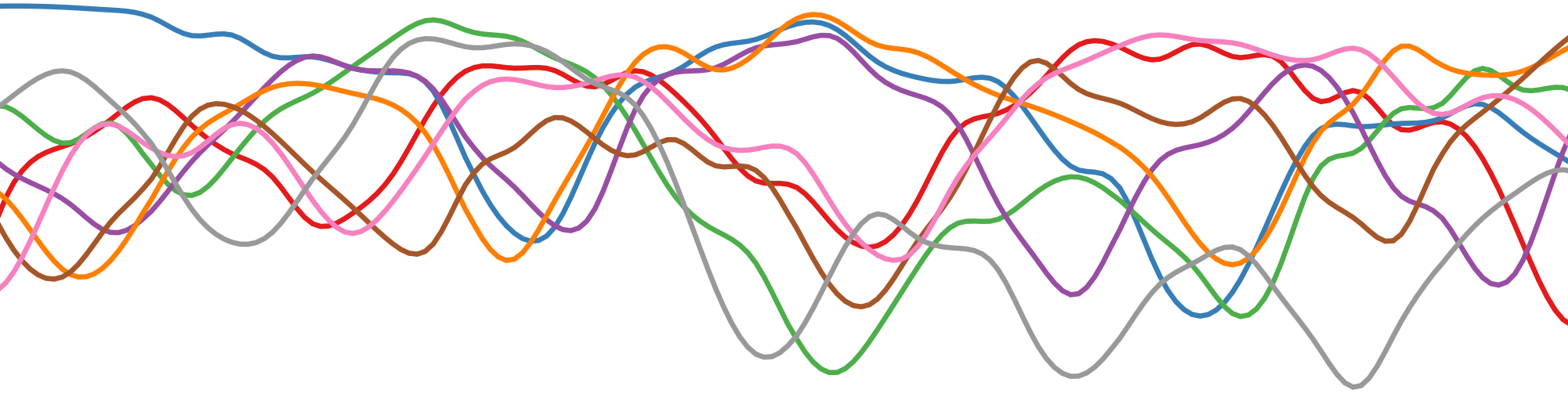
SYNERGY AND INFORMATION IN COMPLEX NEURAL SYSTEMS

LINKING BIOLOGICAL AND ARTIFICIAL INTELLIGENCE



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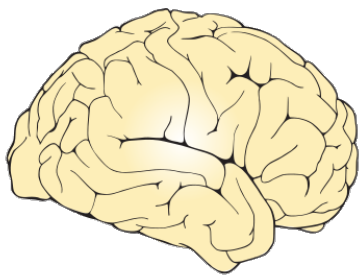
Queen Mary University of London

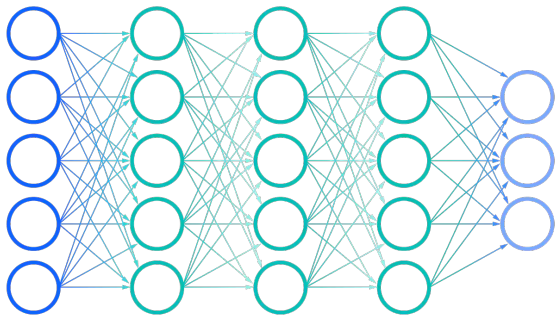
RESEARCH GOAL

Goal:

Discover the principles of *collective behaviour*.

Behaviour of large groups of agents acting as a whole.

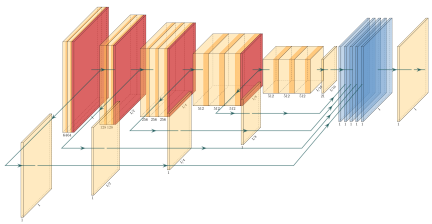




RESEARCH GOAL

Why care about collective behaviour?

