A Complex Systems Approach to Study Human Nature

An introduction to the analytical toolbox of Complexity Science

❄️🤦🏾🌿Why Complexity Science? 🌪️🌊🤦🏻 10:00 - 11:00

I. Introduction to the mathematics of change 11:00 - 12:30

- Modelling (nonlinear) growth and Deterministic Chaos
- Predator-Prey dynamics
- Basic timeseries analysis

II. Quantifying Recurrences in State Space 13:30 - 15:30

- Takens' Theorem and State-Space reconstruction
- Recurrence Quantification Analysis of continuous and categorical data
- Cross-Recurrence Quantification Analysis of dyadic interaction

III. Fractal Scaling, Network Topology and Early Warning Signals 15:30 - 17:00

- Scaling phenomena in time and trial series of human behaviour and physiology
- Small-world and Scale-free networks
- Early Warning Signals in clinical interventions

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Complexity Workshop Köln
12-05-2017

Radboud University Nijmegen

What kind of science is cognitive- behavioural- neuro- social- life- science?

"If Psychology is ever to become anything more than a mere aggregation of opinions it can only be by the establishment of some datum universally agreed to."

– Herbert Spencer (1855)

"All science is either physics or stamp-collecting"

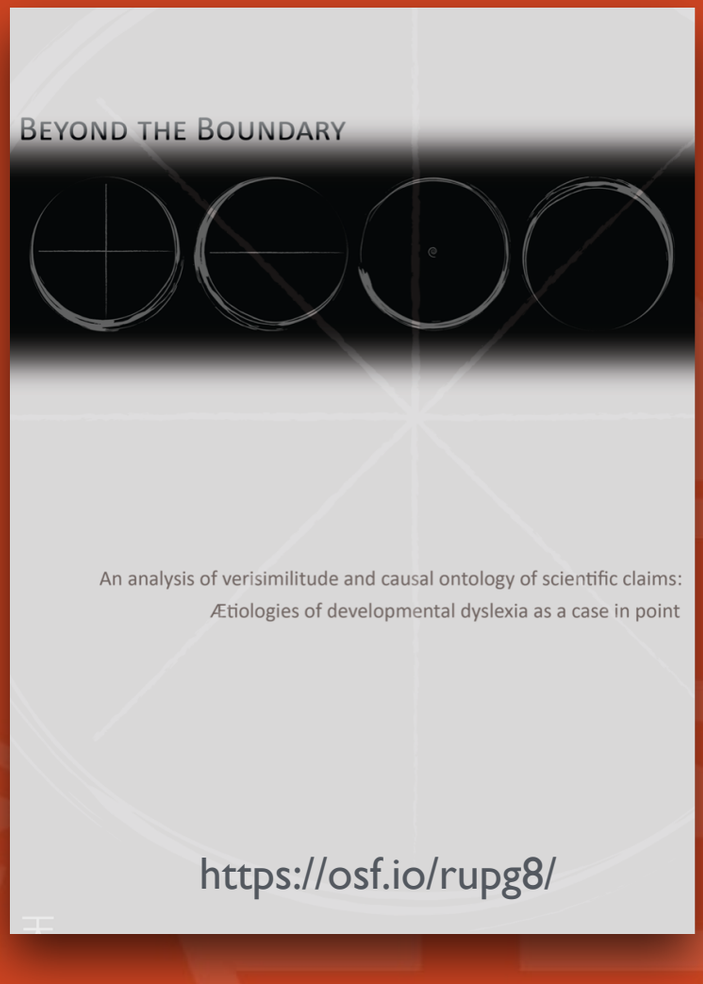
"If your result needs a statistician,
then you should design a better experiment."

-Ernest Rutherford (1871-1937)

❄️🤦🏾🌿Why Complexity Science? 🌪️🌊👩🏻‍🔬

Sane As it Ever Was

The Historical Meaning of the Crisis in Psychology
Dealing with theoretical diversity



- Statistical - **QRPs, NHST**
- Methodological - **Correlation vs. Independence**
- Historical - **“We are young”**
- Socio-Cultural - **Incentives, soft-science**
- Incidental - **“Nothing to see here … we are fine”**
- Theoretical / Formal - **Object of study, Context sensitivity**
- Philosophy of science - **Causal ontology**

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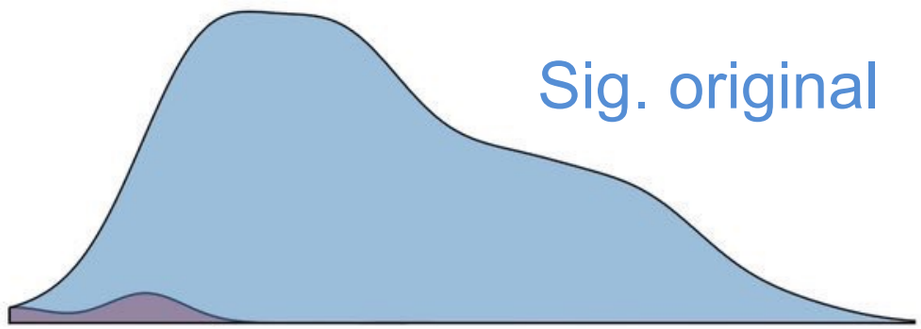


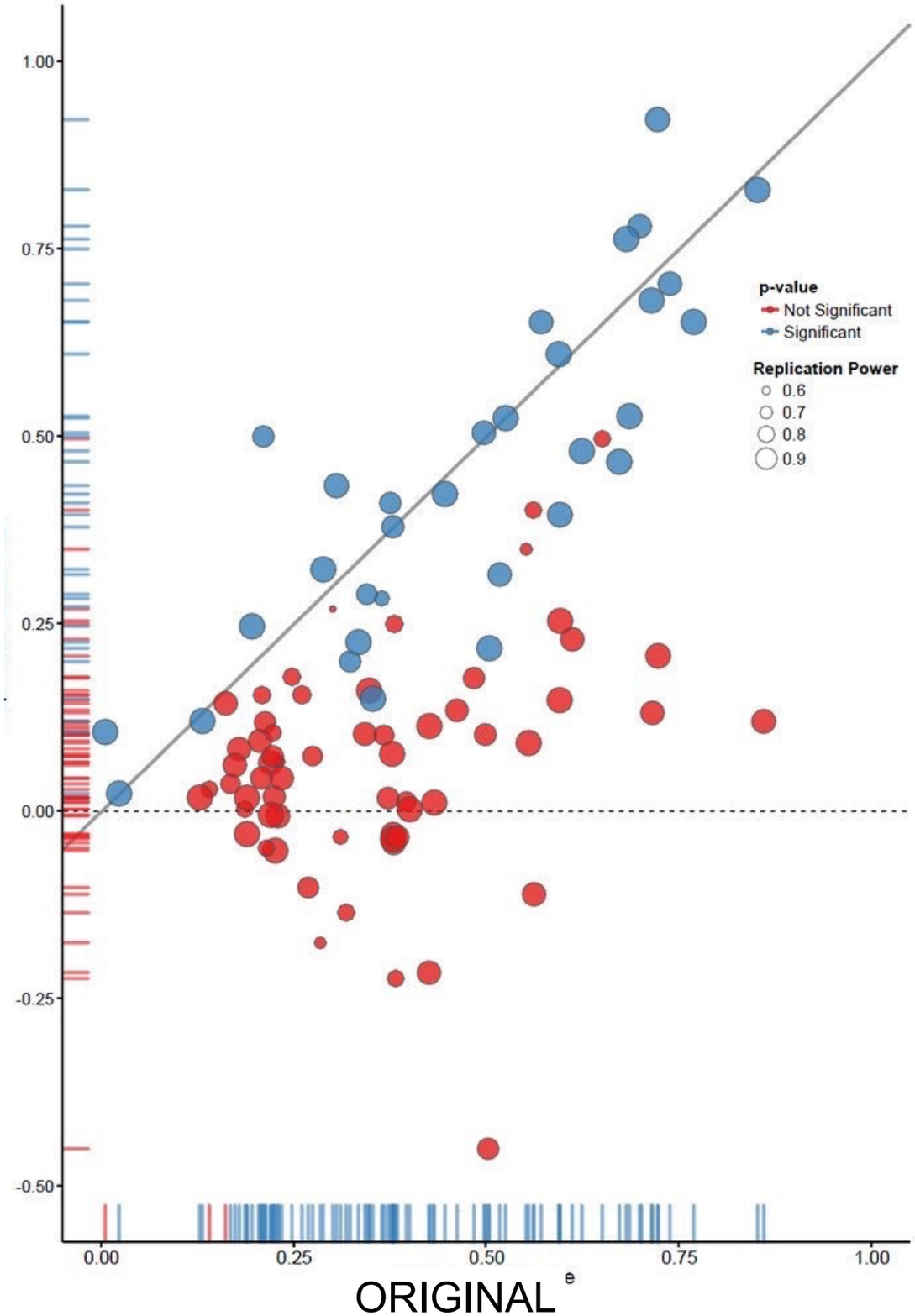
Sig. original

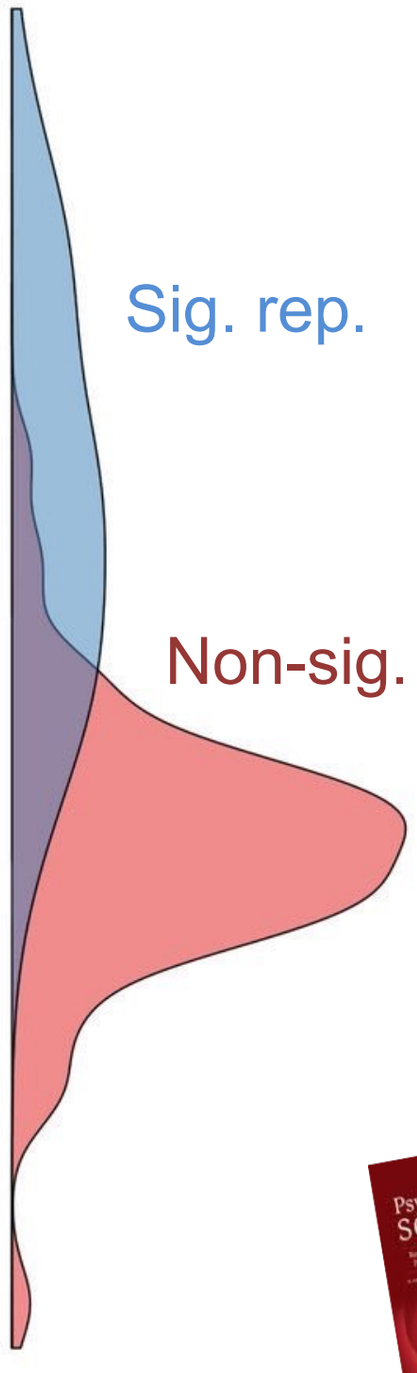
Expected success:

- 89% (97 sig. studies)

Results:

- 36% ($p < .05$)
- 47% (within 95%BI)
- 39% (subjective)





Sig. rep.

Non-sig. rep.

"Replication crisis"

Estimating Reproducibility of Psychological Science

Away with Statistics? Or social science?

Andrew Gelman: The time-reversal heuristic

One helpful (I think) way to think about such an episode is to turn things around. **Suppose the attempted replication experiment, with its null finding, had come first**. A large study finding no effect. **And then someone else runs a replication** under slightly different conditions **with a much smaller sample size and found statistical significance under non-preregistered conditions**. Would we be inclined to believe it? I don't think so. At the very least, we'd have to conclude that any such phenomenon is fragile.

http://andrewgelman.com/2016/03/03/more-on-replication-crisis/

What could be the nature of (ir)reproducibility in the Empirical Social Sciences?

Young Science?

Hardest Science?

Context sensitivity…. wrong use of statistics?

Complex subject matter!

Development, adaptation, learning
Behaviour depends on specific events in individual history
Many factors, parts, many interactions

Claims of Eternal Youth

"Modern Psychology surely began, not "three or four years ago," with the publication of the Willenshandlung, –but some forty years ago, with Fechner's notion of the definite functional correlation of psychical with physical processes. The modern psychologist is the experimental psychologist."

- Titchener,(1893, p. 456, emphasis added)

Box 0.1: A (non-exhaustive) comparison between announced origins of modern psychology (hyper-links to text in electronic document) and origins of modern versions of other disciplines of science.

Herbart (1824; 1825)	Psychology as a Science (Synthetic & Analytic Volume)
Combe (1834)	Principles of Physiology
Spencer (1855)	The Principles of Psychology
Fechner (1860)	The Elements of Psychophysics
Carpenter (1874)	Principles of Mental Physiology
Münsterberg (1888)	Die Willenshandlung
James (1890)	The Principles of Psychology (Volumes I & II)
Wundt (1874; 1897)	Principles of Physiological Psychology Outlines of Psychology
Titchener (1898)	The Postulates of a Structural Psychology

Modern life science / medicine (1855)
Remak / Virchow discover the building block of life, cause of pathology: The cell

Modern Biology: (1859)
Darwin's famous book was published
Spencer: "survival of the fittest" (1864)

Modern (Theoretical) Physics: (1865)
Maxwell's dynamical theory of the electromagnetic field

Modern (Cognitive) Neuroscience: (1868)
F.C. Donders' mental chronometry

Modern Mathematics: (1859-1900)
Riemann, Minkowski, Poincaré, Hilbert

The Great Schism of 1925 - 1935

Theories of physics become extremely accurate in predicting measurement outcomes

Vygotsky: Historical meaning of Crisis in Psychology

Popper (1934)
Logik der Forschung

Hilbert & Bernays (1934)
Grundlagen der Mathematik

Mathematics

Kolmogorov (1933)
Grundbegriffe der Wahrscheinlichkeitsrechnung

Statistics

Neyman & Pearson (1933)
On the Problem of the Most Efficient Tests of Statistical Hypotheses

Fisher (1925)
Statistical Methods for Research Workers

Fisher (1935)
The Design of Experiments

NHST

WAR **1925** **1935** WAR

Social Sciences

Vygotsky (1925-1928)
The Historical Meaning of the Crisis in Psychology

Jastrow (1935)
Has Psychology Failed?

Physical Sciences

Einstein (1916-1918)
General Relativity Theory

von Neumann (1932)

Born, Heisenberg & Jordan (1926)

Schrödinger (1935)

Dirac (1930)

QM

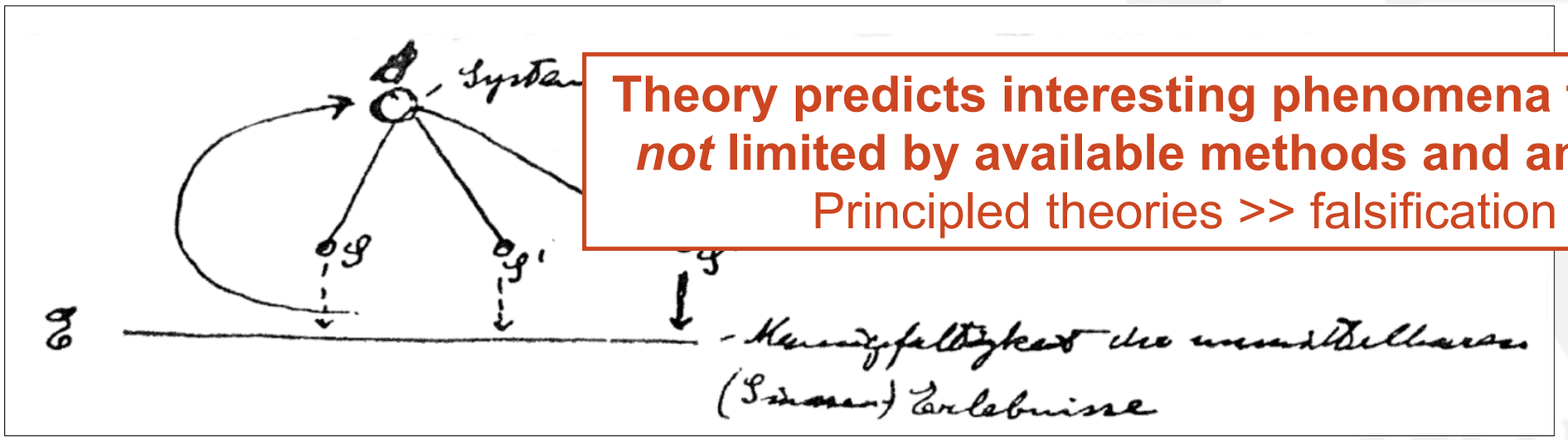
"Invention" of Fisher & N-P hypothesis testing

The Historical Meaning of the Crisis in Psychology

"When one mixes up the **epistemological** problem with the **ontological** one by introducing into psychology **not the whole argumentation but its final results**, this leads to the distortion of both."

