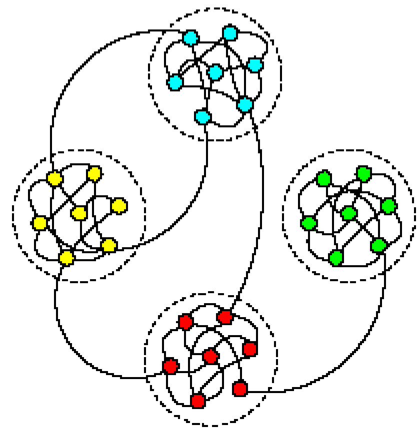
Why did Nature opt for Networks ?

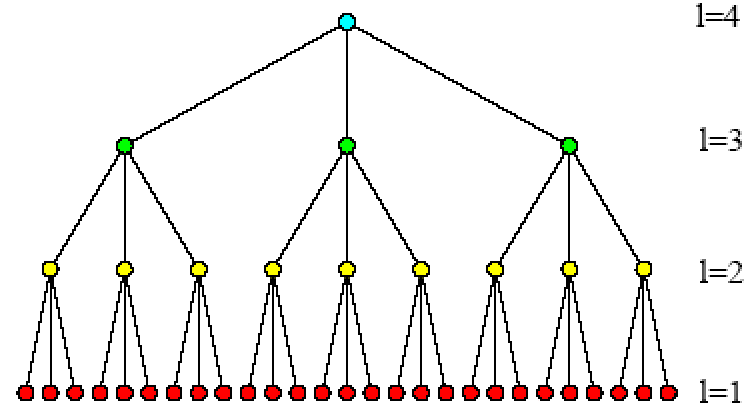




- Why did a central nervous system (brain) evolve at all instead of a nervous system equivalent to a collection of reflex arcs ? Also relevant for cell-signalling