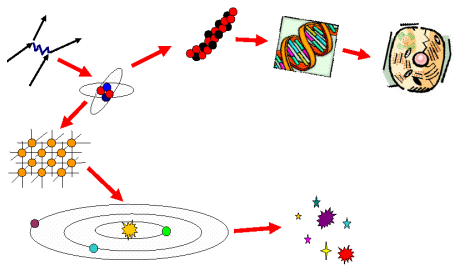
To build better systems



To understand ourselves

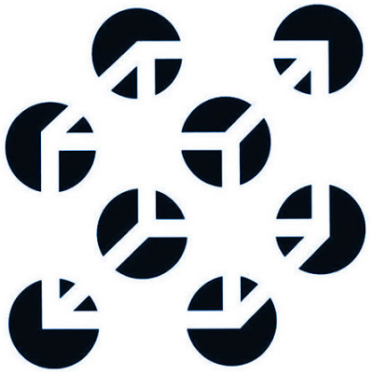
To fix it when it breaks

To understand the world

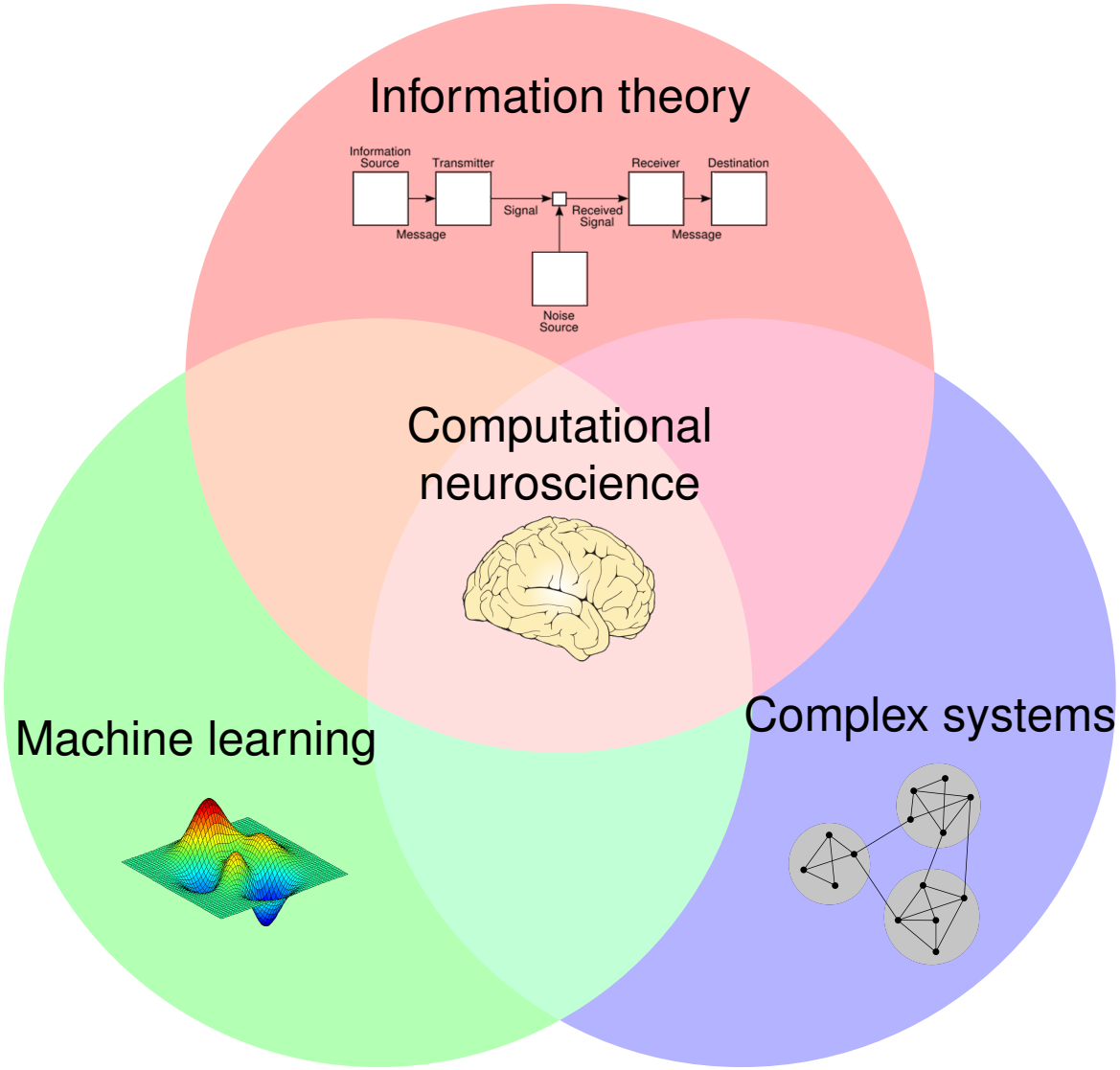


COMMON PRINCIPLE: EMERGENCE

Informally: "the whole is more than the sum of its parts."



INTERDISCIPLINARITY AT HEART



RESEARCH OBJECTIVE

Objective:

Study of complex systems with rigorous computational and statistical tools.

Methods:

- Information theory
- Machine learning

Application:

- Computational neuroscience

Rationale:

Complexity enables new connections between ML and neuroscience.

THIS TALK

PART I

Theory: Information theory for collective phenomena

PART II

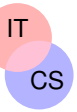
Practice: Data analysis tools, insights, and new results

PART III

What's next: Ongoing research and future outlook

THEORY

ENTROPY AND INFORMATION

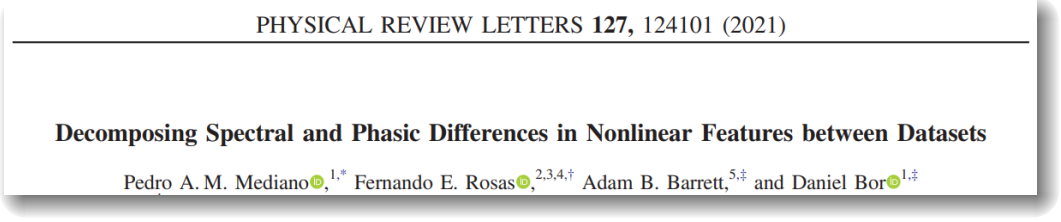


- Building block of information theory: Shannon entropy.

$$H(X) = -\sum_x p_x \log p_x$$

Entropy is hard to estimate from real data!

Practical estimator based on Lempel-Ziv's compression algorithm.