Hypothesising after the results are known: HARKING
Constructive theories >> data-driven, exploratory >> presented as confirmatory

Einstein (quoted by Heisenberg):
"It's the theory that decides what may be observed"



Theory predicts interesting phenomena to study *not* limited by available methods and analyses
Principled theories >> falsification

A drawing by Albert Einstein explaining his philosophy of science. Taken from a letter sent to Maurice Solovine, 7th of March 1954 (cf. van Dongen, 2010).

A: System der Axiome
E: Mannigfaltigkeit der Unmittelbaren Sinneserlebnisse
S: Gefolgerte Sätze

THEORY = METHODS

Random variables; Independent processes; Probabilities of random events; Random fields; Unique independent causes (of variance components)

Why do dyslexic subjects differ on almost any observed variable from average readers?

All modalities of perception
(Beaton, Edwards, & Peggie, 2006; Breznitz, 2003; Goswami, Fosker, Huss, Mead, & Szűcs, 2010; Huss, Verney, Fosker, Mead, & Goswami, 2010; Skoyles, 2004; Talcott et al., 2003; Tallal, 2004)

Motor control
(McPhillips & Jordan-Black, 2007; Nicolson & Fawcett, 2006; Ramus, Pidgeon, & Frith, 2003; Savage, 2004)

Balance
(Rochelle & Talcott, 2006; Stoodley, Fawcett, Nicolson, & Stein, 2005)

Attention
(Reynolds & Besner, 2006; S. E. Shaywitz & B. A. Shaywitz, 2008; Valdois, Bosse, & Tainturier, 2004)

Cognitive abilities
(Aleci, Piana, Piccoli, & Bertolini, 2010; Heim et al., 2008; Helland, 2007)

Fluency of naming
(Araujo, Pacheco, Faisca, Petersson, & Reis, 2010)

Learning
(Menghini, Vicari, Mandolesi, & Petrosini, 2011; Nicolson, Fawcett, Brookes, & Needle, 2010; Vicari et al., 2005)

Language
(Berninger, 2000; Joanisse, Manis, Keating, & Seidenberg, 2000; Koster et al., 2005)

Adding Fish Oil (Omega-3 fatty acids) to the diet
(e.g. Cyhlarova et al., 2007)

Using coloured lenses and coloured overlays to improve reading fluency
(Lightstone, Lightstone, & Wilkins, 1999; Whiteley & Smith, 2001)

Music therapy
(e.g. Overy, 2003)

Intensive training with tonal sweeps and acoustically modified speech
(e.g. Tallal, 2004)

Playing Action Video Games
(Franceschini et al., 2013)

Exercise based training
(Reynolds, Nicolson, & Hambly, 2003, 2006)

Presenting stimuli to visual, auditory and touch modalities opposite a dysfunctional hemisphere
(e.g. Smit-Glaudé, van Strien, Licht, & Bakker, 2005)

Training Rapid Serial Naming of pictures, colours, numbers and letters
(Eleveld, 2005)

Random variable 1:

Reading

random sample of:

a) dyslexic readers pct.10 or 25

b) average readers IQR

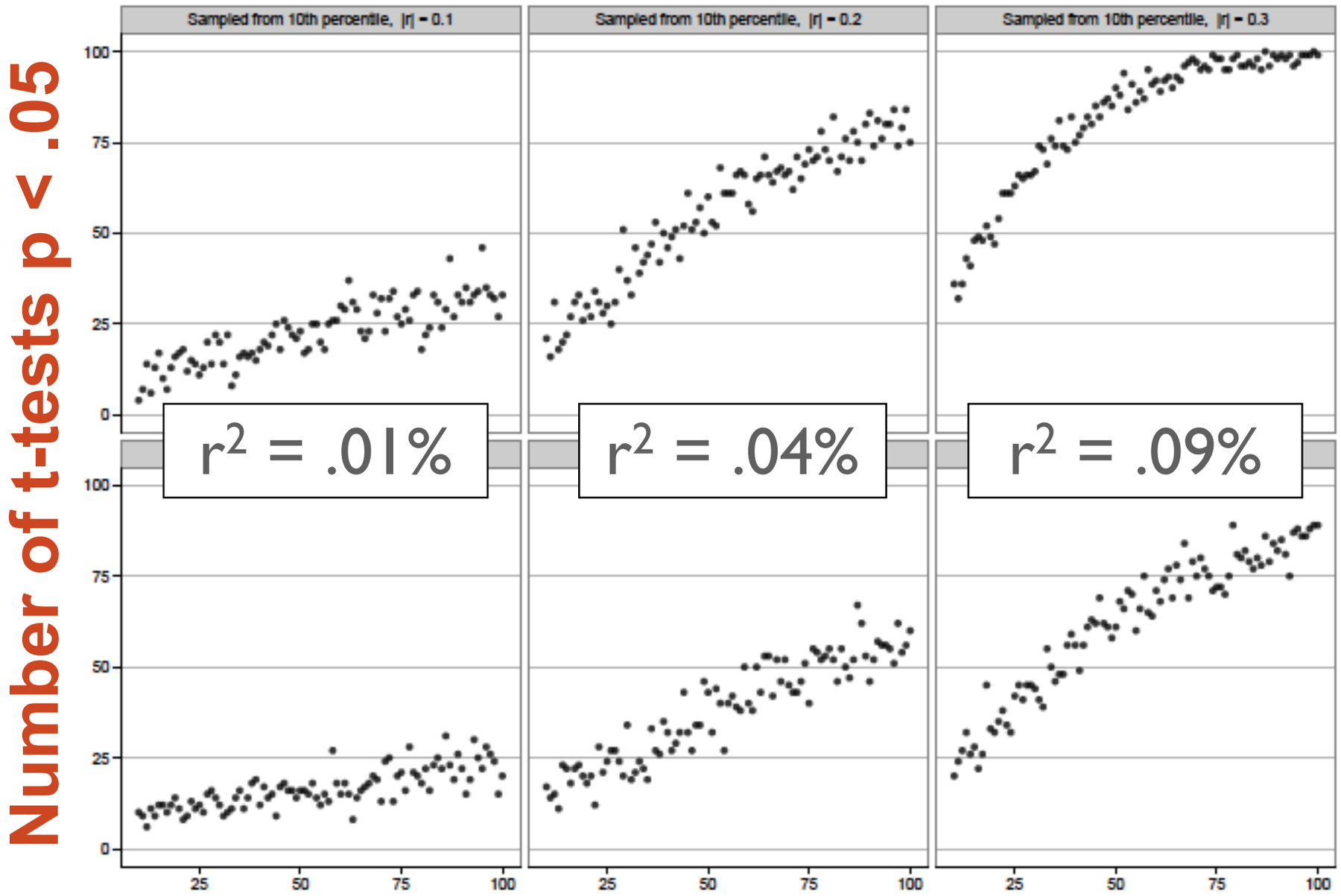
In sample a) and b) observe random variable 2:

XYZ

Do a t-test between means of XYZ in a) and b)

THEORY = METHODS

Random variables, independent processes, probabilities of random events, unique independent causes (of variance)



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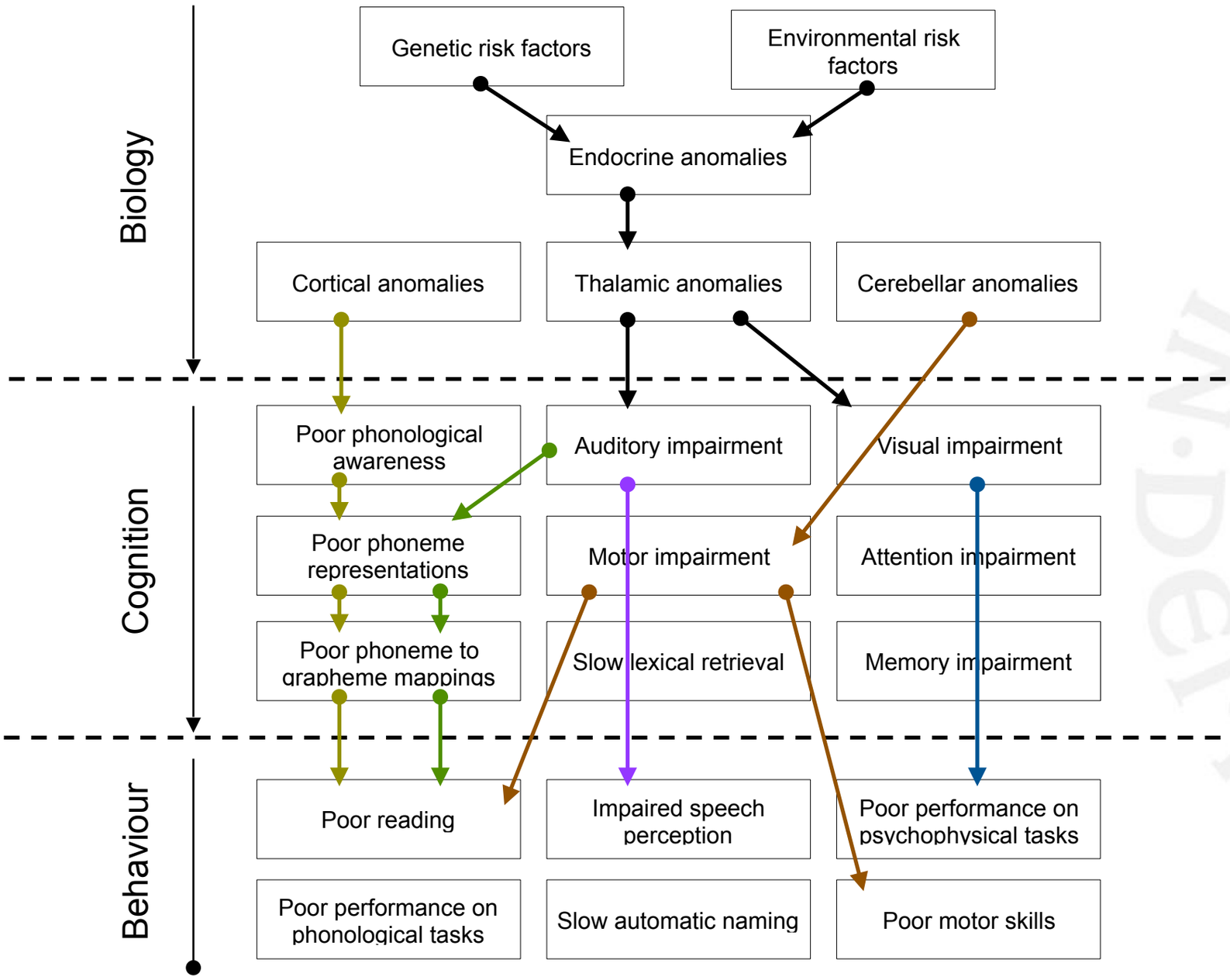


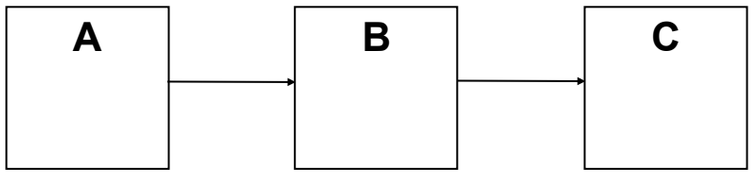
component dominant dynamics

assumption of independence of components is problematic

Two types of Dynamics

different phenomena
different goals of research
different toolbox

Component dominant dynamics



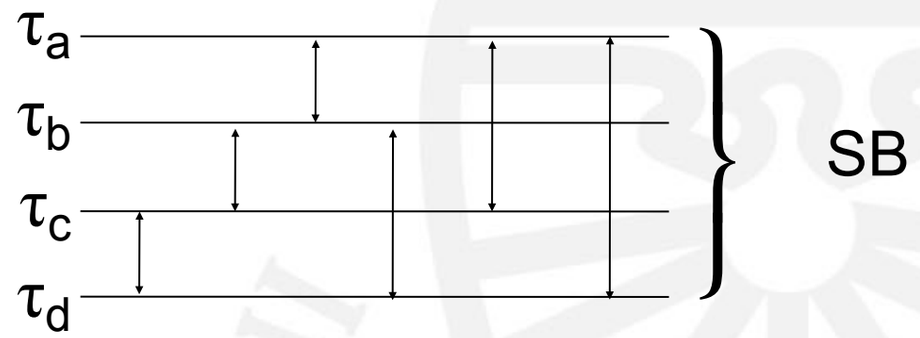
= SB

System: Ergodic system

System Behaviour: The behaviour of individual (neurological-, genetic-, cognitive-) components and processes dominate the global behaviour of the system. Interactions between components are linear and additive.

Goal of research: look for a linear arrangement of sources of variation in observed behaviour and/or generalize behaviour of a sample of systems to the average behaviour of a population of systems

Interaction dominant dynamics



System: Complex dynamical system

System Behaviour: The collective interactions between (neurological-, genetic-, cognitive-) components and processes dominate the global behaviour of the system. Interactions may be nonlinear and multiplicative and across multiple (time-)scales.

Goal of research: (mathematically) describe a system whose interactions explain observed behaviour and/or study and quantify the dynamics of system behaviour under different constraints & contexts (body, environment)

Two paradigms for explaining behaviour

Machine Metaphor

- Parts exist for each other, but not by means of each other
- Parts act together to meet the things purpose, but their actions have nothing to do with the thing's construction
- **Open to efficient cause (predicative logic)**
- Human behaviour: **Computation; Information processing**

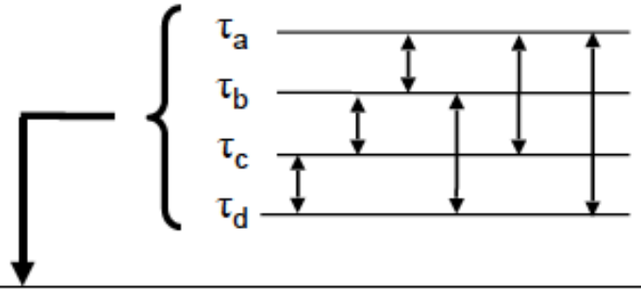
Organism Metaphor

- Parts are both causes and effects of the thing, both means and end
- Parts act together but also construct and maintain themselves as a whole
- **Closed to efficient cause (impredicative logic)**
- Human Behaviour: **Concinnity; Embodied and Embedded**

Concinnity: Harmony in the arrangement or interarrangement of parts with respect to a whole.