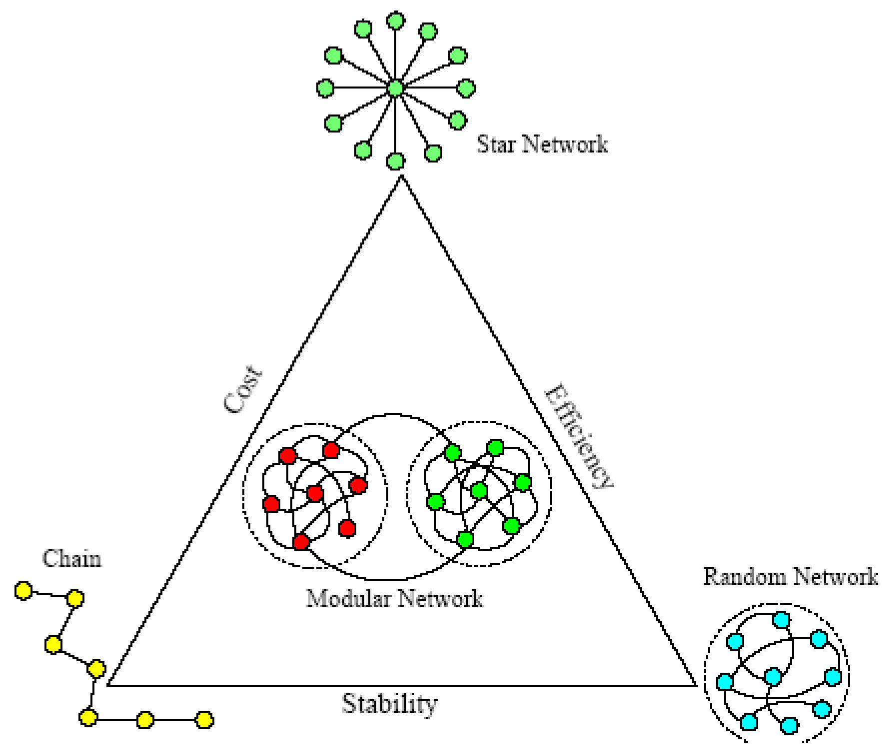
Evolution of Complex Networks





The mesoscopic organizational features of networks

- modular structure
- hierarchical levels
- core-periphery organization

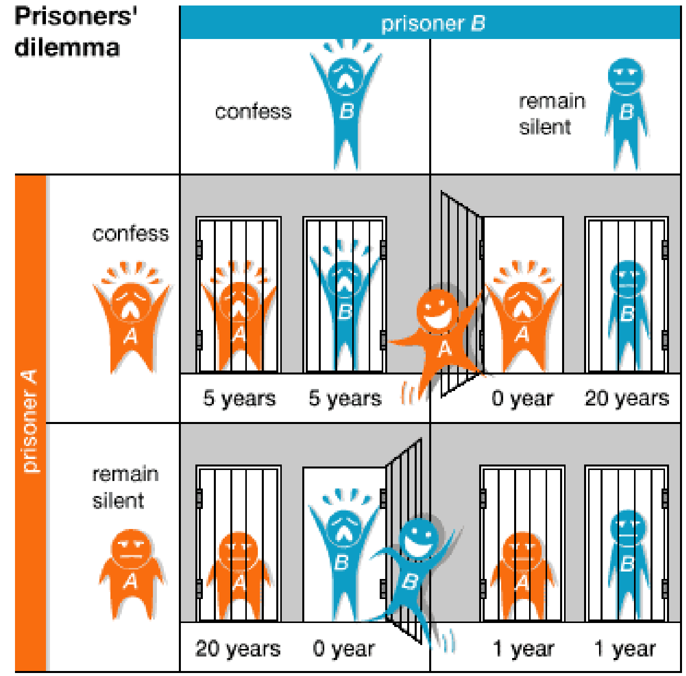


Can we explain their emergence as a result of optimizing between different structural & dynamical constraints ?

Co-ordination in complex networks

How can co-operation and modular structure coevolve ?

Game theoretic strategies by agents interacting on networks



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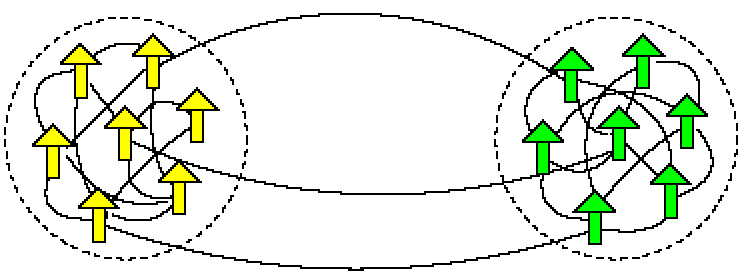

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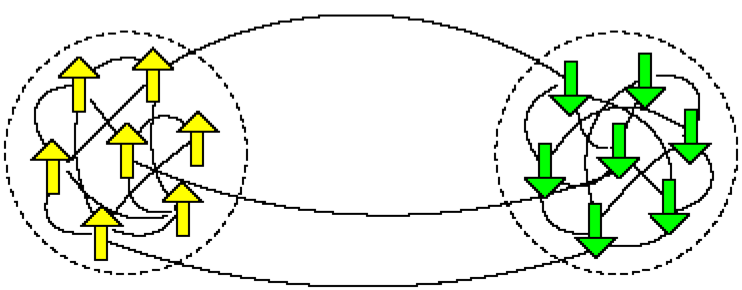


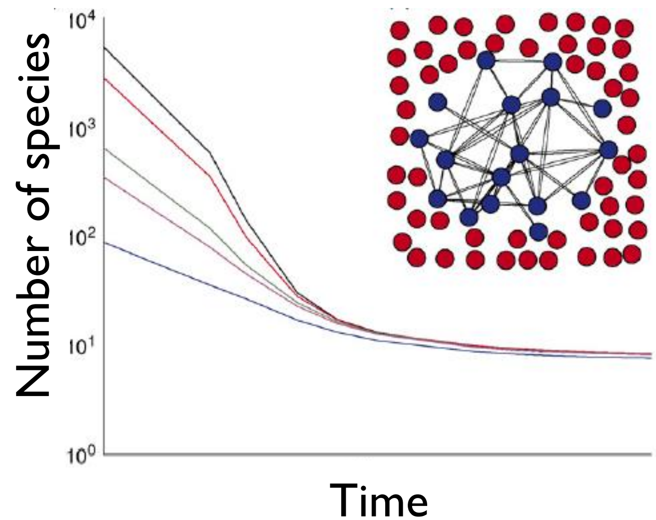
Collective behavior and Communities:

Spin dynamics on modular structures

Robustness of Complex Systems

How do complex systems "rebound" from major perturbations ?