PHYSICAL REVIEW LETTERS **127,** 124101 (2021)

Decomposing Spectral and Phasic Differences in Nonlinear Features between Datasets

Pedro A. M. Mediano,[1,*] Fernando E. Rosas,[2,3,4,†] Adam B. Barrett,[5,‡] and Daniel Bor[1,‡]

Physical Review Letters
APS physics

(IF: 9.2)

Fernando Rosas

Daniel Bor

Adam Barrett

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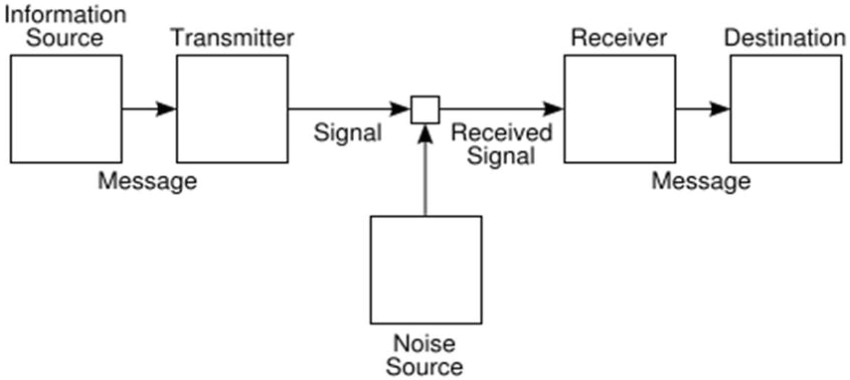
UNIVERSITY OF CAMBRIDGE

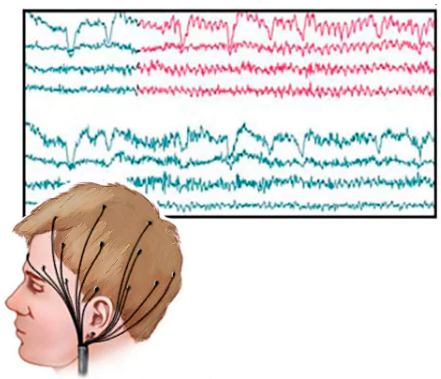
UNIVERSITY OF SUSSEX

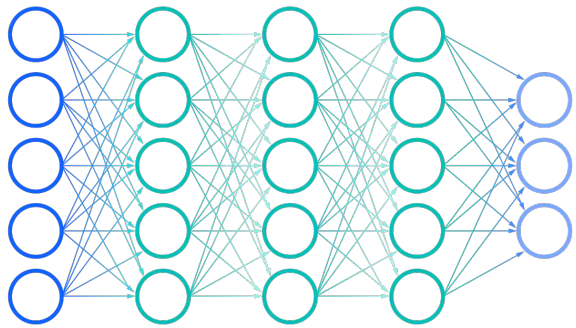
INFORMATION BEYOND SHANNON

- Shannon's mutual information: from sender to receiver.



- But complex systems have many more than two parts!





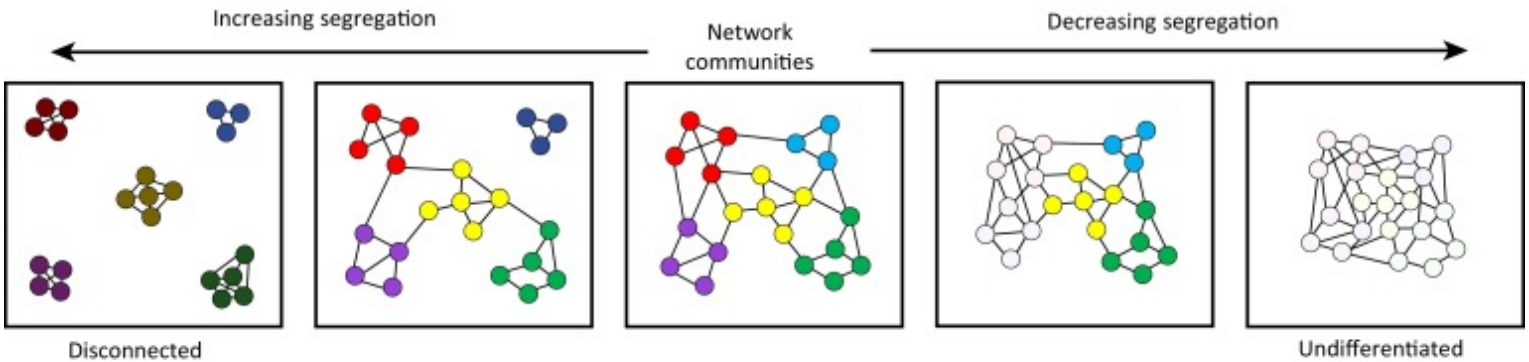
Plain information theory is insufficient for complex systems!

INSPIRATION FROM NEUROSCIENCE

Inspiration from neuroscience: Integrated Information Theory (IIT).

Brain dynamics result from two opposing forces:

- **Segregation**: brain regions can act independently of each other;
- **Integration**: and they can also integrate into high-level cognition.

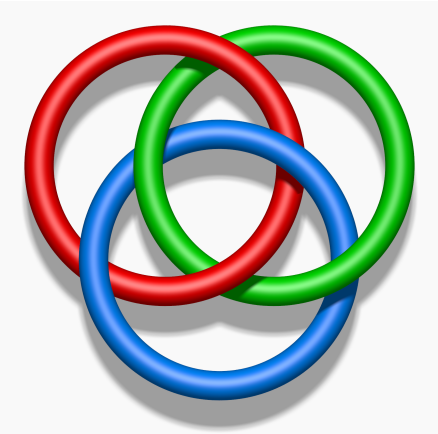


- Has lead to multiple measures of *integrated information*, Φ.

BEYOND IIT: SYNERGY AND REDUNDANCY

- Two variables can either be correlated (i.e. coupled) or not, and this is measured by *mutual information*.

- With 3+ variables there are different **types of correlations**: some are visible from the parts, some aren't.



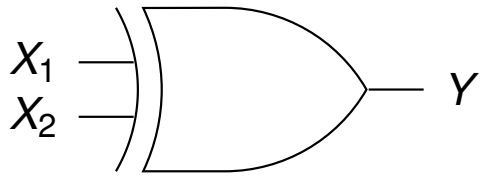
Synergy

Redundancy

EXAMPLE: XOR LOGIC GATE

Perfect example of synergy: XOR.