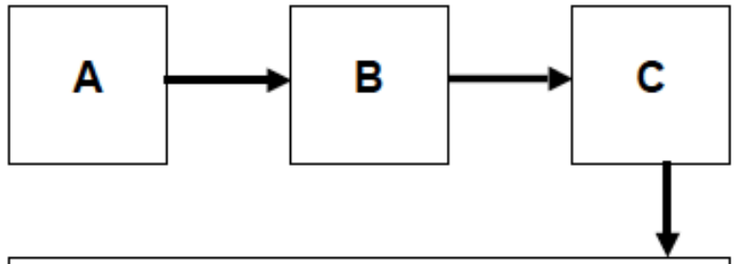
Adapted from Turvey (2007)

Interaction dominant dynamics



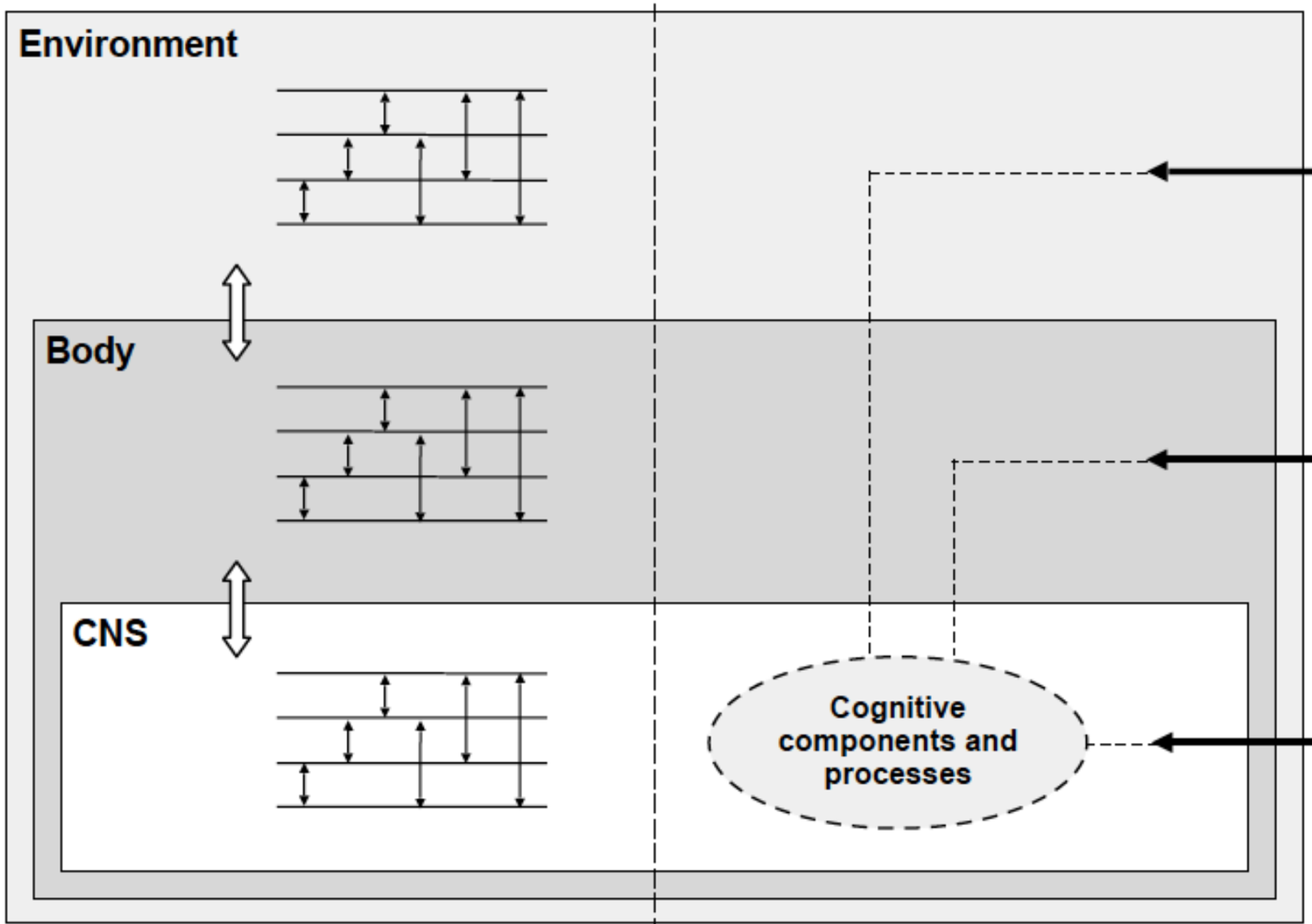
Behavior emerges from interaction between many processes on different timescales in body and environment

Component dominant dynamics



Behavior is the result of a linear arrangement of a virtual architecture of cognitive components and processes

Place of measurement of efficient causes



Environmental factors, Performance and perception measures, Social interactions, …

Genetic, immunological, endocrine systems. Biophysical composition, physiology, Organic chemistry, …

Structure and function of the cortex, cerebellum, brainstem, neural pathways. Neurochemistry, …

Theories operate within (mathematical) formalism:

Random events / processes
Independent / Memory-less
Linear / Polynomial
Efficient causes

Random events / processes
Deterministic / Temporal correlations
Linear / Nonlinear
Efficient causes / Circular causality

component dominant dynamics

The Law of Large Numbers (Bernouiili, 1713) +
The Central Limit Theorem (de Moivre, 1733) +
The Gauss-Markov Theorem (Gauss, 1809) +
Statistics by Intercomparison *(Galton, 1875)* =
Social Physics *(Quetelet, 1840)*

Collectively known as:
The Classical Ergodic Theorems

Molenaar, P.C.M. (2008). On the implications of the classical ergodic theorems: Analysis of developmental processes has to focus on intra individual variation. *Developmental Psychobiology, 50*, 60-69

interaction dominant dynamics

Deterministic chaos (Lorenz, 1972)
(complexity, nonlinear dynamics, predictability)

Takens' Theorem (1981)
(phase space reconstruction)

Systems far from thermodynamic equilibrium
(Prigogine, & Stengers, 1984)

SOC / $\frac{1}{f^{\alpha}}$ **noise** (Bak, 1987)
(self-organized criticality, interdependent measurements)

Fractal geometry (Mandelbrot, 1988)
(self-similarity, scale free behaviour, infinite variance)

Aczel's Anti-Foundation Axiom (1988)
(hyperset theory, circular causality, complexity analysis)

Ergodicity

- A random process $X(t)$ is ergodic if all of its statistics can be determined from a sample function of the process
- That is, the ensemble averages equal the corresponding time averages with probability one.

Thus, you obtain two different results: one statistical analysis over the entire ensemble of people at a certain moment in time, and one statistical analysis for one person over a certain period of time. The first one may not be representative for a longer period of time, while the second one may not be representative for all the people.

The idea is that an ensemble is ergodic if the two types of statistics give the same result. Many ensembles, like the human populations, are not ergodic.

https://larspsyll.wordpress.com/2016/11/23/what-is-ergodicity-2/

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An introduction to the analytical toolbox of Complexity Science

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What are the interesting phenomena social and life sciences should study?

Do we have the right tools for the job?

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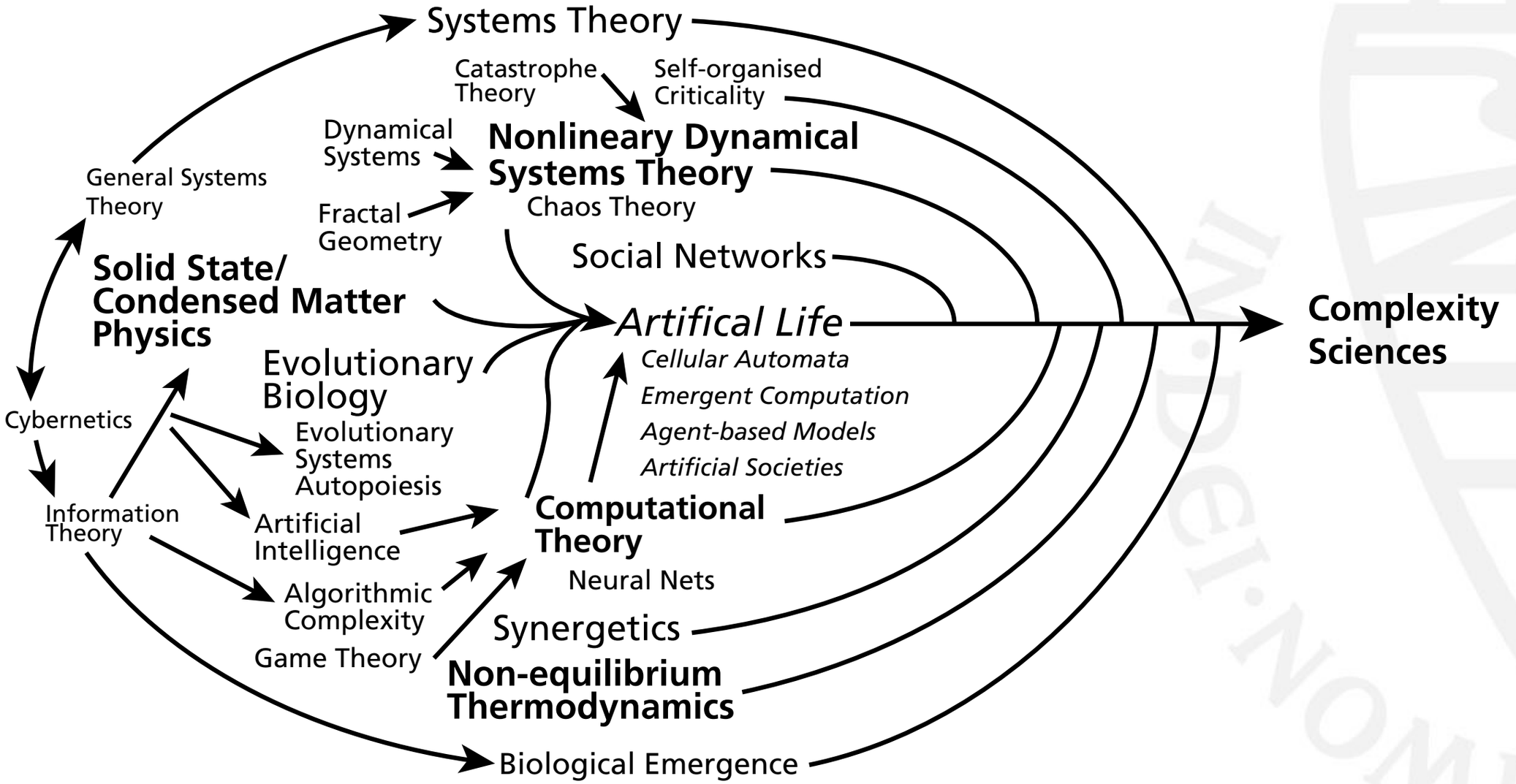
Complexity Science - Some basic concepts



The many foundations of complexity science.

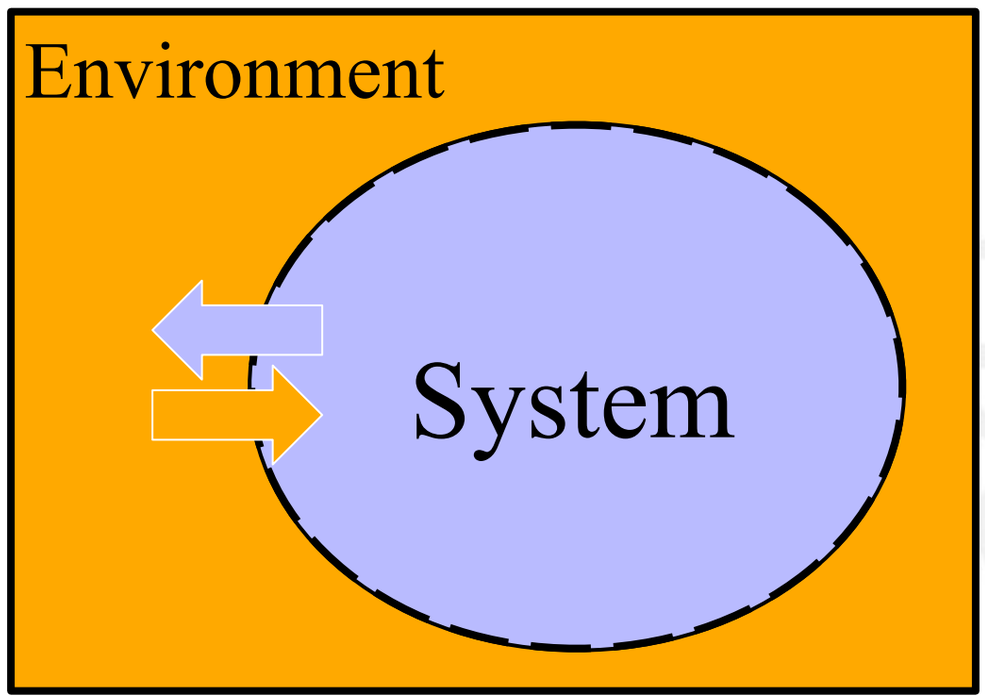
Complexity Science - Some basic concepts

Grip on banks
Grip on transport
Grip on obesity
Grip on cancer
Grip on traffic
Grip on complexity
Grip on innovation
Grip on climate
Grip on desertification
Grip on biodiversity
Grip on jet lags

The physicists are coming!

What is a system?

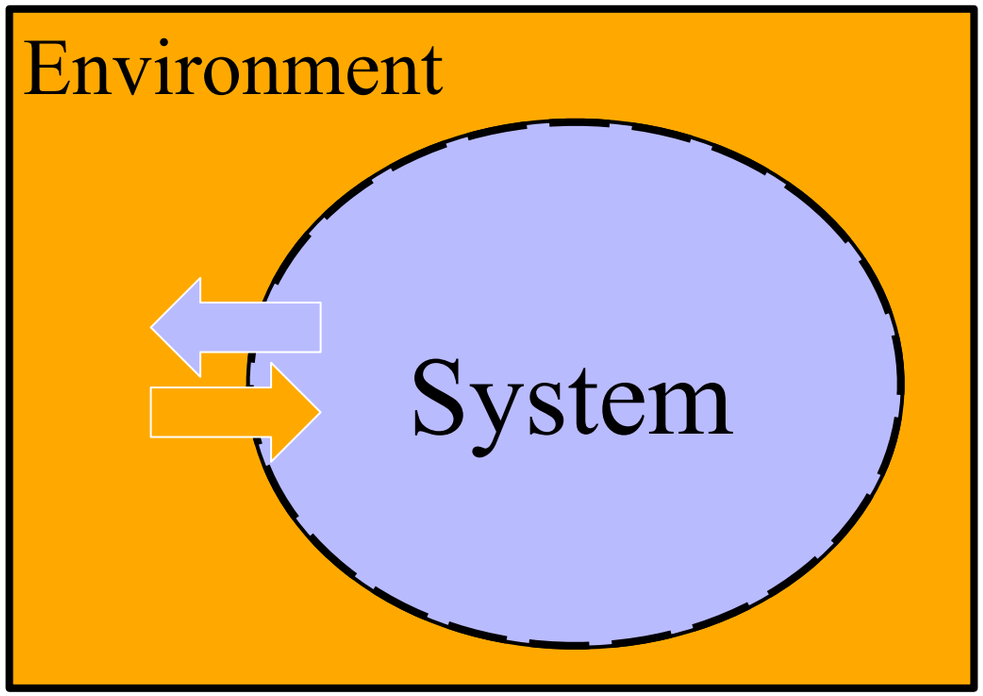
Closed and Open Systems



Continuous exchange of matter, energy, and information with the environment.

When is it a complex system?

Many parts constitute a whole according to some organising principle… +



Continuous exchange of matter, energy, and information with the environment.

- **Open** system
- at least locally **dissipative** (able to increase & maintain complexity of internal structure by using energy)
- at least locally **non-ergodic** (time averaged behaviour ≠ space averaged behaviour, interaction biography)
- Behaviour dynamics can be **linear** or **non-linear, component-dominant** or **interaction-dominant**
- Properties and patterns **emerge** through physical mechanism of **self-organisation**

What are the interesting phenomena?
What kind of theory do we need to understand human behaviour?

Epke wanted to win by a combination never before performed on a tournament:

casina - kolman

… but made an “error” in the *casina* movement…

so he <u>decided</u> to follow up with another combination that had never been performed:

casina - kovacks

and won the world-cup anyway!