Networks with nonlinear dynamics are *non-extensive* systems: evolve to configurations that are independent of initial values

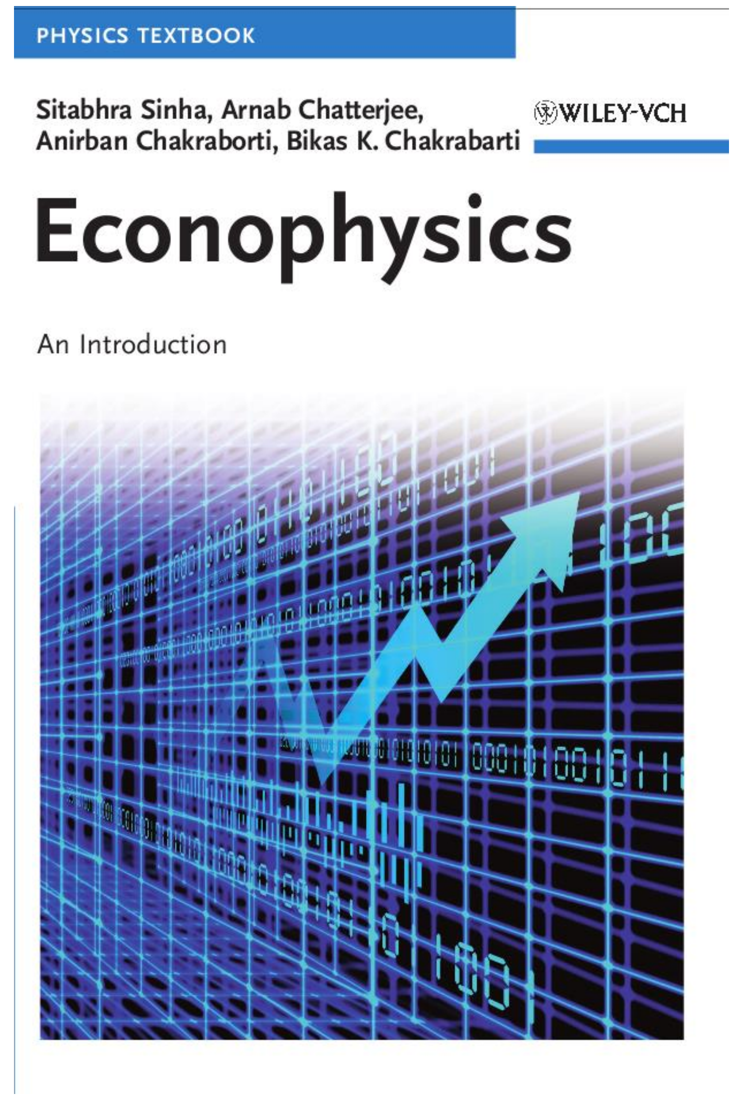


Mt St Helens Eruption

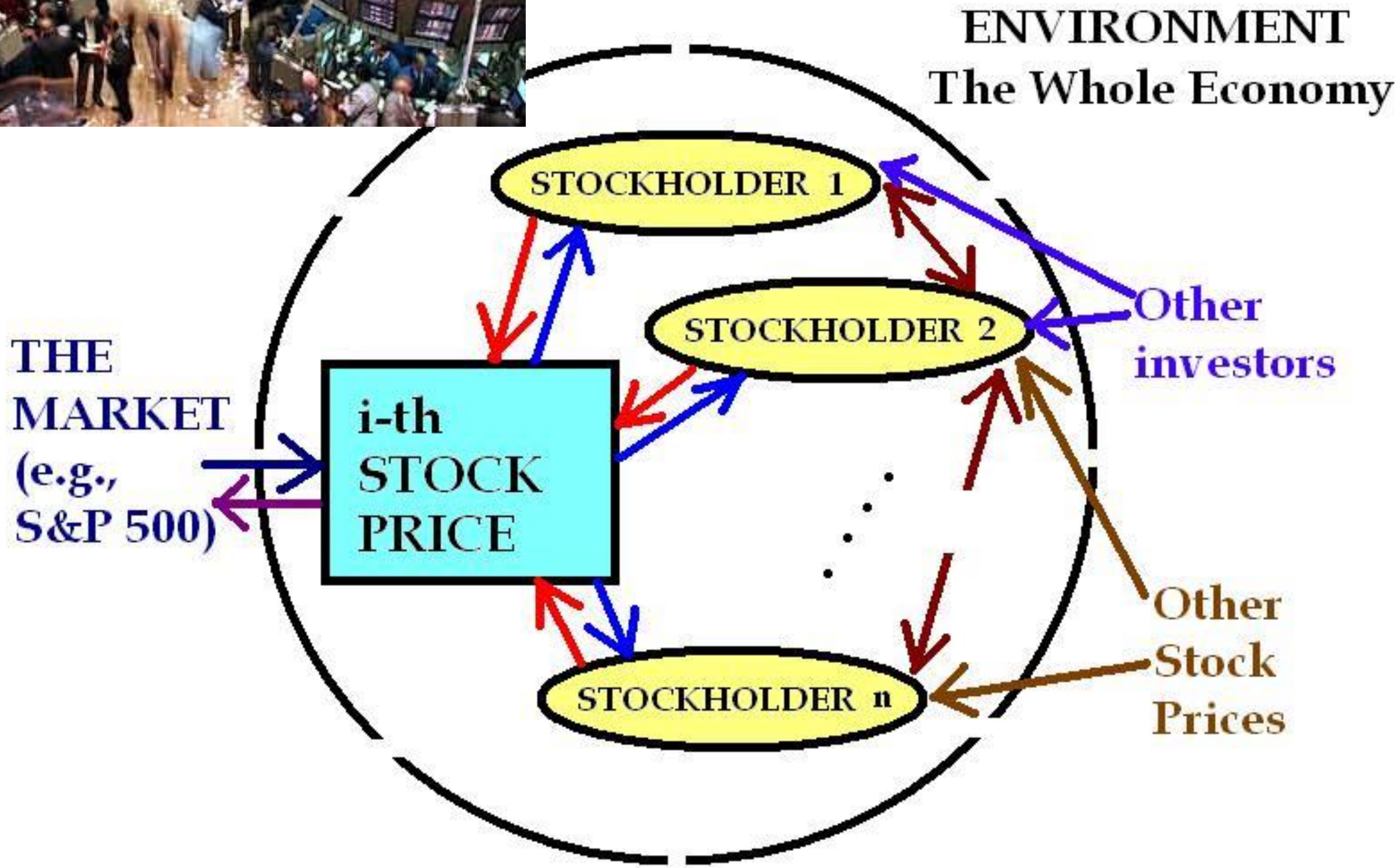
Statistical Patterns