X_1	X_2	Y
0	0	0
0	1	1
1	0	1
1	1	0



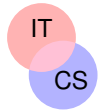
- Knowing one input tells you nothing:

$$I(X_1; Y) = I(X_2; Y) = 0$$

- Knowing both inputs tells you everything:

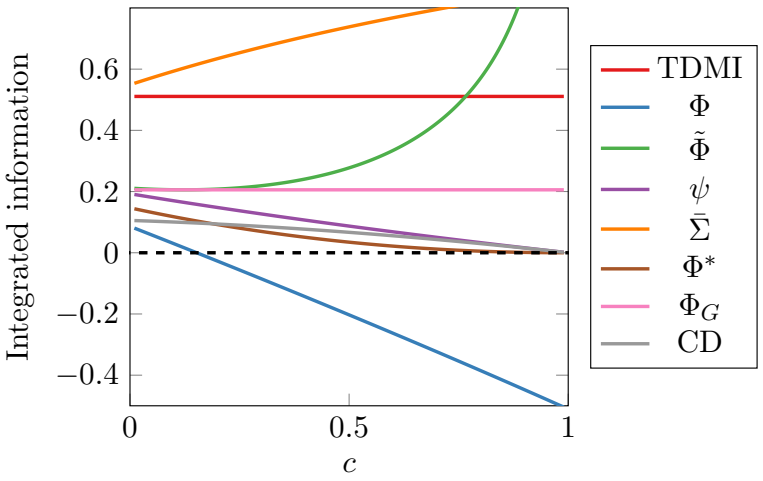
$$I(X_1 X_2; Y) = 1$$

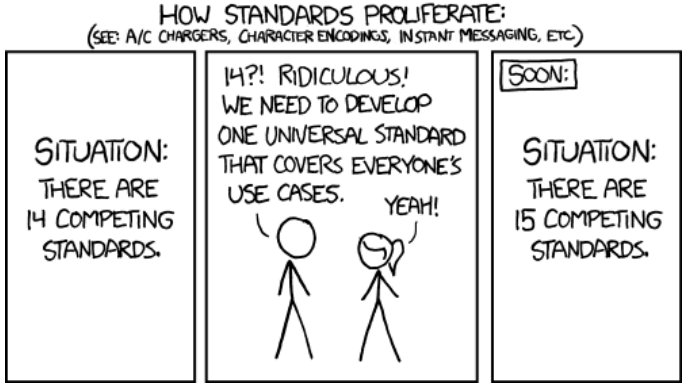
INTEGRATED INFORMATION THEORY



- First complete, systematic review of Φ measures.

Many measures proposed, still no consensus.

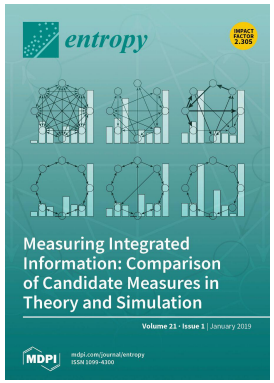




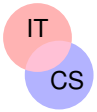
Adam Barrett

Anil Seth

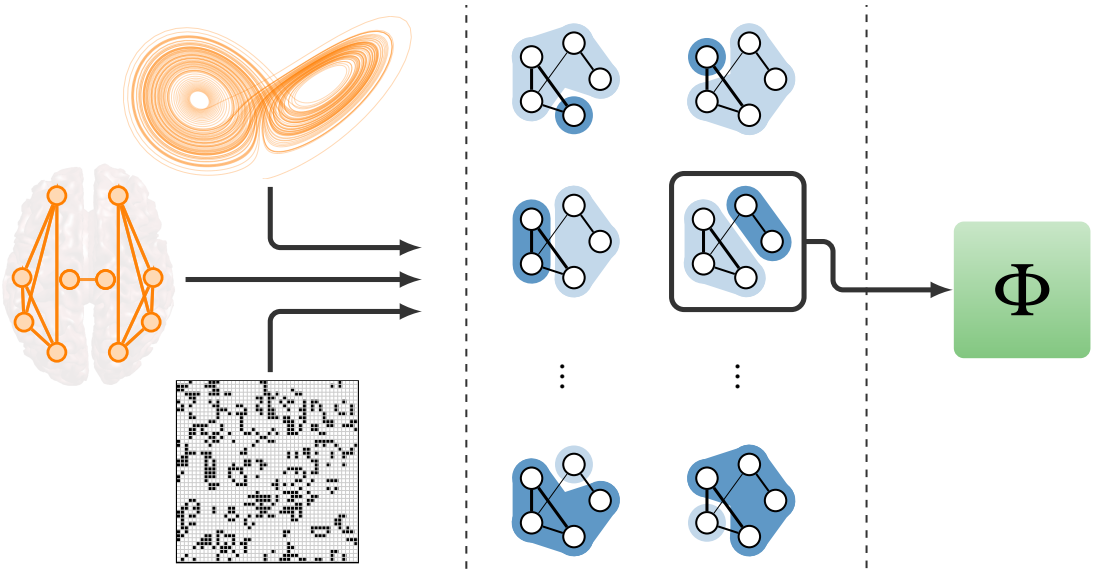
University of Sussex



INTEGRATED INFORMATION THEORY



- Multiple contributions extending and applying IIT.
  $\rightarrow$ 18 full-length papers on IIT and related topics in my PhD.



entropy

AIP Chaos

Trends in Cognitive Sciences
(IF: 15.4)


Murray Shanahan


Fernando Rosas


Adam Barrett


Anil Seth

Imperial College London

US University of Sussex

A PRACTICAL MEASURE OF SYNERGY

IT CS

- New measure: O-information, $\Omega(\boldsymbol{X}^n)$.