Epke Zonderland @ world-cup Paris 2011

If this is “just”motor control:
Why didn’t he just continue on auto-pilot?
Why add an untrained manoeuvre?

video: http://dewerelddraaitdoor.vara.nl/Video-detail.628.0.html?&tx_ttnews[tt_news]=21424&tx_ttnews[backPid]=626&tx_ttnews[cat]=148&cHash=5239d7f7ac63c6404ce39d51c23987eb

What are the interesting phenomena?
What kind of theory do we need to understand human behaviour?

Participants can inspect the randomly scrambled cube for max. 15 seconds.

There are about 43,252,003,274,489,856,000 possible permutations of the cube.

Particpants place the cube on the Stackmat and their hands on the timer area of the Stackmat.

Once their hands leave the timer area, the timer starts.

In the video Erik Akkersdijk, a 19-year old boy from Deventer, the Netherlands, solves the cube in a world record: 7.08 seconds!!

It is currently the European record, the current world record is: 6.24 seconds by 16-year old Feliks Zemdegs of Australia.

The average solving time at speedcubing championships is ±10 seconds

Erik Akkersdijk @ Czec open speedcubing world championships 2008

Is this “just” cognition?

sources: www.speedcubing.com

video: www.youtube.com/watch?v=VzGjbjUPVUo

What are the interesting phenomena?
What kind of theory do we need to understand human behaviour?

- Cognition can be ultrafast
- Adaptation of behaviour can be super fast
- Behaviour and cognition can be anticipatory across many timescales
- Organisation of behaviour across many temporal and spatial scales
- Behaviour is emergent, self-organising rather than extensively planned and controlled

Do we have the right tools (theory and methods) to study these phenomena?

What are the interesting phenomena?
What kind of theory do we need to understand human behaviour?

AUTOMATICITY

- Strange: Typical human cognitive skills (Chess) are easy to automate!
- Chess, Go! and Watson, the Jeopardy champion!

Computer beats Jeopardy! champs - is world domination far behind?

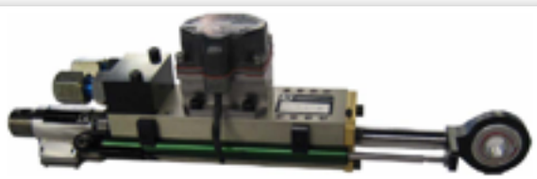
What are the interesting phenomena?
What kind of theory do we need to understand human behaviour?

EMBODIED, EMBEDDED COMPUTATION

Go-kart Engine

Old Pentium

Hydraulic Actuator Package



38 sensors for proprioception
6 gyroscopes for balance
4 sensors for vision and tracking
11 sensors to monitoring homeostasis (internal states)

Big Dog Video: http://www.youtube.com/watch?v=cNZPRsrwumQ

Boston Dynamics: http://www.bostondynamics.com/ (includes technical report on Big Dog)

What are the interesting phenomena?
What kind of theory do we need to understand human behaviour?

- Cognition is ultrafast, Classical Computation is Ultraslow.
- Intelligent behaviour is adaptive, Automaticity is Maladaptive.
- Virtual-Physical-dualism: Emulating virtual machines on evolved hardware:

"This **interpretive view of computation** is responsible for the widespread use of functional models to understand cognition and computer programs to simulate mental behavior. Such models, however, fail to tell us anything about physical characteristics of the brain's information processing, only that we can interpret the brain as computing some class of functions. Yet it is from those physical characteristics that minds emerge, underscoring the importance of understanding the basis of this phenomenon. Certainly we won't understand it by identifying the class of functions the brain can be interpreted as computing, nor is that even a remotely realistic goal given the complexity of the brain and our behaviors." (Boyle, 1994, p. 452)

Do we have the right tools? Do we need principled theories?

Young Science? >> modern physics, biology, robotics and AI are just as young or younger

Hardest Science? >> Probably, but maybe we should try harder

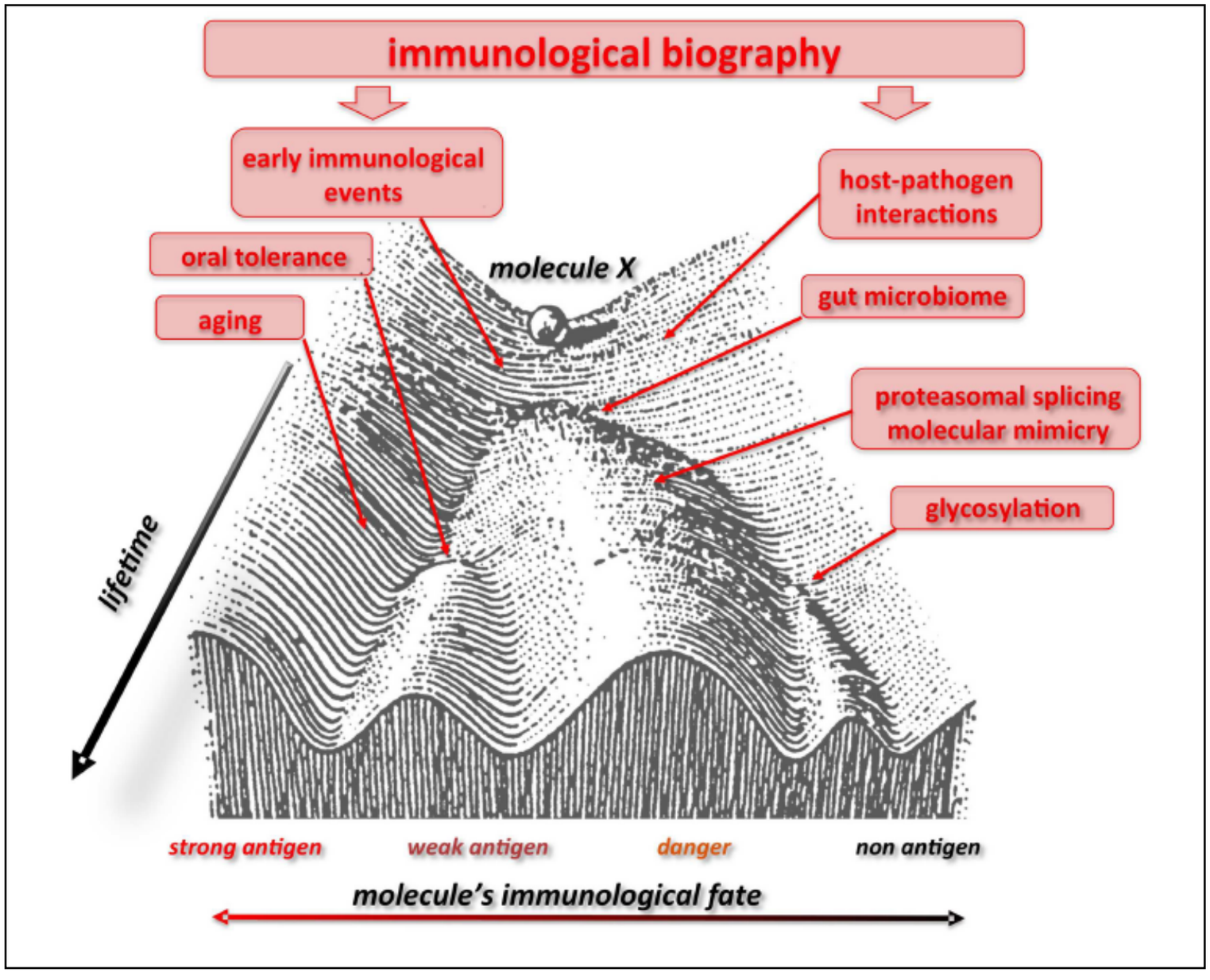
Context sensitivity… >> **Emergent behaviour** and/or **Sensitive dependence on initial conditions**

Complex subject matter! >> Complex System: **many interactions** (dependencies, coupling) **on many different scales**

Development, adaptation, learning >> Dynamics, **non-ergodic**

Behaviour depends on events in individual history >> **Interaction biography**

TOOL 1: Unique histories predict unique futures



interaction biography
=
unique history
of interactions

lifeless systems:
biography is irrelevant
(laws of physics)

living systems:
biography is crucial

The End of Average (Todd Rose)

- *Background:* Complexity Science / **Science of the Individual** / Systems Biology

Principle of jaggedness

no individual corresponds to average

Principle of context

no behaviour is context independent

THE FAILERS...

struggled more in stressful situations

had more trouble paying attention

had greater difficulty maintaining friendships

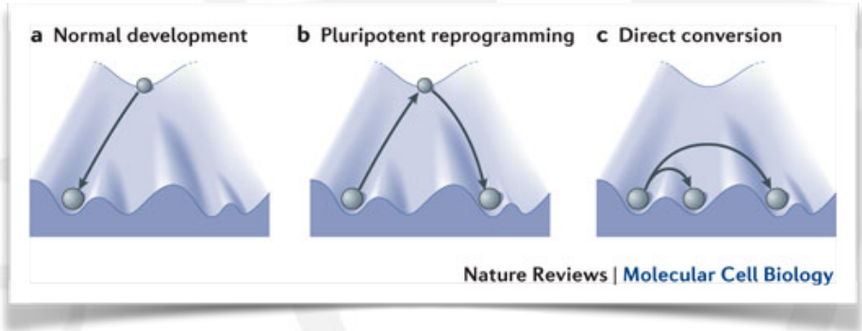
scored lower on the S.A.T. (by over 200 points)

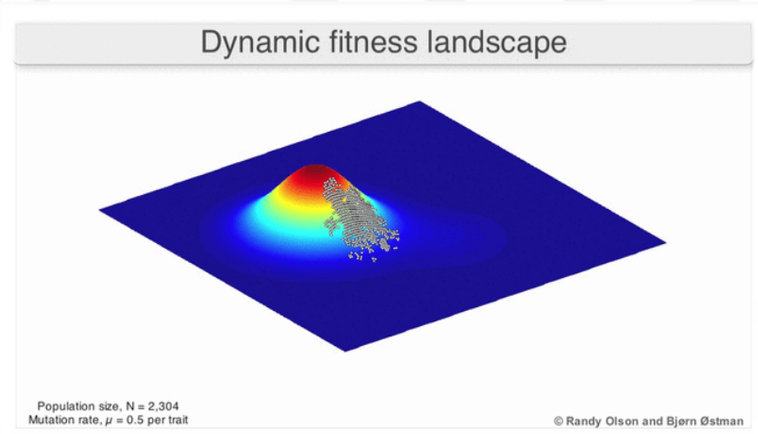
prone to a much higher higher body-mass index

were more likely to have drug addictions

Principle of pathways

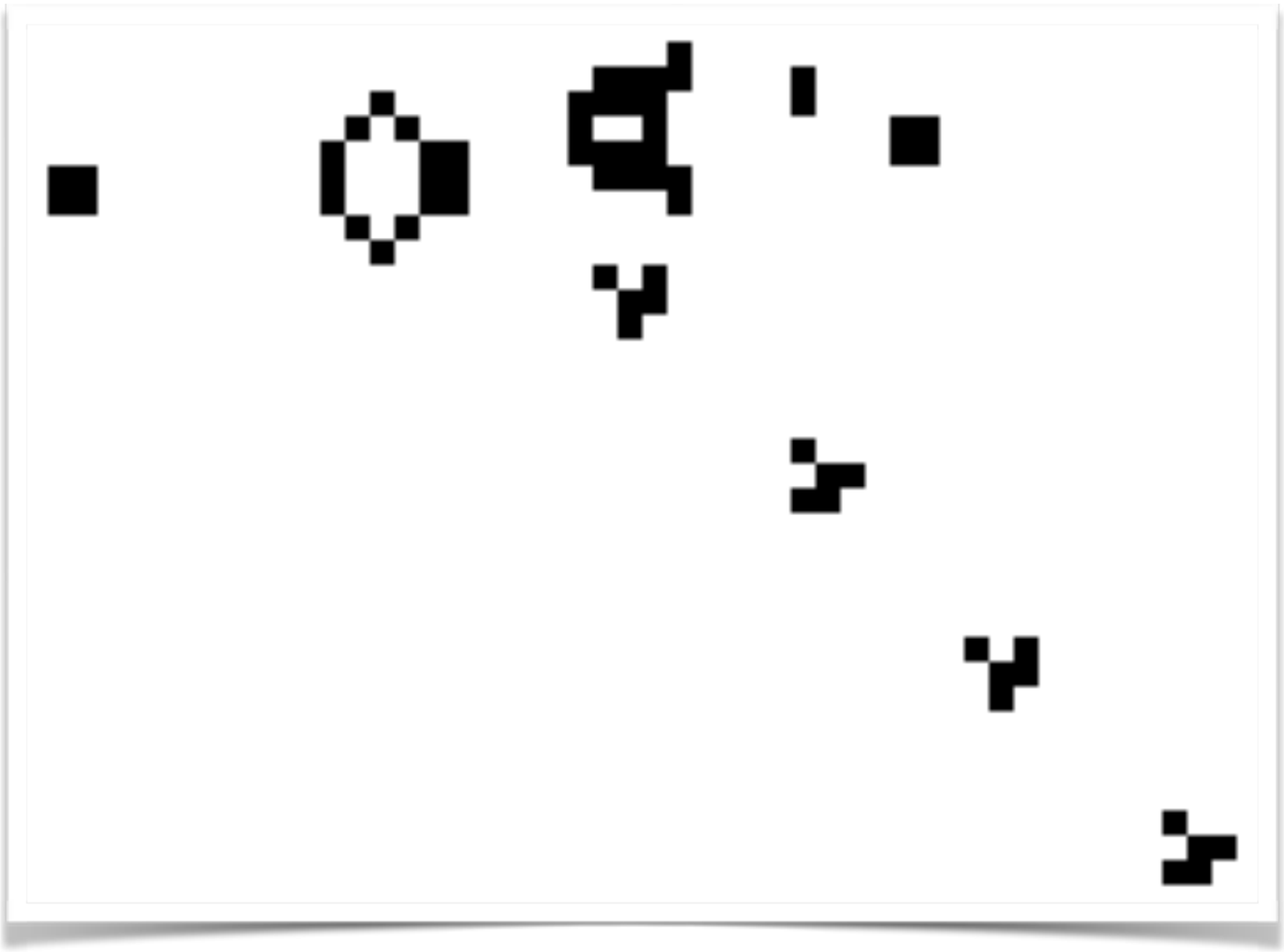
multiple trajectories to 'success'





TOOL 2: Emergent patterns... swarms, schools due to MICRO-MACRO level interactions

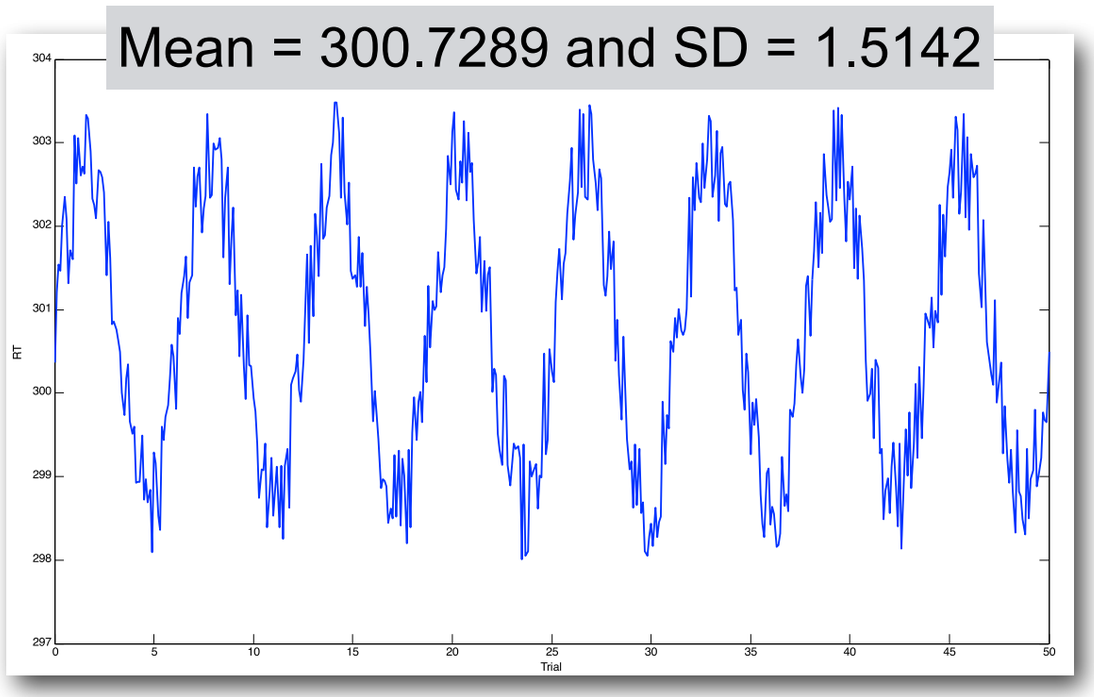
Glider gun creating “Gliders”