Theories for the organizing principles of complex systems do not only apply to biological systems but also…

e.g., in economic systems

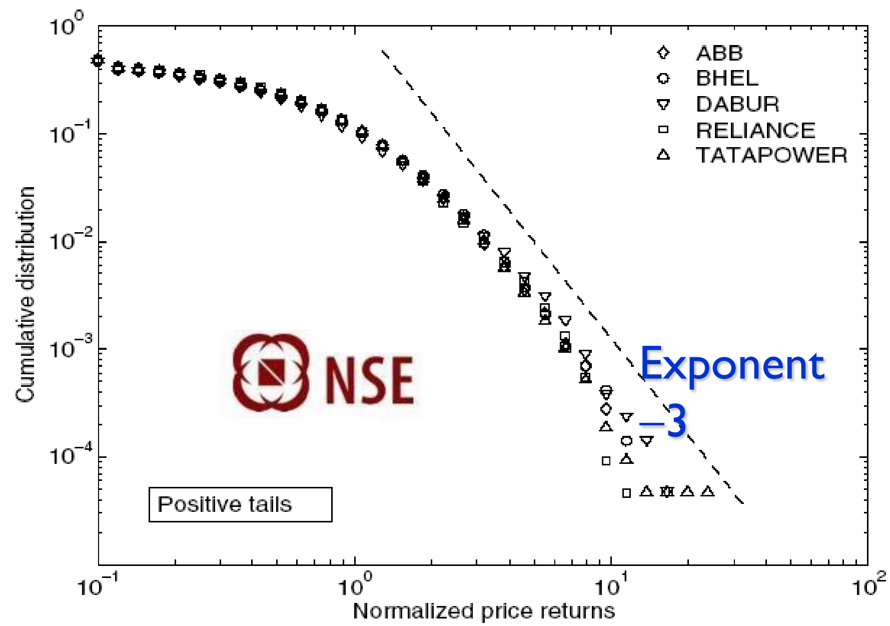


The Market according to Physics



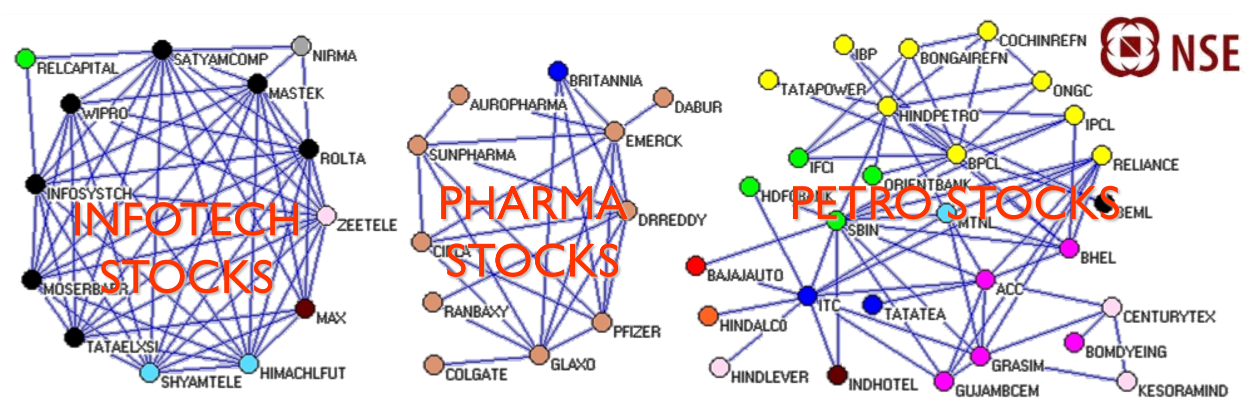
Financial Markets ≡ Complex system of interacting stocks