Quantifying high-order interdependencies via multivariate extensions of the mutual information

Fernando E. Rosas, Pedro A. M. Mediano, Michael Gastpar, and Henrik J. Jensen
Phys. Rev. E **100**, 032305 – Published 13 September 2019

redundancy!

$\Omega(\boldsymbol{X}^n) > 0$

synergy!

$\Omega(\boldsymbol{X}^n) < 0$

Fernando Rosas

Henrik Jensen

Michael Gastpar

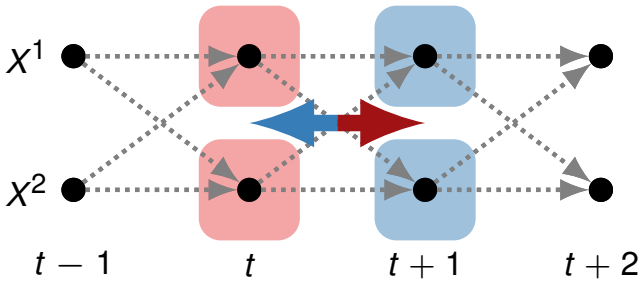
Imperial College London

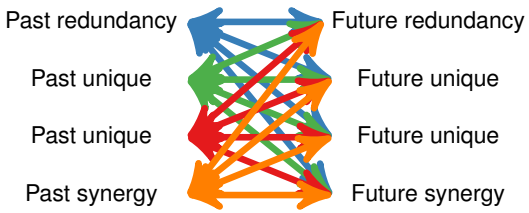
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

INTEGRATED INFORMATION DECOMPOSITION

Integrated information decomposition:
Decomposition of Φ into redundant and synergistic components.

- New family of information measures for multivariate data.





nature physics
(IF: 20.0)

nature neuroscience
(IF: 24.9)


Andrea Luppi


Fernando Rosas


Daniel Bor


Adam Barrett

Imperial College London
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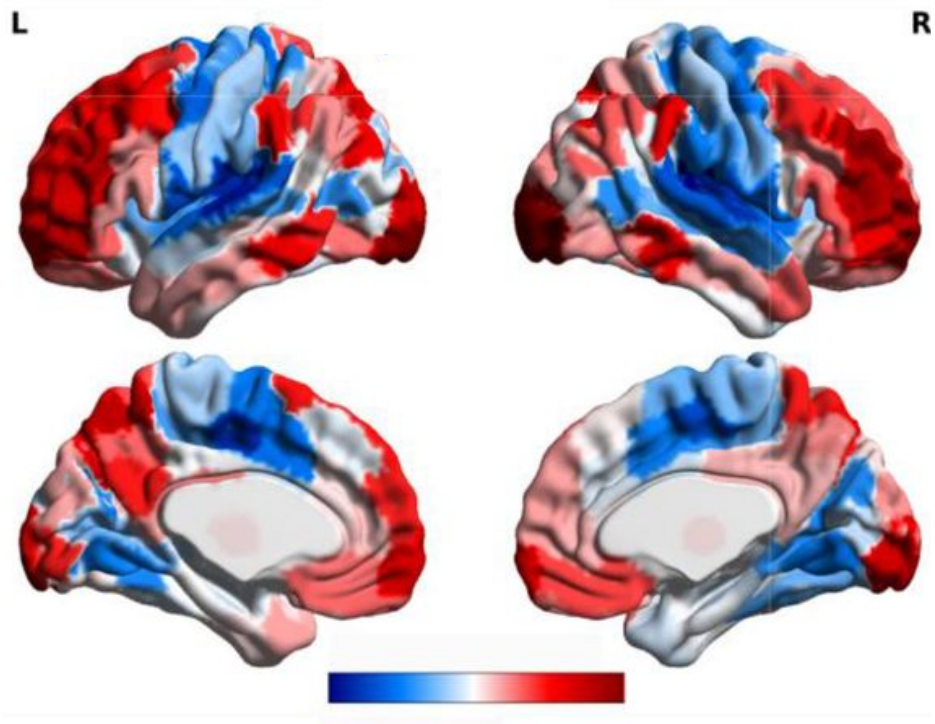
UNIVERSITY OF SUSSEX

SYNERGY IN THE BRAIN

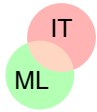
- We calculate the **synergy-redundancy** distribution in the brain.

Synergy higher in areas related with high-level cognitive function.
Redundancy higher in areas related with sensorimotor processing.