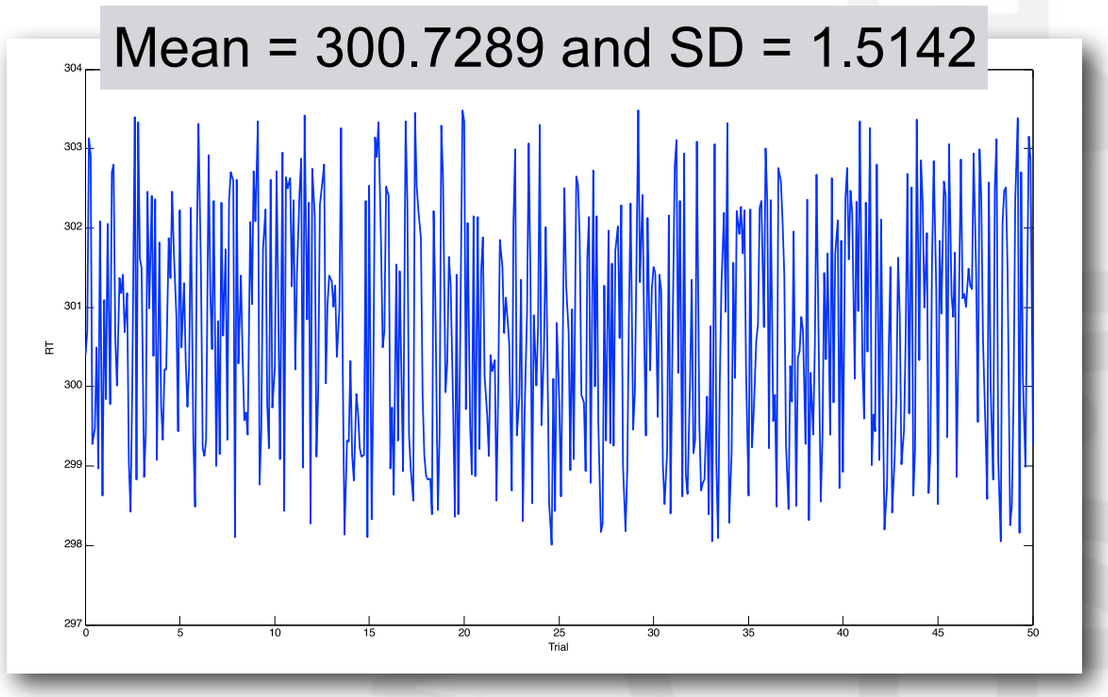


http://en.wikipedia.org/wiki/Gun_(cellular_automaton)

http://www.google.com/imgres?imgurl=http://www.projects-abroad.org/_photos/_global/photo-galleries/en-uk/cambodia/_global/large/school-of-fish.jpg&imgrefurl=http://www.projects-abroad.org/photo-galleries/?content=cambodia/&usg=__xPQQdvCtelyjDbZZu79223c58A

Patterns: “Analyse then Aggregate!”

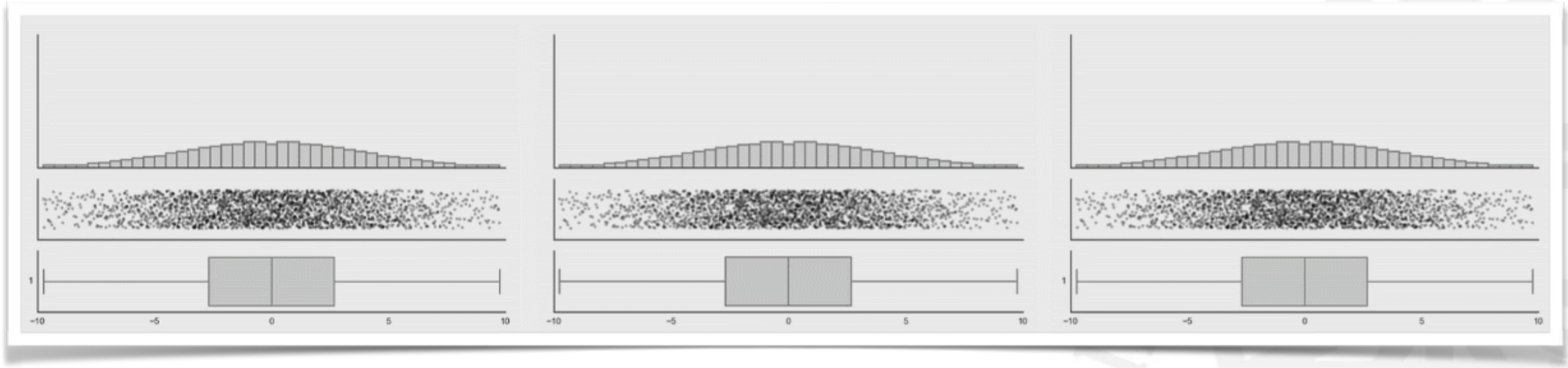


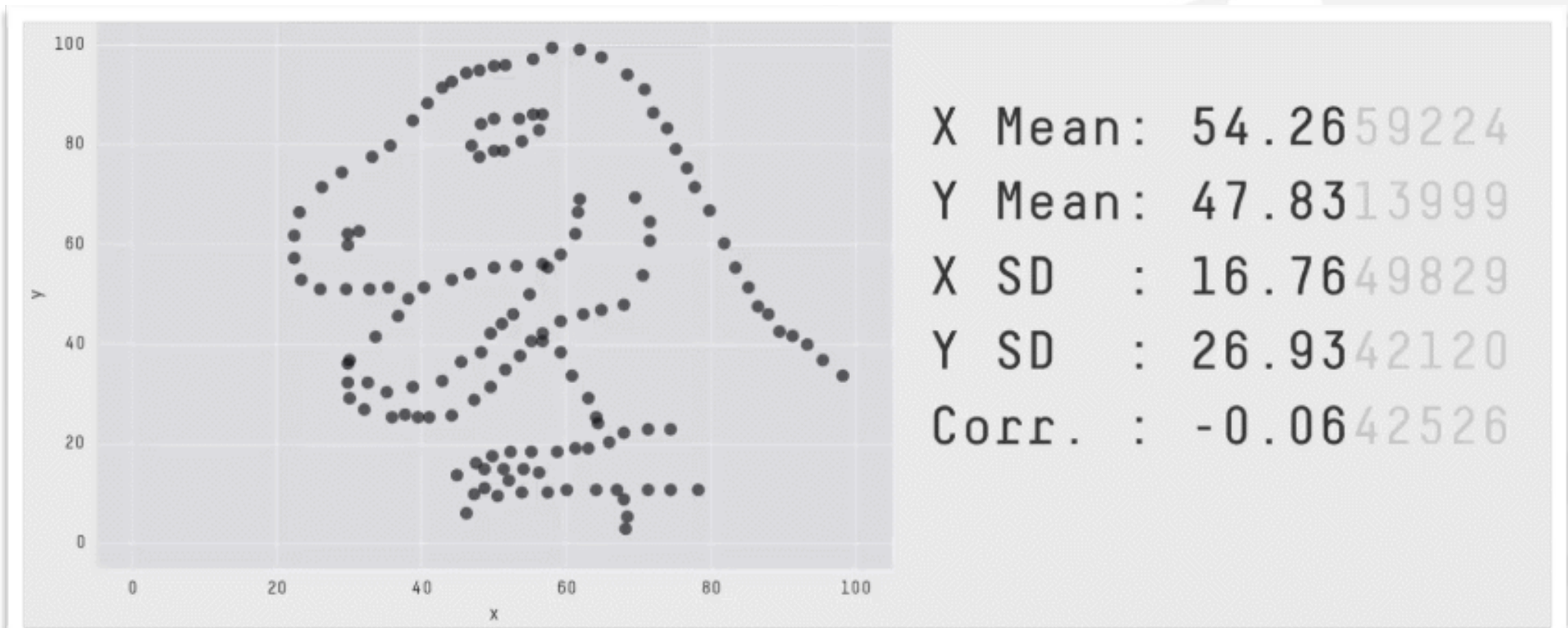


- The first process is very different from the second yet the central tendency measures are the same (MEAN, SD, etc. are equal).

- How can we characterise this difference?
    1. Quantify patterns of dependencies in the data as: deterministic/periodic/ stochastic, stable/unstable fluctuations …
    2. For each individual, each measure, in each context of interest
    3. Aggregate (if necessary)

“Analyse then Aggregate!”
same stats - different patterns



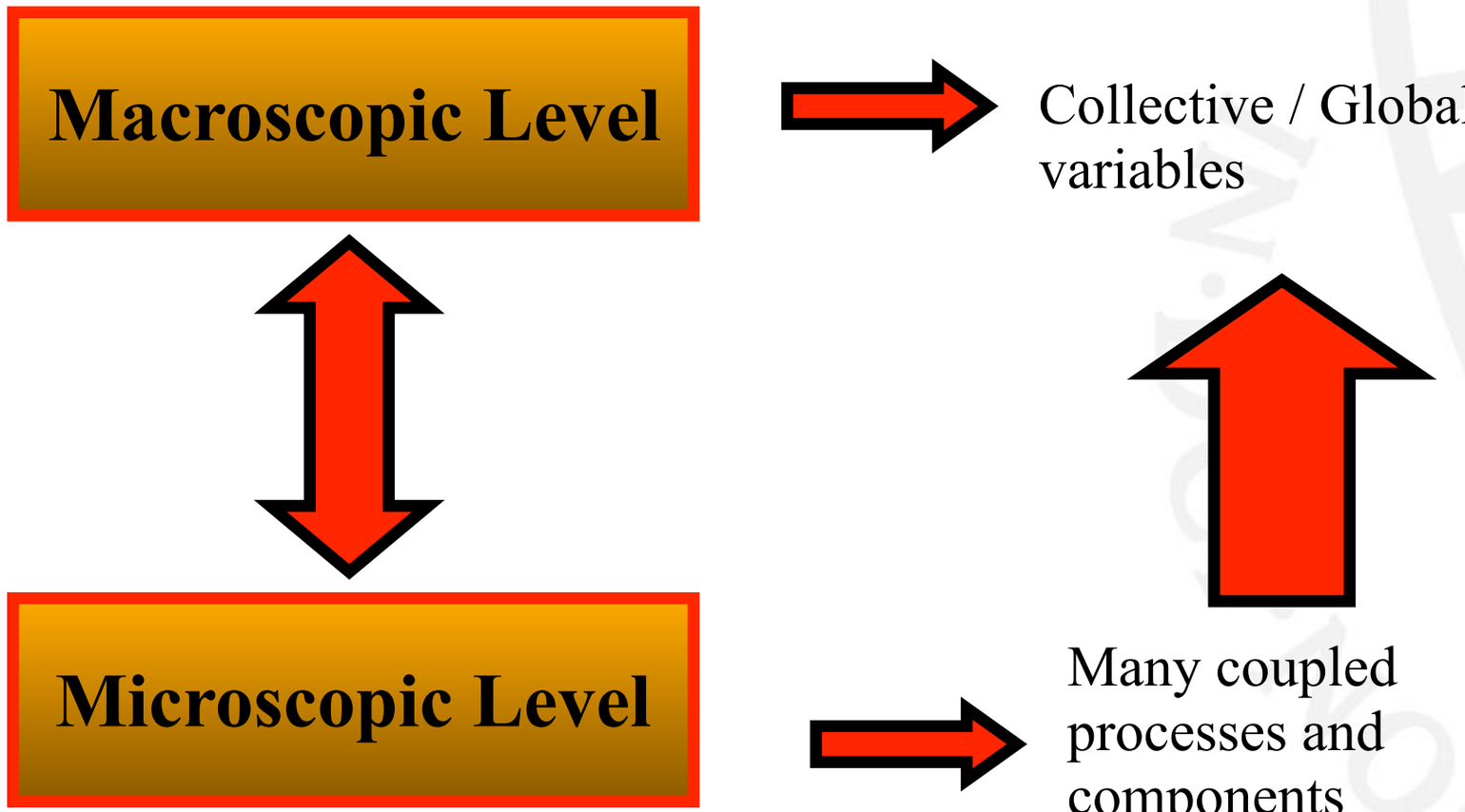


Matejka, J., & Fitzmaurice, G. (2017, May). Same Stats, Different Graphs: Generating Datasets with Varied Appearance and Identical Statistics through Simulated Annealing. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Sys*

https://www.autodeskresearch.com/publications/samestat

Behavioural Science Institute
Radboud University Nijmegen

TOOL 2: MICRO-MACRO level interactions = Multi-scale



Levels of Analysis:
Micro - Macro >> Emergent properties

Forms and properties are emergent, not expected from components: 1 watermolecule does not possess the property “wet”

Micro - Macro >> Emergent properties

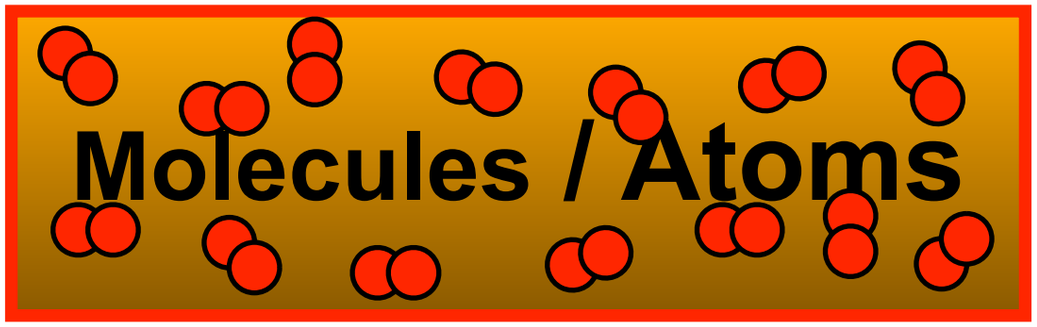
State of Matter (*solid / liquid / gas*)

Temperature, Volume, Pressure, Energy, Entropy

Thermodynamics

Theory of averaging

Laws of Mechanics

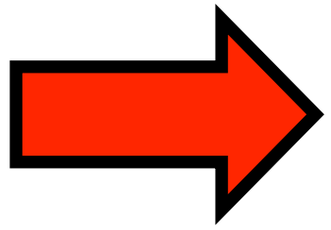


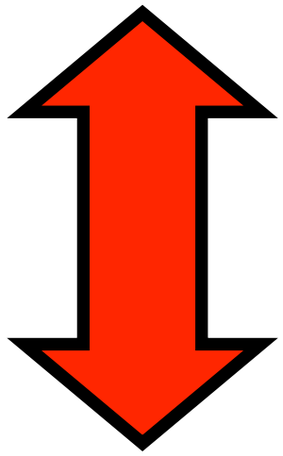
Interactions between and structure of the particles

Micro - Macro >> Emergent properties

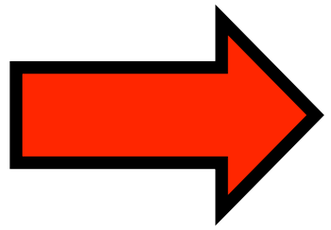
Much to be filled in!