Universality (?) of the distributions of market variables : “Inverse cubic” power law tail of fluctuations distribution



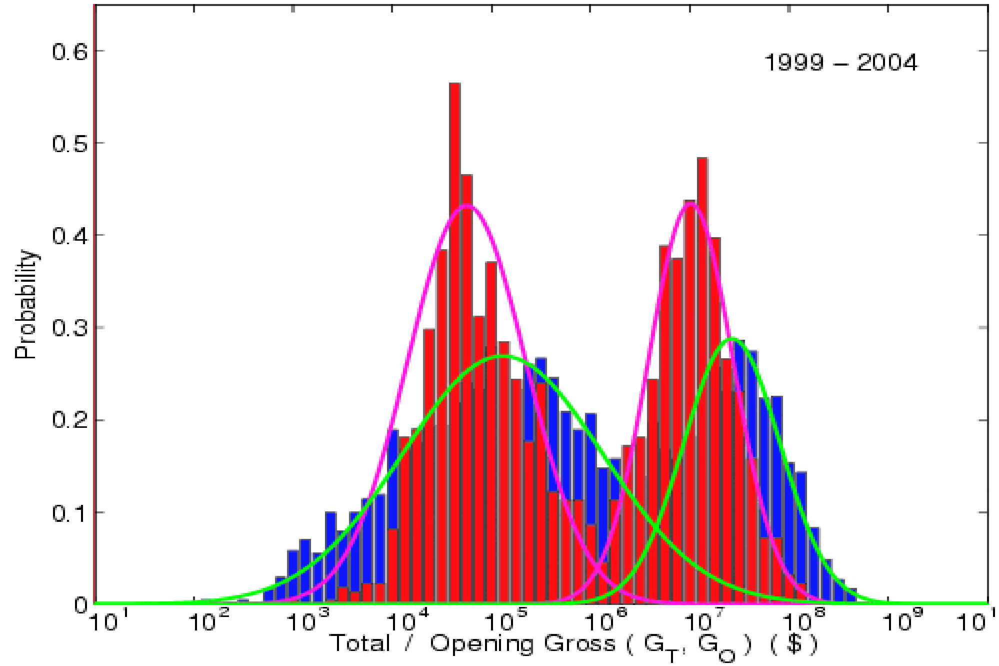
Cross-correlation of stock movements:

First picture of how network of stock interactions develop

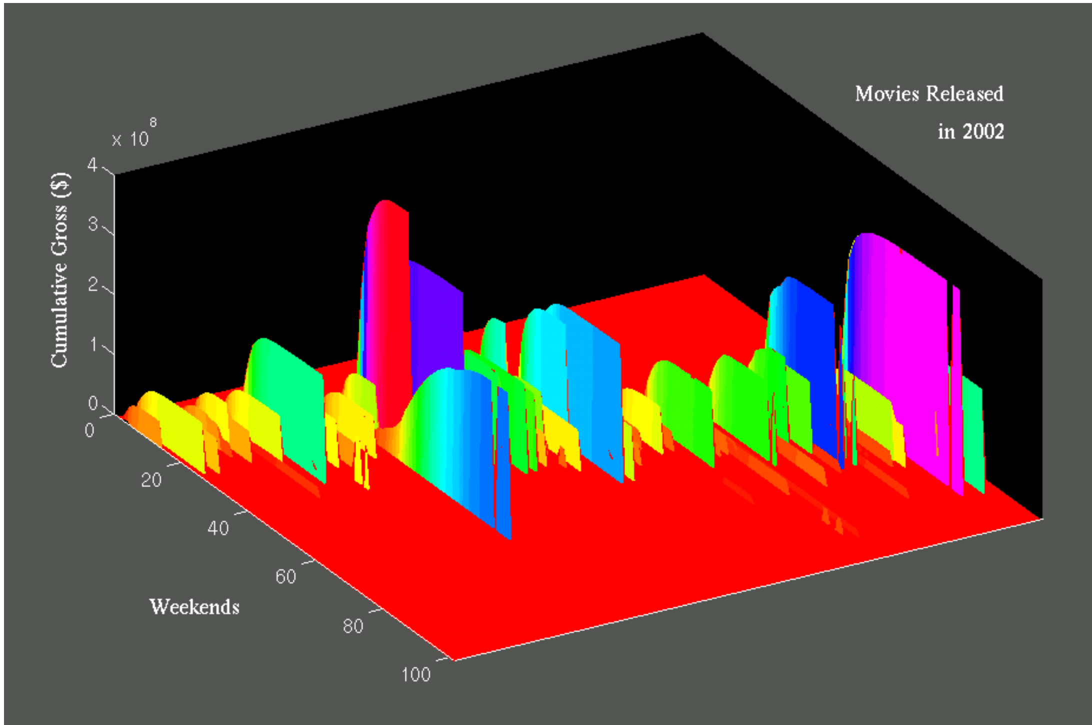


Sociophysics

Emergence of a popular product / idea ≡ self-organization of collective behavior among interacting agents



Universal features of popularity dynamics: popularity for several product types (including movies) have bimodal, log-normal distributions and power-law decay with time



Patterns in Symbolic sequences

How to identify lingusitic writing ?

What is language ? A system of syntactic communication capable of encoding ideas of arbitrary complexity

Syntax = Compositionality + Recursion

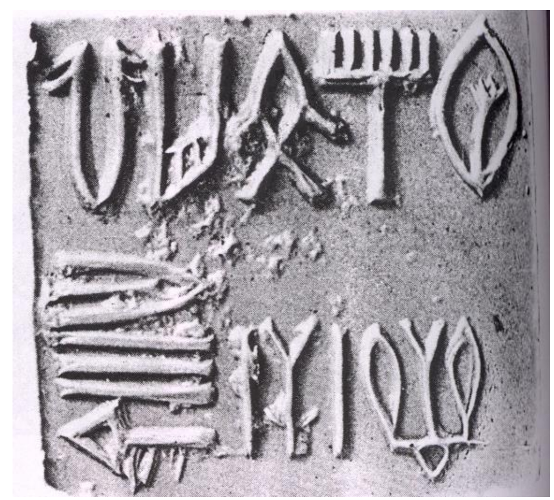
("words/letters") (embedding)

Test for a sign system as writing:

Look for syntactic structure in a symbolic string

Segmentation of sign sequences: Does it reveal frequently used sign clusters ? Are they placed in specific arrangements ?

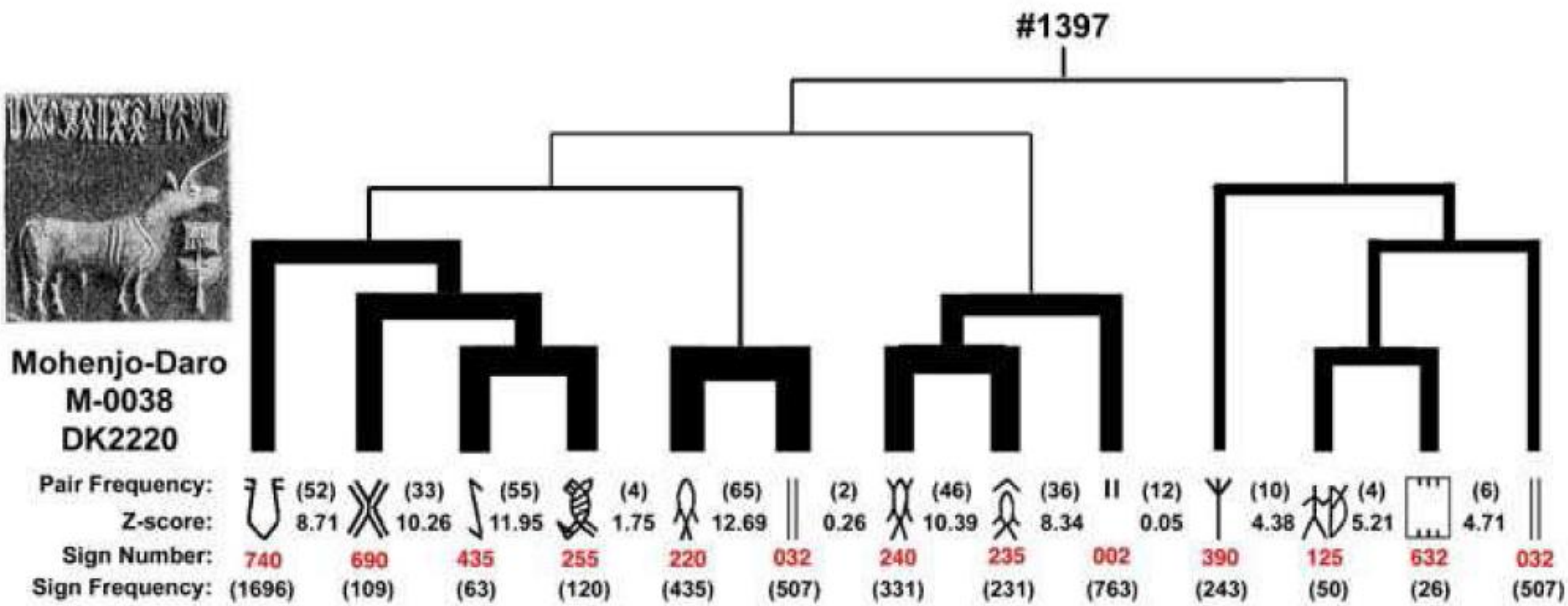
The undeciphered Indus symbolic sequences