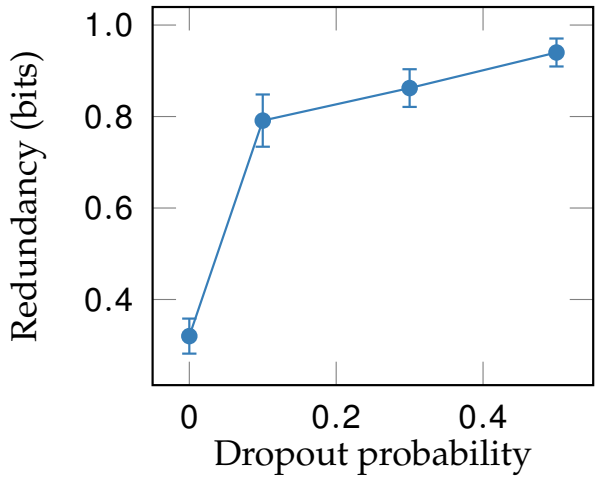
Synergy minus Redundancy rank gradient

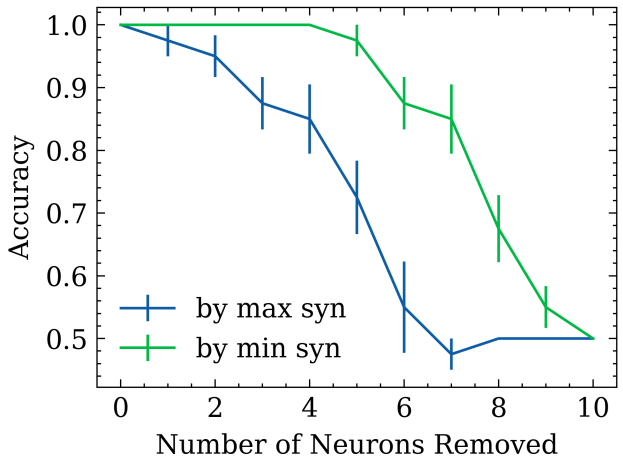
SYNERGY IN NEURAL NETWORKS



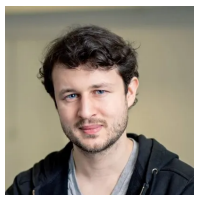
- We calculate synergy between layers of small neural nets.

Synergy increases when network learns multiple tasks.
Redundancy increases when subject to noise (dropout).





Alexandra Proca



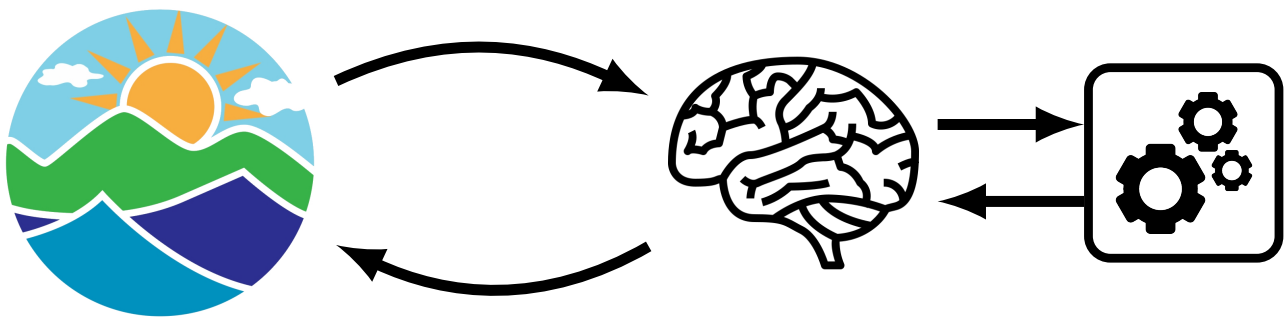
Matt Crosby

UCL
Imperial College London

LINKING MINDS AND MACHINES

✓ **Redundancy** provides reliable I/O to the system.
→ Higher in sensorimotor areas, robust to noise.

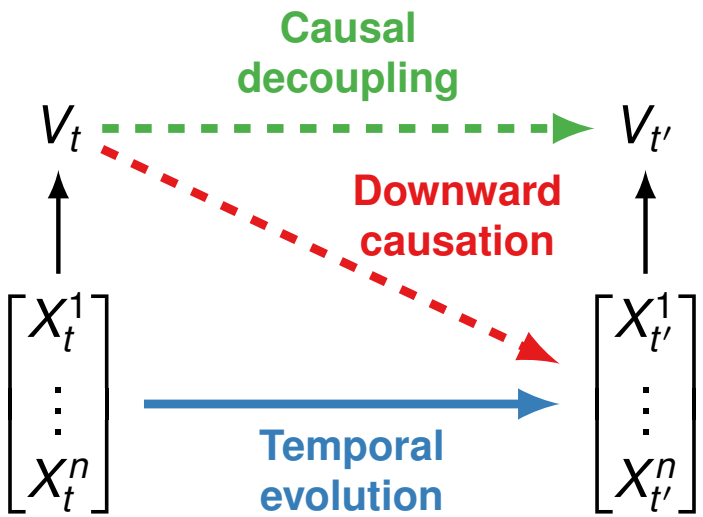
✓ **Synergy** supports general-purpose high-level cognition.
→ Higher in associative areas and multitask networks.



FORMALISING CAUSAL EMERGENCE

- Informal definition: when 'macro' variable V_t has information about the future not present in 'micro' variables X_t^i.

Tight links between emergence and synergy; tractable emergence lower bounds.



PLOS COMPUTATIONAL BIOLOGY

THE ROYAL SOCIETY PUBLISHING


Fernando Rosas


Henrik Jensen


Daniel Bor


Adam Barrett

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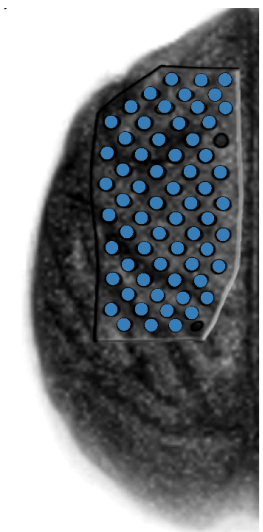
US UNIVERSITY OF SUSSEX