Behavior/Cognition (Development)

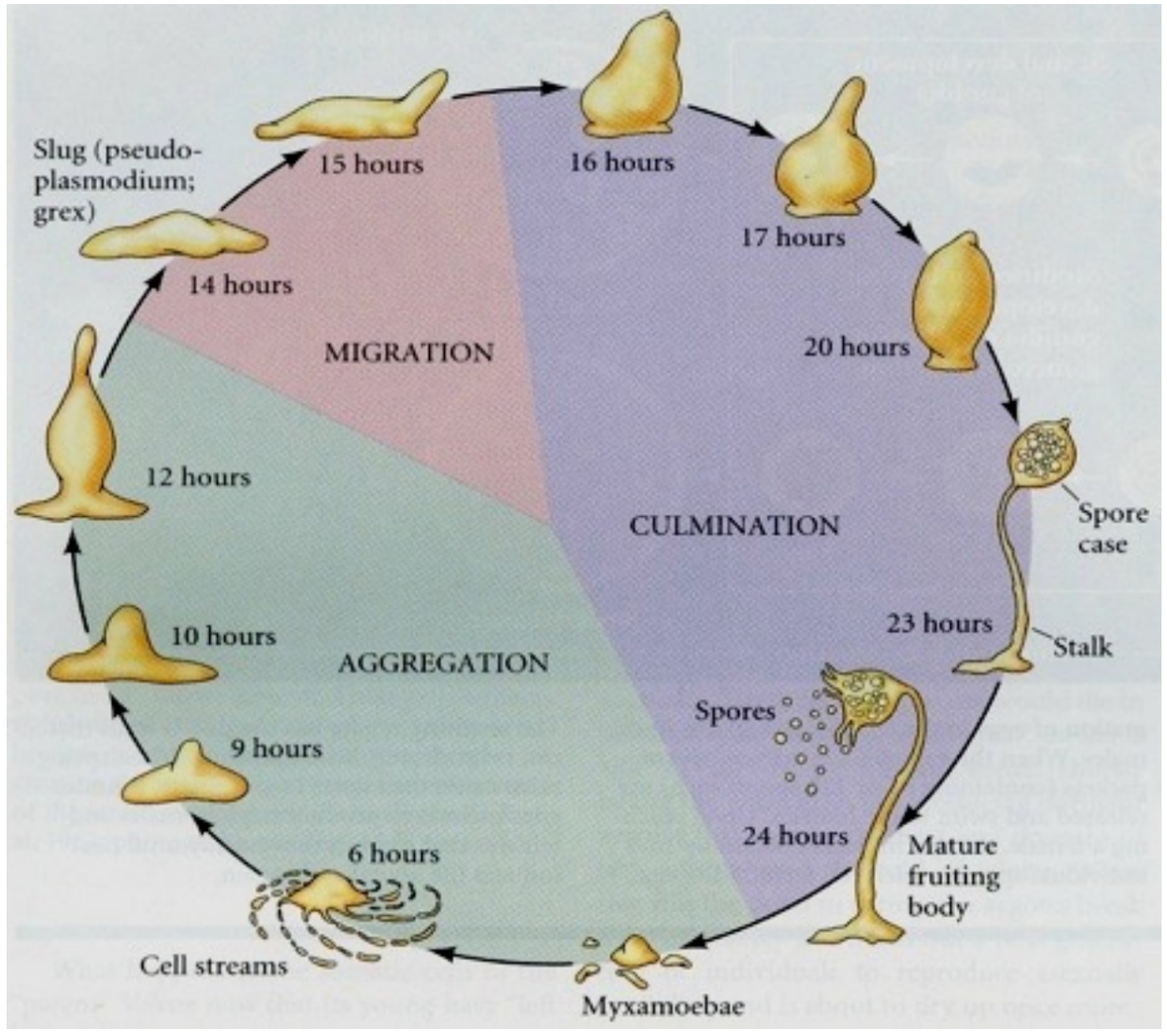




Brain/Body/Others Environment

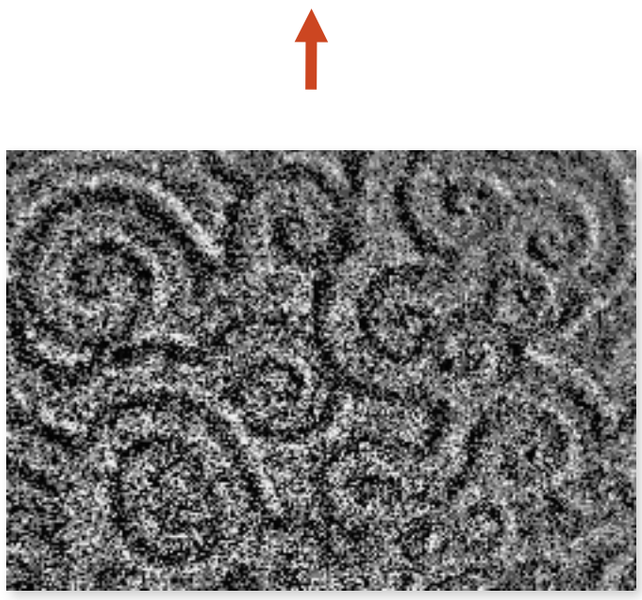


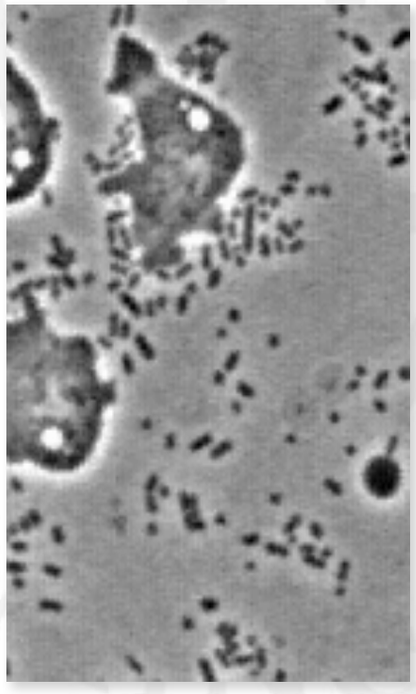
Emergence, Holism and Self-Organization: The life-cycle of *Dictyostelium*



1. Free living myxamoebae feed on bacteria and divide by fission.
2. When food is exhausted they aggregate to form a mound, then a multicellular slug.
3. Slug migrates towards heat and light.
4. Differentiation then ensues forming a fruiting body, containing spores.
5. It all takes just 24 hrs.
6. Released spores form new amoebae.

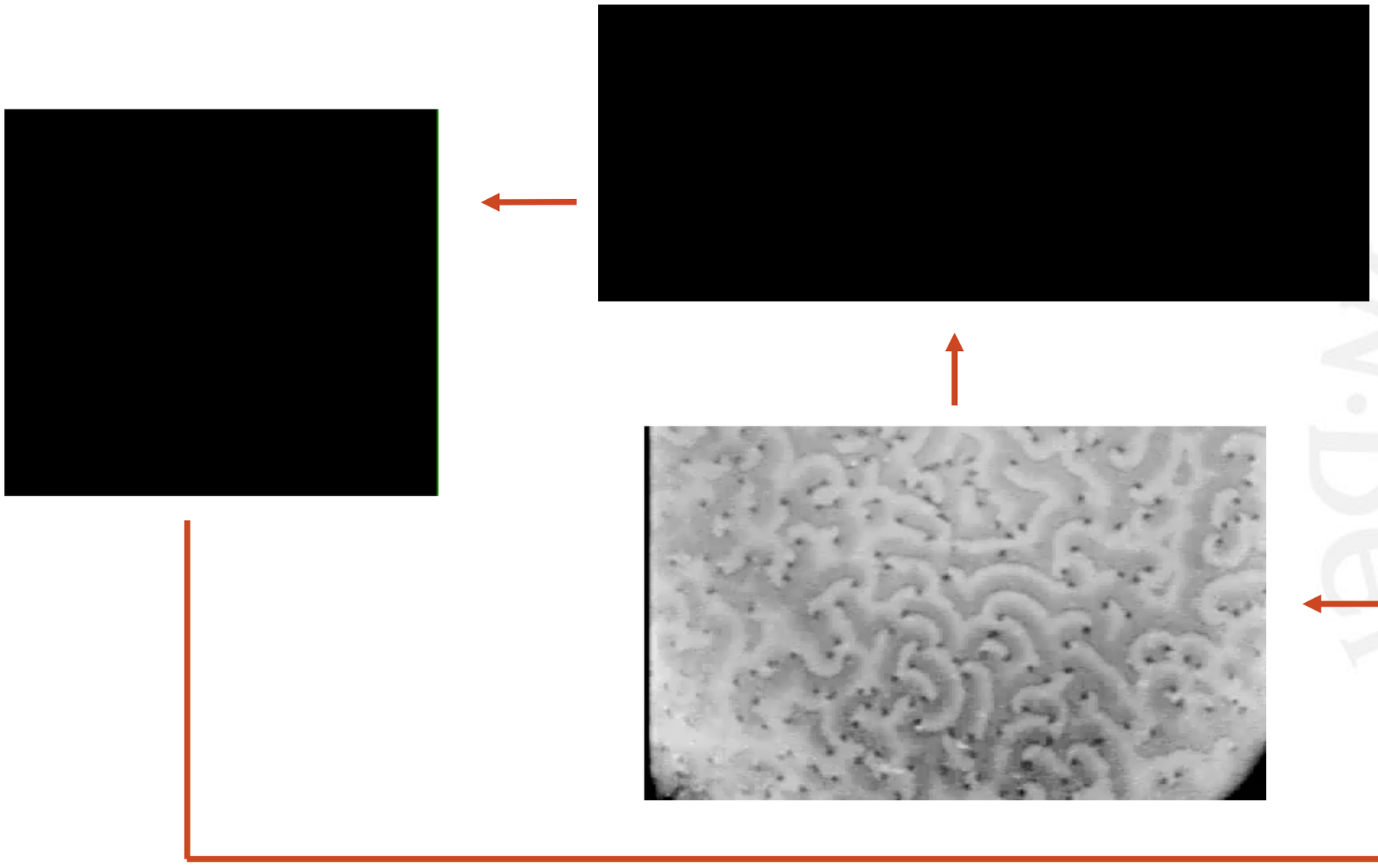
TOOL 3: Control parameter & Order parameter





Forms are emergent:
not expected from components
but arise from interactions between components

Order parameter: Labelling states of a complex system

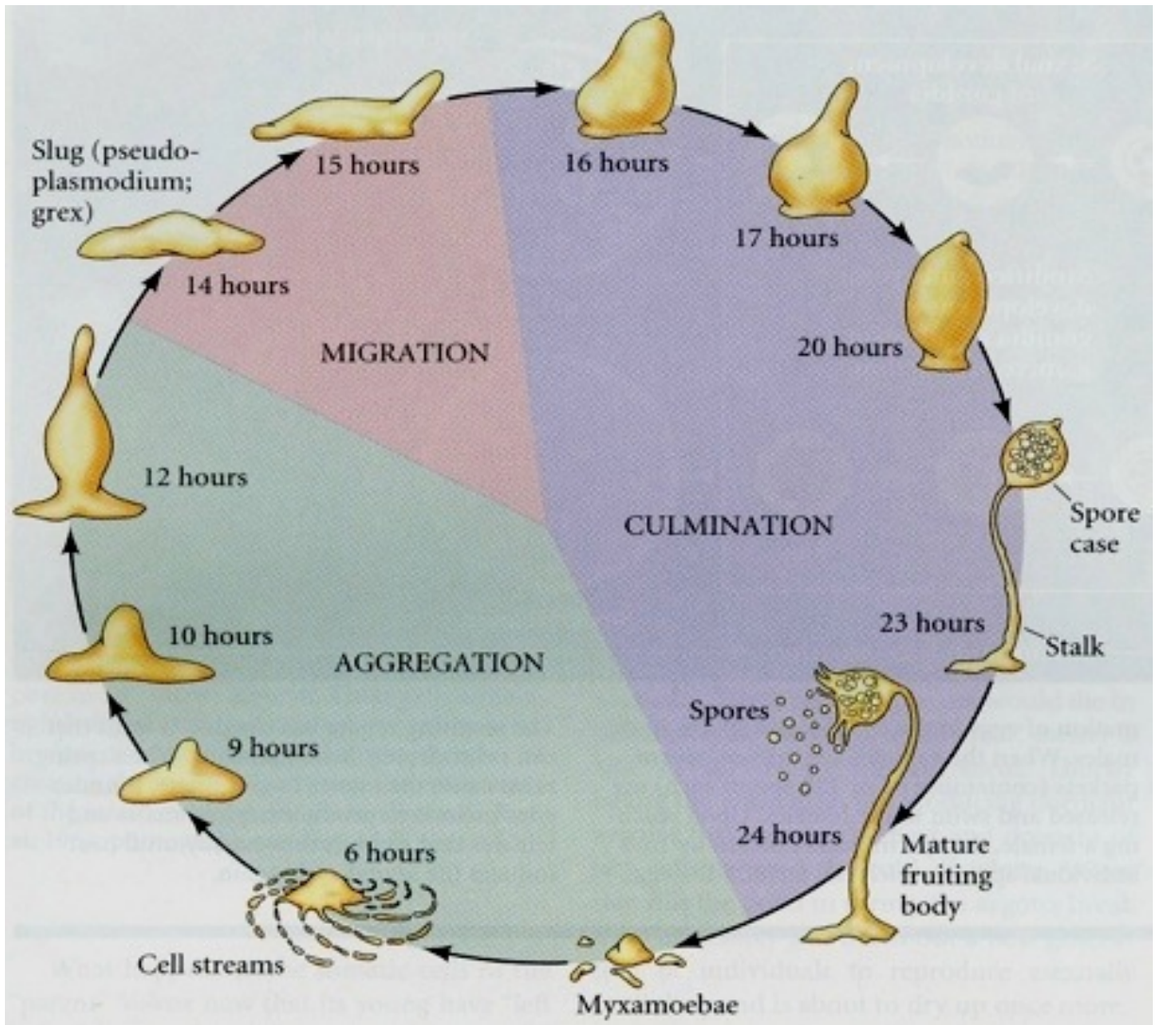


Forms are emergent, self-organised:

Arise from interactions between components

→ reduction of degrees of freedom

TOOL 3: Control parameter & Order parameter



Order parameter: the qualitatively different states

Control parameter: available food (actually concentration of a chemical that is released if they are starving)