From Mahadevan, 1977

Segmentation using significant pairs

Successively merge pairs according to decreasing z-score

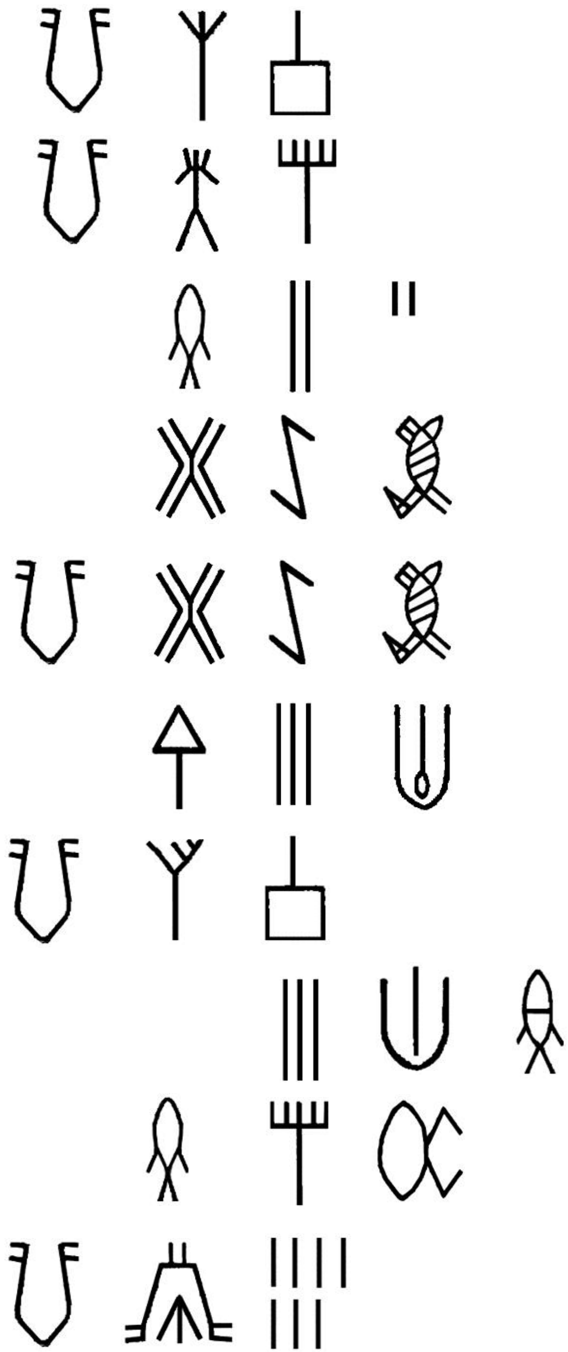


M Izhar Ashraf

An Indus "Lexicon"

By carrying out segmentation separately for corpus of inscriptions from Mohenjodaro (MOH) and Harappa (HAR), frequently used motifs of sign clusters identified

By aligning the motifs, similar groups of signs can be identified – e.g., signs possibly representing numbers