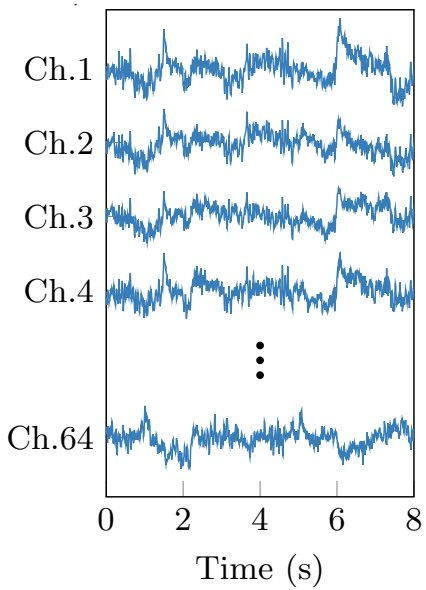
FORMALISING CAUSAL EMERGENCE

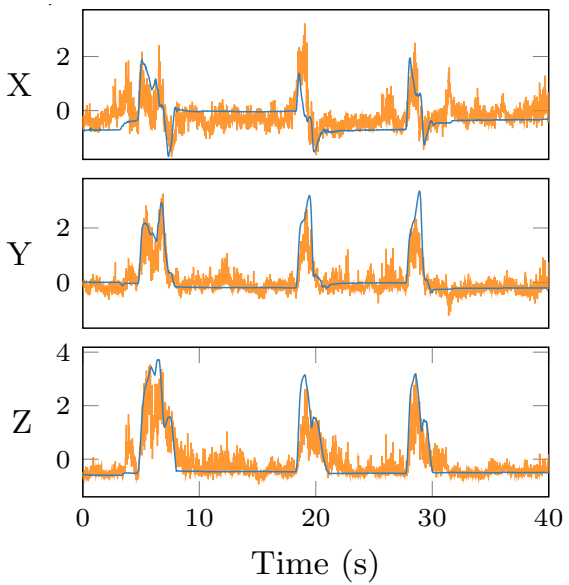
Example of emergence: **neural activity** during motor control.

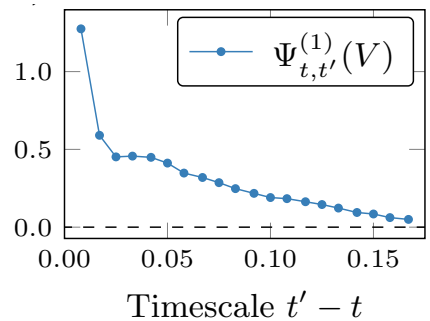
- **Micro variable**: 64-channel brain activity.
- **Macro variable**: 3D SVM-decoded hand motion.

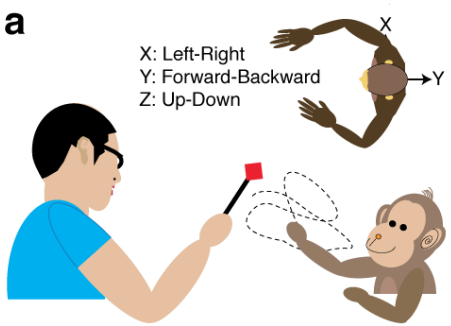
$\Psi(V) > 0$
$\Downarrow$
emergence











EMERGENCE MEETS ART: SYNCH.LIVE

ML CS

- Participants move freely, trying to synchronise their hat lights.
  $\rightarrow$ Real-time feedback by computer vision and online learning.

First-person experience of collective emergence.

Madalina Sas

Hillary Leone

Daniel Bor

Fernando Rosas

Imperial College London

UNIVERSITY OF CAMBRIDGE

IMPACT

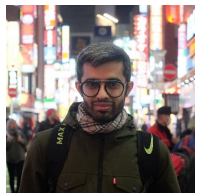
✓ Fertile ground for new research: 9 MSc + 4 PhD projects based on these theories

Alexandra Proca
Andrew Esterson
Connie Sheeran
J.C. Farah
Hugh Spaughton

Alberto Liardi
Stefan Milhacea
Jennifer Fielder
Tycho Tax


Andrea Luppi


Madalina Sas


Hardik Rajpal

1 open PhD position in QMUL

✓ Internationally well-received: follow-up research by multiple independent labs.


A Framework for the Time- and Frequency-Domain Assessment of High-Order Interactions in Brain and Physiological Networks

Luca Faes,[1,*] Gorana Mijatovic,[2] Yuri Antonacci,[3] Riccardo Pernice,[4] Chiara Barà,[4] Laura Sparacino,[4] Marco Sammartino,[4] Alberto Porta,[5] Daniele Marinazzo,[6] and Sebastiano Stramaglia[7]

Decomposing past and future:
Integrated information decomposition based on
shared probability mass exclusions.

Thomas F. Varley[1,2*]

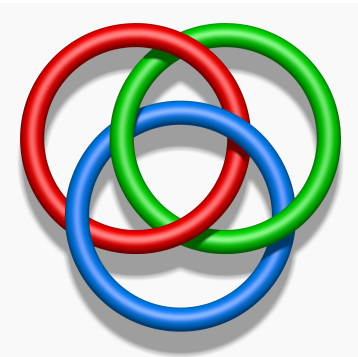
Quantifying Dynamical High-Order Interdependencies From the O-Information: An Application to Neural Spiking Dynamics

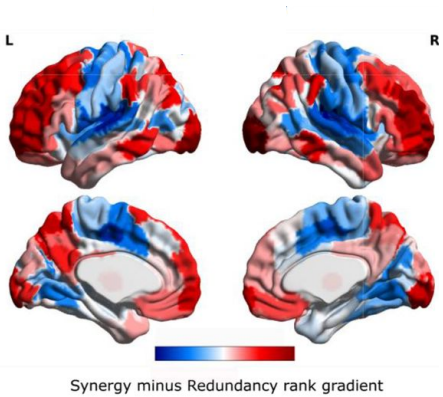
Sebastiano Stramaglia[1,2*], Tomas Scagliarini[1], Bryan C. Daniels[3] and Daniele Marinazzo[4]