Experiments:
Find out if the process is reversible... add food

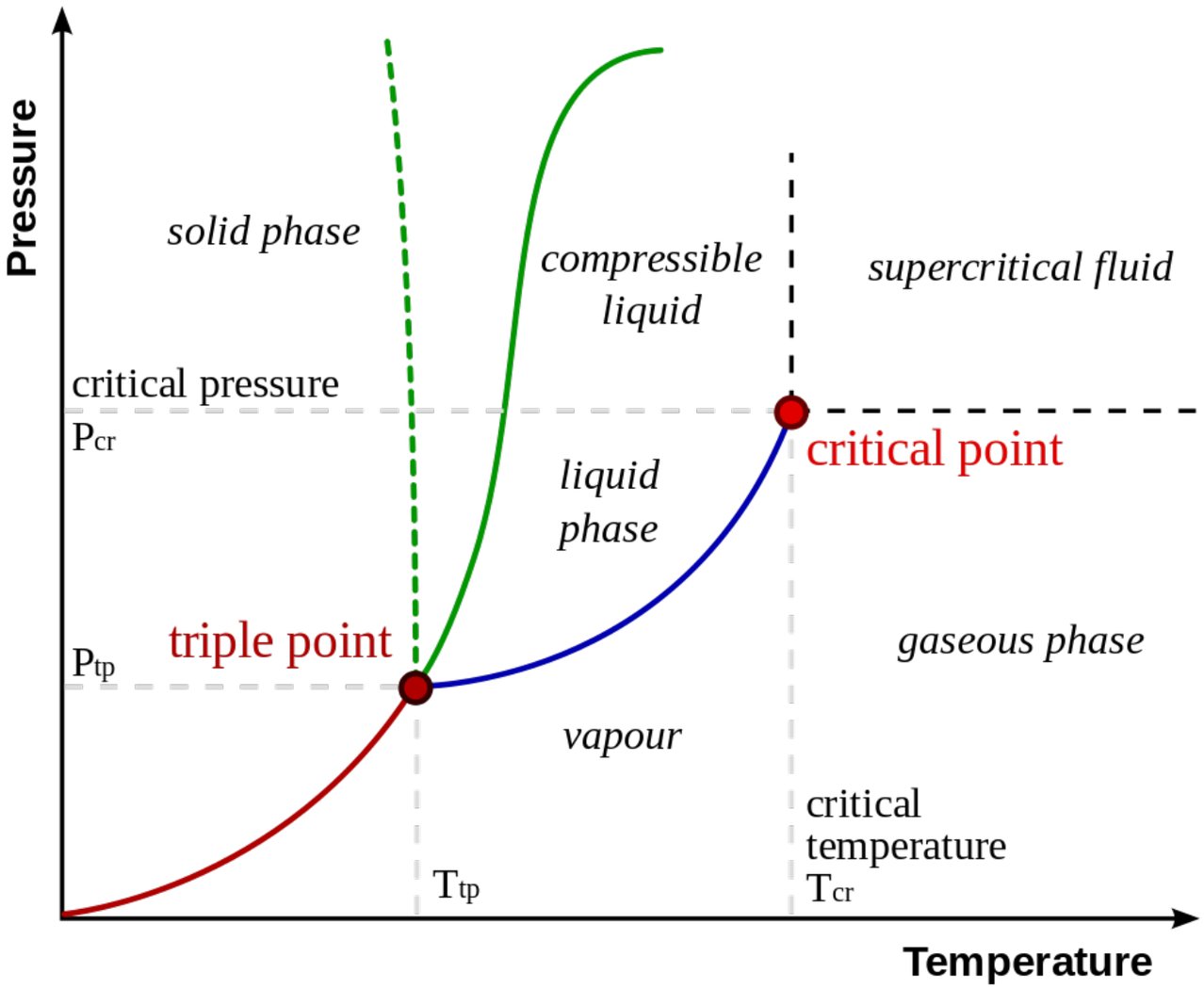
perturb the system during the various phases...

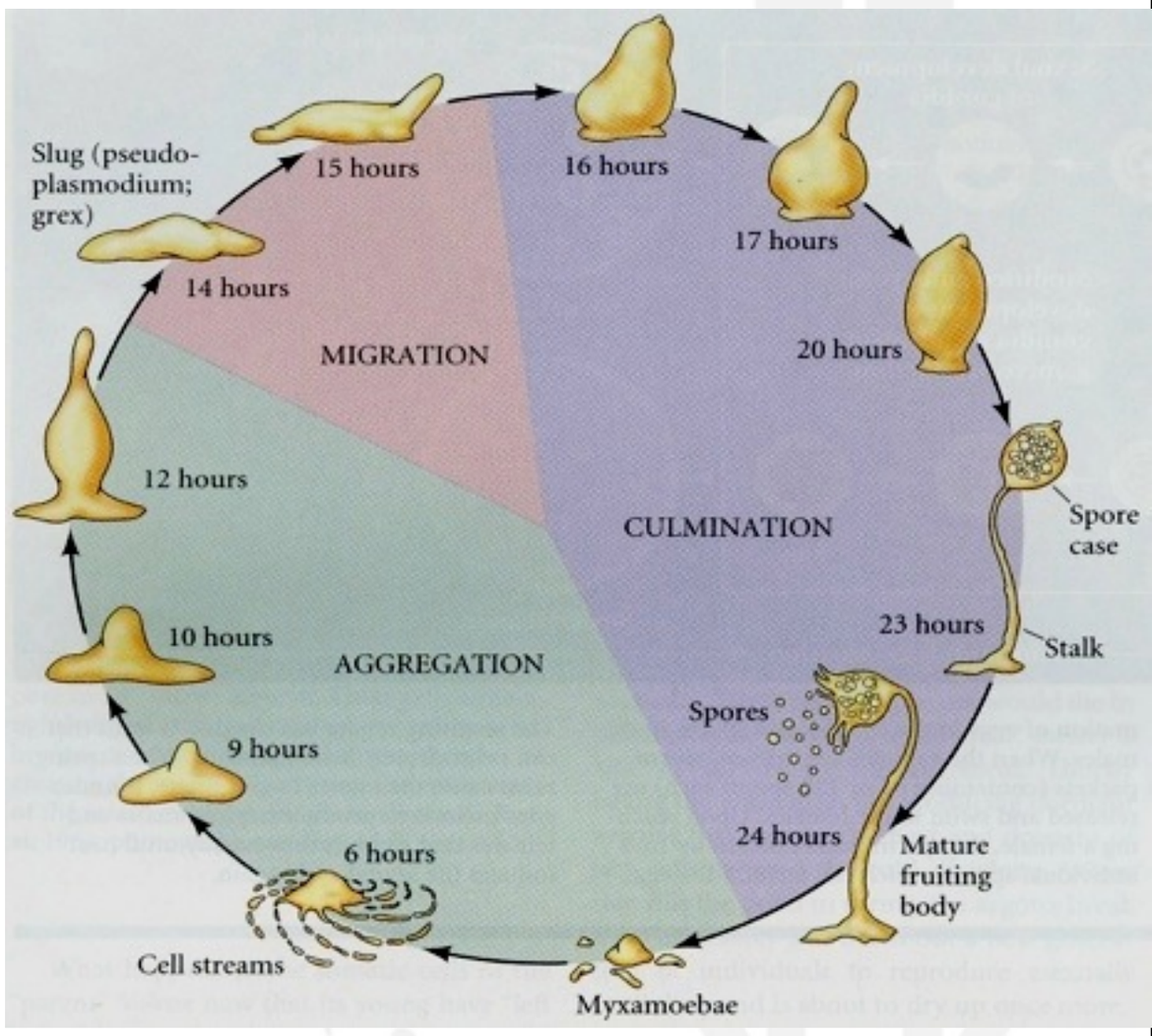
the degrees of freedom of the individual components are increasingly constrained by the interaction:

free living amoebae... slug... immovable sporing pod

nb State space and Phase Space (or: Diagram) are different concepts, but often used interchangeably to describe a State Space…

TOOL 4: State space & Phase space





The order parameter is often a qualitative description of a macro state / global organisation of the system, conditional on the control parameters:

A space listing all the possible states and transitions is a **phase space:**

H_2O: Ice (Solid), Water (Liquid), Steam (Vapour)

Disctyostelium: Aggregation (Mound), Migration (Slug), Culmination (Fruiting Body)

State Space

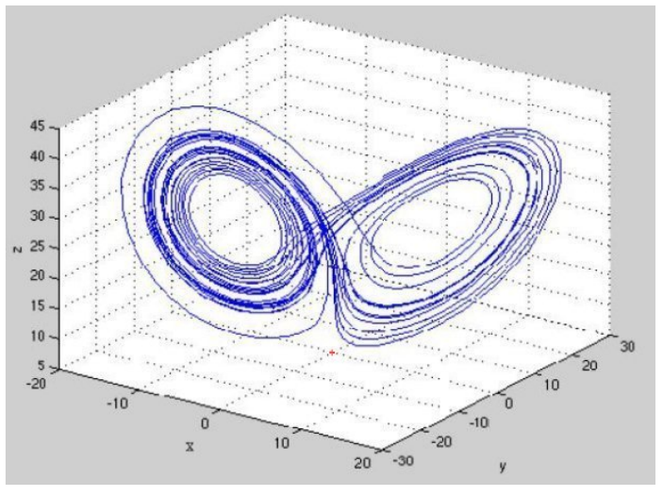
A state space is spanned by a system's state variables, usually coupled equations

Represents the degrees of freedom available to the system.

Every potential configuration (state) of system represented by a point in state space. Change of state over time = Trajectory through the space.

Generally, state space not completely filled by trajectories = Attractors.

$$\frac{dx}{dt} = a(y - x)$$
$$\frac{dy}{dt} = x(b - z) - y$$
$$\frac{dz}{dt} = xy - cz$$



http://universe-review.ca/I01-18-LorenzEqs2.jpg

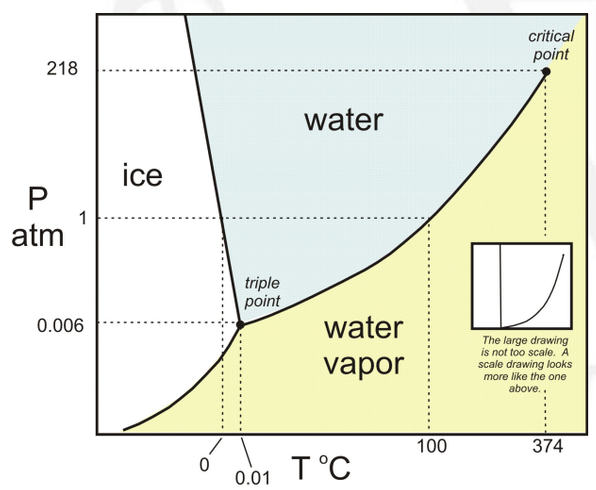
Phase Diagram

A phase diagram describes the order parameter of a system (in reality mostly unknown!)

Represents qualitatively different states.

Every combination of relevant control parameters is labelled by a state. Time does not have to be represented in the space.

Generally, a phase diagram is completely filled labelled regions of qualitatively different states.



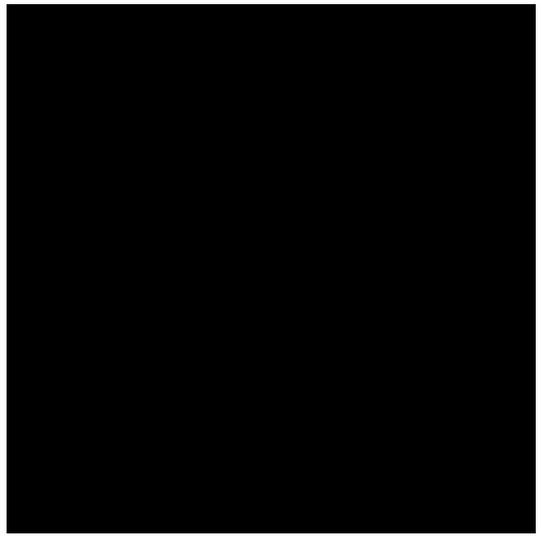
http://cft.fis.uc.pt/eef/FisicaI01/fluids/h2o_phase_diagram.jpg

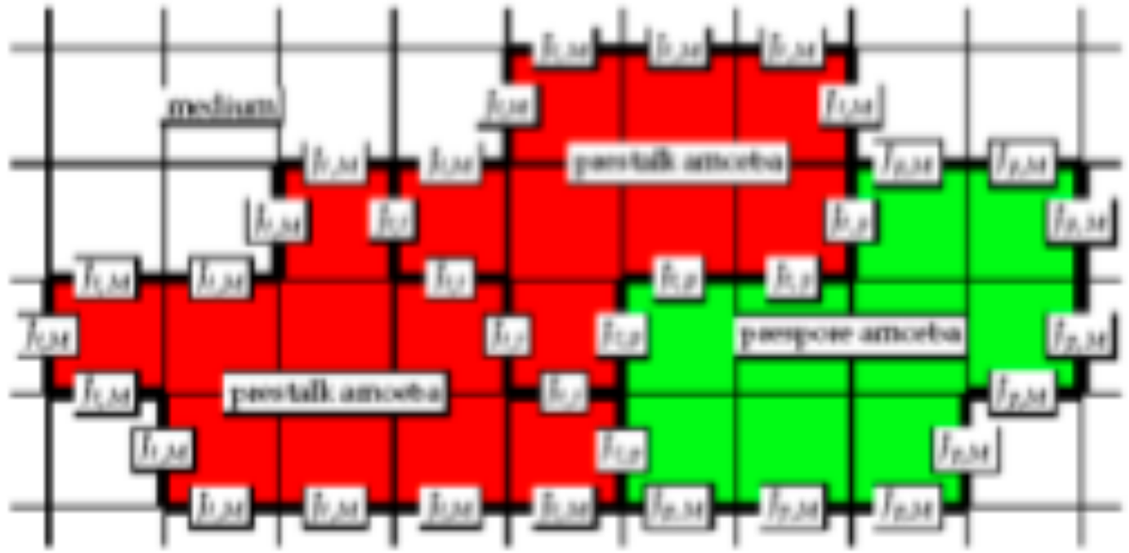
TOOL 5: Dynamical mathematical models

From Pattern Formation to Morphogenesis

Multicellular Coordination in *Dictyostelium Discoideum*

A.F.M. Marée (2000). Proefschrift, UU.



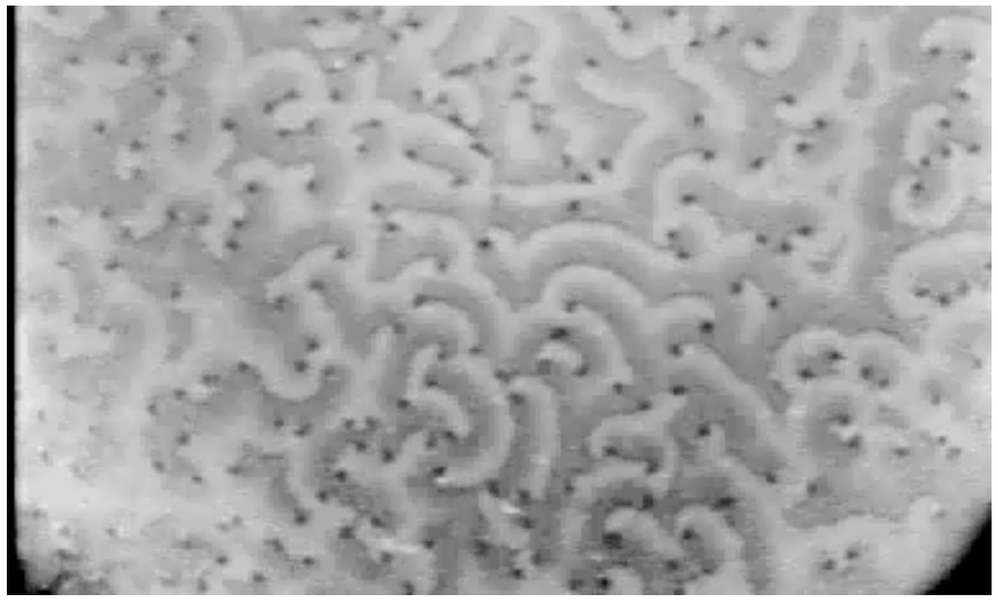


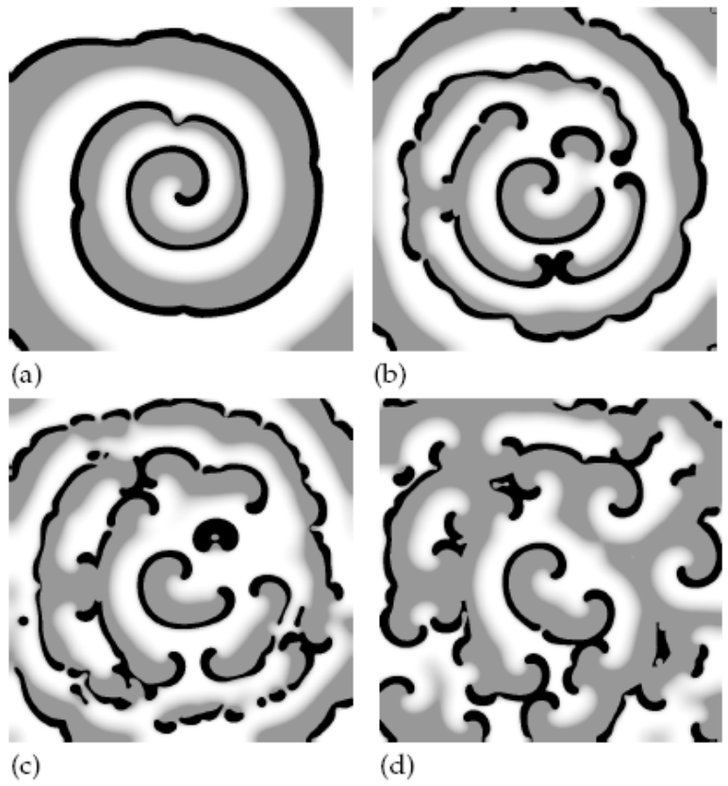
Two-Scale Cellular Automata with Differential Adhesion

$$H_\sigma = \sum_{\text{all } \sigma,\sigma' \text{ neighbours}} \frac{J_{\tau_\sigma,\tau_{\sigma'}}}{2} + \sum_{\text{all } \sigma,\text{medium neighbours}} J_{\tau_\sigma,\tau_{\text{medium}}} + \lambda(v_\sigma - V)^2, \quad (1.1)$$