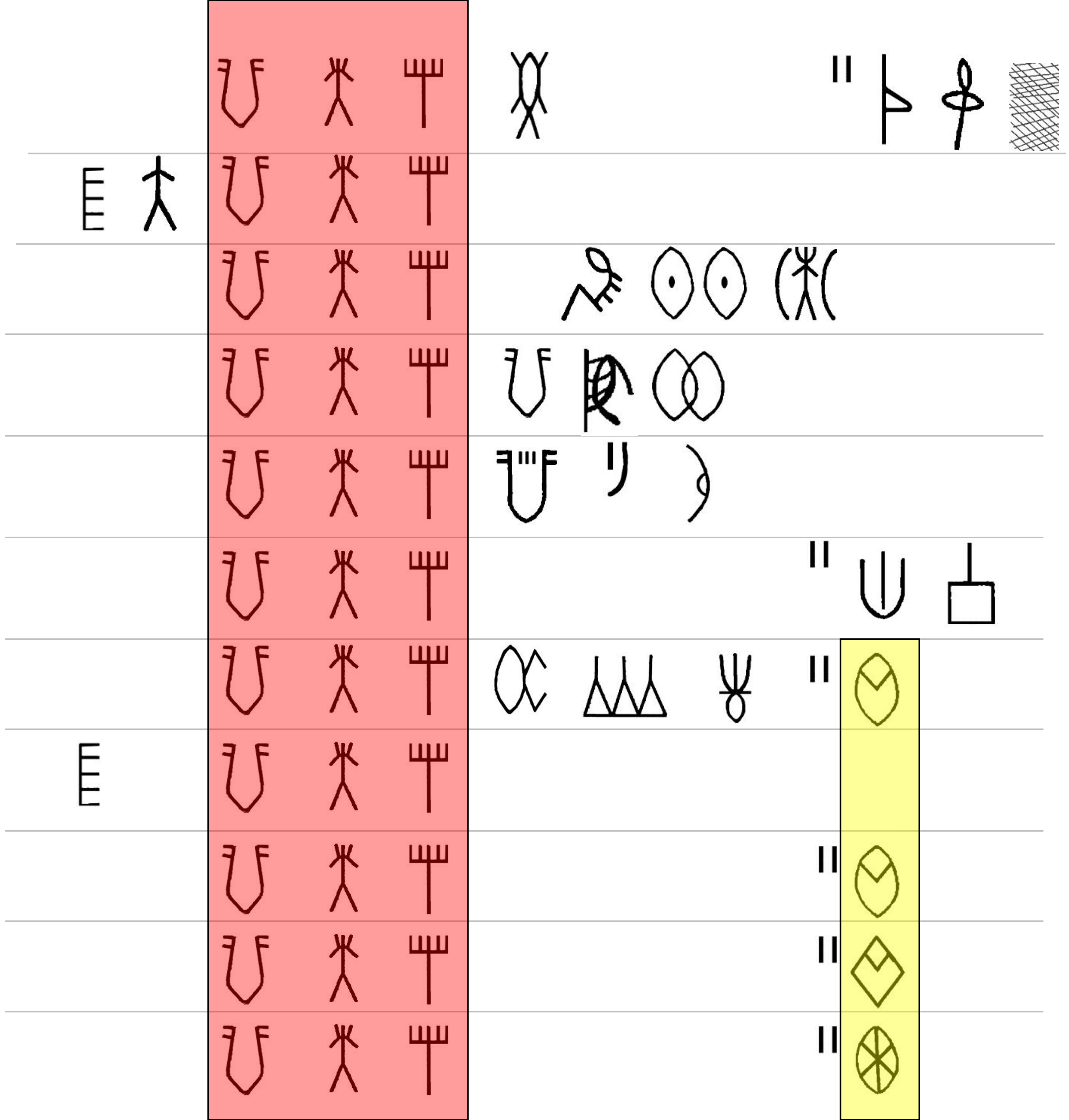


MOH	HAR	OTH	TOT
15	12	4	31
20	2	1	23
16	3	2	21
14	5	1	20
14	3	1	18
7	6	1	14
6	7	0	13
11	2	0	13
10	3	0	13
7	2	1	10

Multiple Sequence Alignment

Using frequently used "words" from the Indus lexicons as anchors to align inscriptions – insert gaps for better match betn sequences

Helps identify groups of signs with similar form/function



Towards an Indus "grammar"

The alignment can help in identifying syntactic rules

Example of a grammar:

$S \rightarrow S1 + S2$

$S1 \rightarrow S1 + S3, \{a, b\}$

$S2 \rightarrow \phi, S2 + S4, \{c, d, e\}$

$S3 \rightarrow \{f, g\}$

$S4 \rightarrow \{j, k\}$

THANKS

Complex Systems Group Homepage
www.imsc.res.in/~shakti/complex_home.html