Spiral Breakup in Excitable Tissue due to Lateral Instability

Marée, A. F. M., & Panlov, A.V. (1997). *Physical Review Letters, 78*,1819-1822.





$$\frac{\partial e}{\partial t} = \Delta e - f(e) - g,$$

$$\frac{\partial g}{\partial t} = D_g \Delta g + \varepsilon(e,g)(ke - g),$$

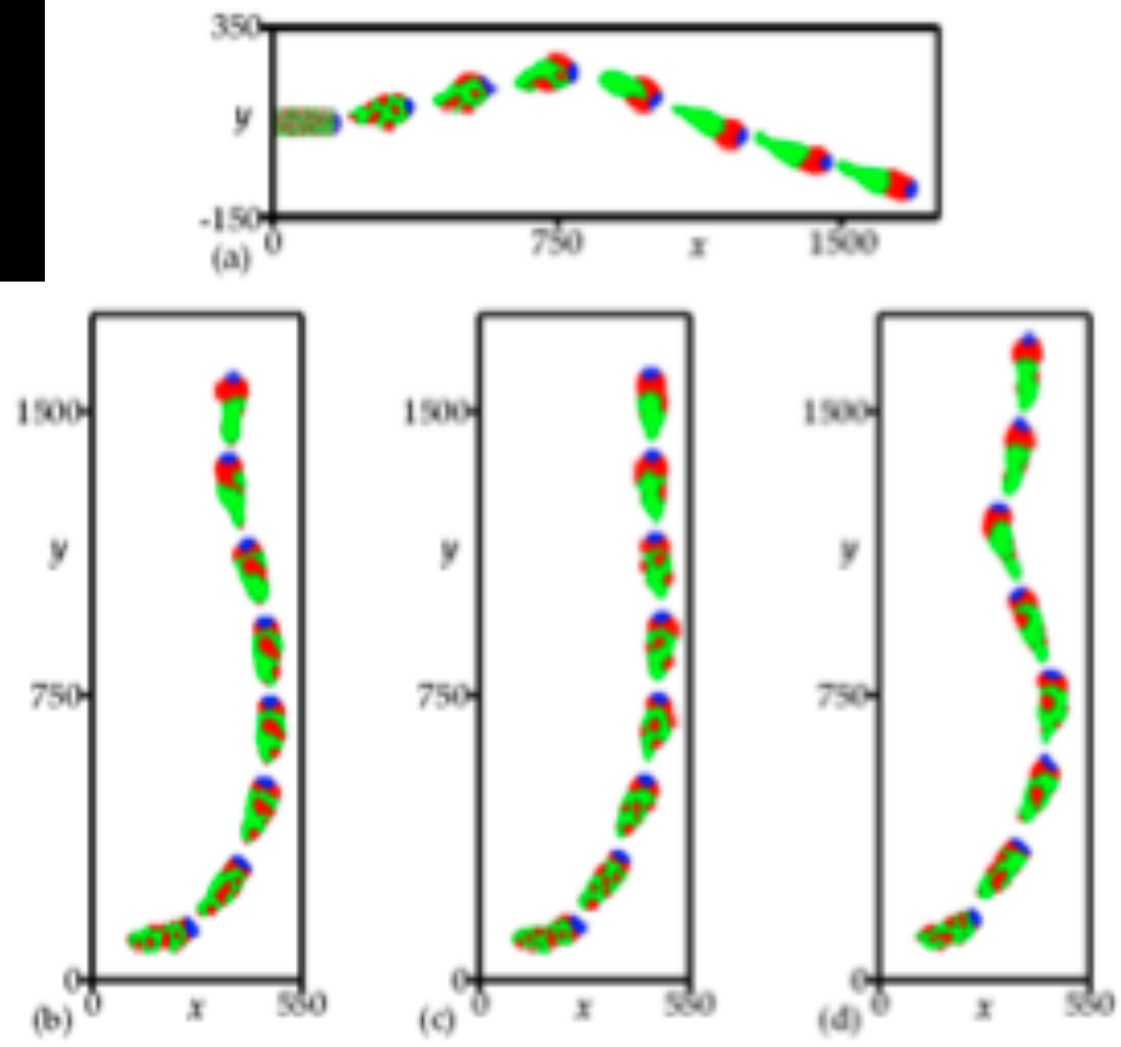
[redacted]

$$H_\sigma = \sum \frac{J_{\text{cell,cell}}}{2} + \sum J_{\text{cell,medium}} + \lambda(v - V)^2,$$

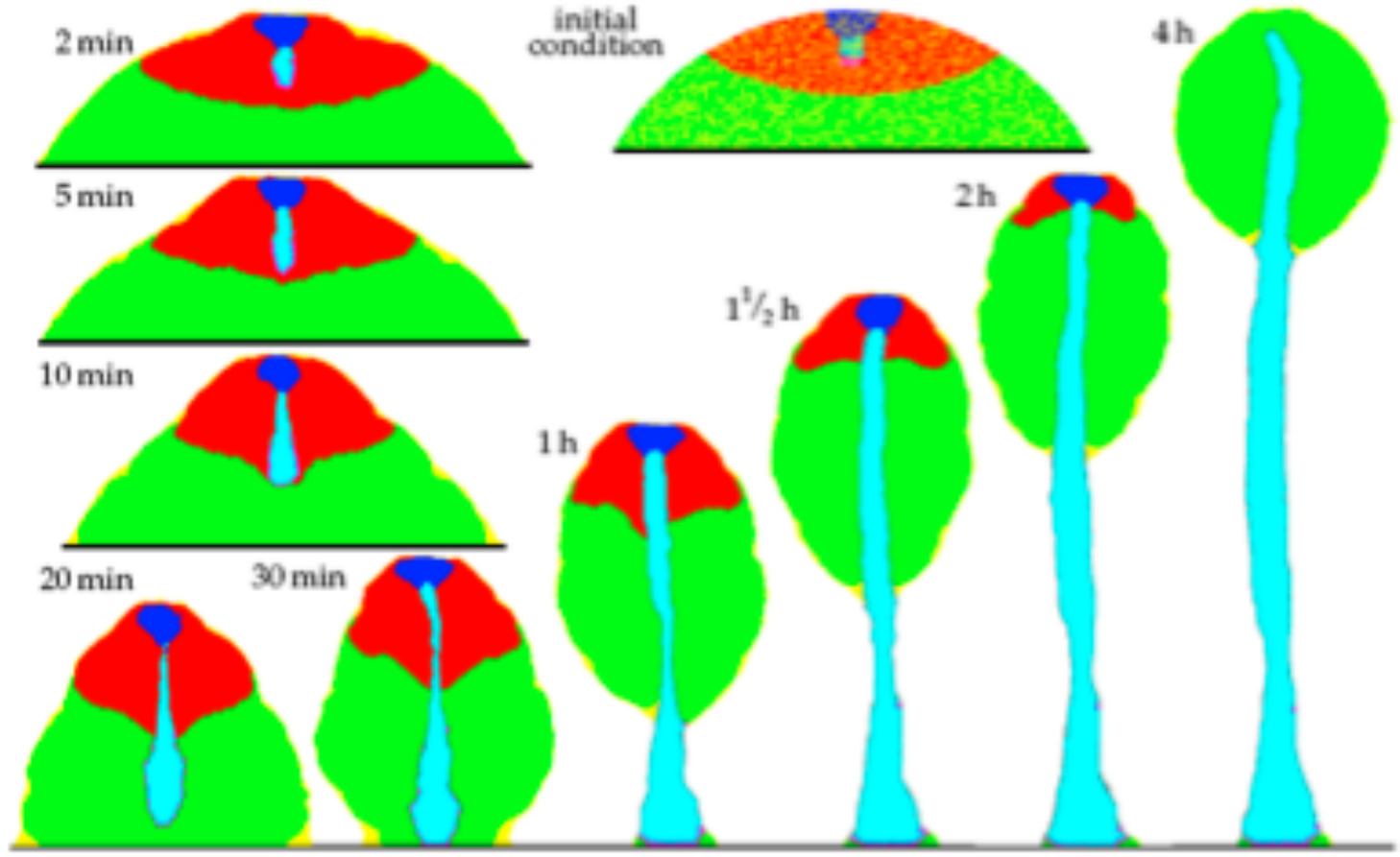
$$\left.\begin{aligned} \frac{\partial c}{\partial t} &= D_c \Delta c - f(c) - r, \\ \frac{\partial r}{\partial t} &= \varepsilon(c)(kc - r), \end{aligned}\right\} \text{inside the amoebae}$$

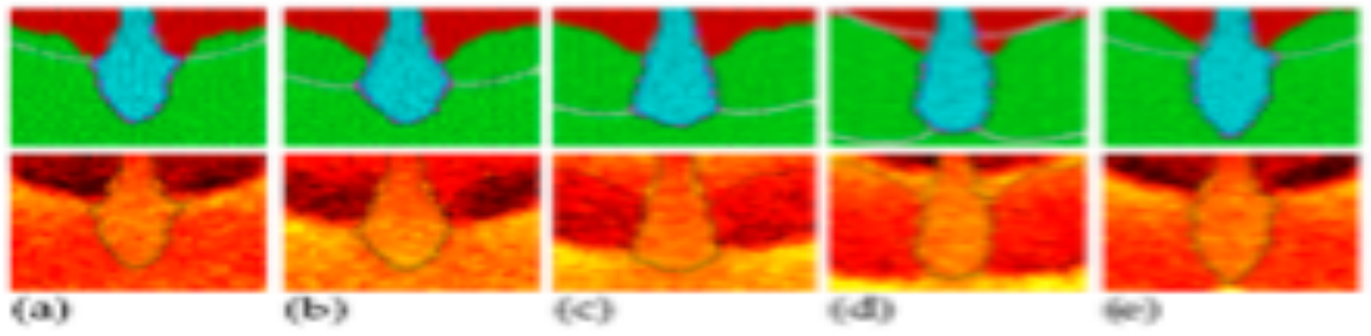
$$\left.\begin{aligned} \frac{\partial c}{\partial t} &= D_c \Delta c - d_c(c - c_0), \end{aligned}\right\} \text{outside the amoebae}$$

$$\Delta H' = \Delta H - \mu(c_{\text{automaton}} - c_{\text{neighbour}}),$$

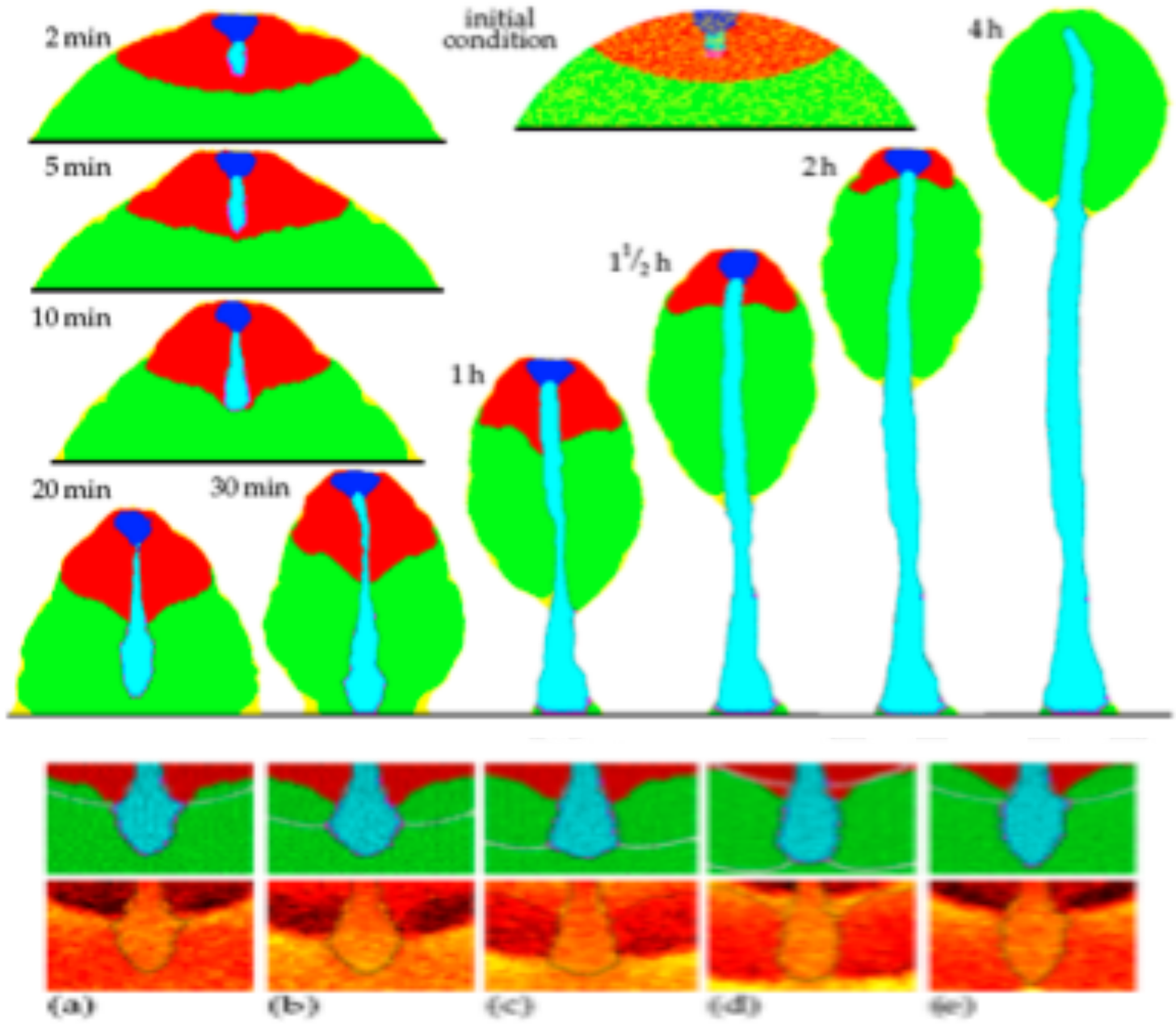


Mathematical model of Dictyostelium





Mathematical model of Dictyostelium



Mathematical model of Dictyostelium

Some assumptions for a Complex Systems Approach to Behavioural- Cognitive- Neuro- science (BCN)

0. Psychological systems, are biological systems, are physical systems, are complex, open, non-ergodic dynamical systems.

1. BCN science studies dynamics of behavioural phenomena rather than statics

2. BCN science develops technology (diagnostic tests, interventions) aimed at behaviour of individuals

3. BCN science studies behavioural phenomena at some aggregate or macro-level that arises from interactions between component processes on multiple temporal and spatial scales…

4. Massive multi-scale interaction instead of massive modularity (cf. Carruthers, 2006)