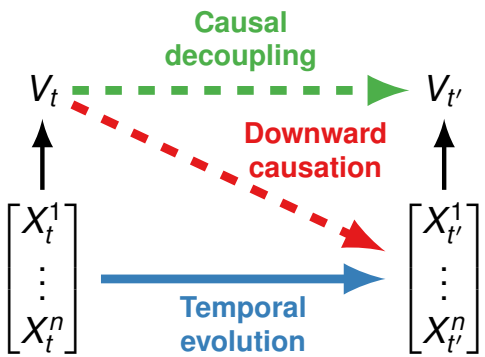
INTERIM SUMMARY

THEORY

- ✓ Significant extensions to information theory for complex systems analysis based on synergy and emergence.
- ✓ New insights linking synergy and redundancy to biological and artificial intelligence.
- ✓ Promising avenues for future research.

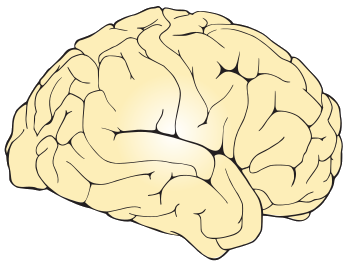






PRACTICE

REAL-WORLD DATA ANALYSIS



Can we apply these ideas to solve real-world problems?

Yes! Let's focus on two examples:

1. Mental health treatment.
2. Diagnosis of neurological disorders.

PRELIMINARIES: OPEN-SOURCE SOFTWARE

- Widely used toolboxes for information-theoretic analyses:

JIDT

IDTxl

- GPU-accelerated estimation of information measures.
  $\rightarrow$ Fastest available estimator of its kind.

Used in >50 published papers.

Joe Lizier

Patricia Wollstadt

Leo Novelli

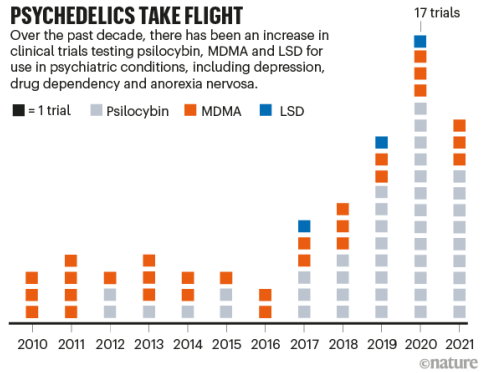
THE UNIVERSITY OF SYDNEY

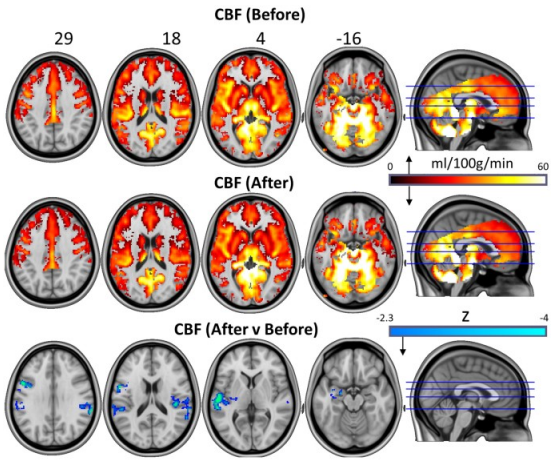
GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

`jlizier/jidt`
`pwollstadt/idtxl`

APPLICATIONS I: PSYCHEDELIC THERAPY

- Psychedelic drugs have resurfaced as promising treatments for mental health.

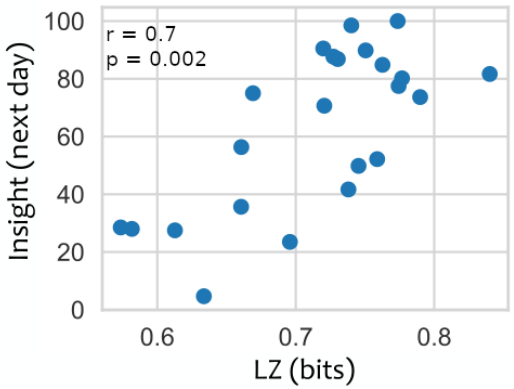


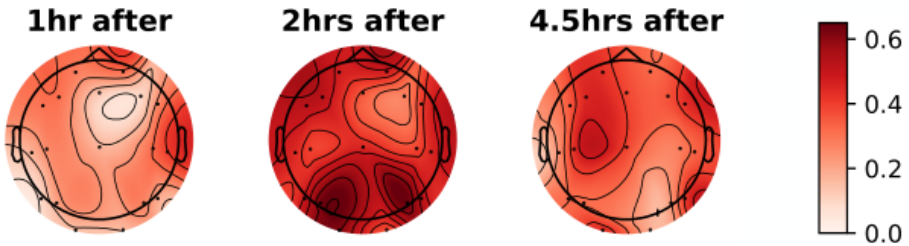


APPLICATIONS I: PSYCHEDELIC THERAPY

Entropy-based regressor predicts psychological outcomes of psychedelic therapy.

- Prospective patent application.





Feature importance

Taylor Lyons

Fernando Rosas

Chris Timmermann

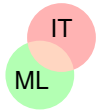
Robin Carhart-Harris

Imperial College London

UCSF

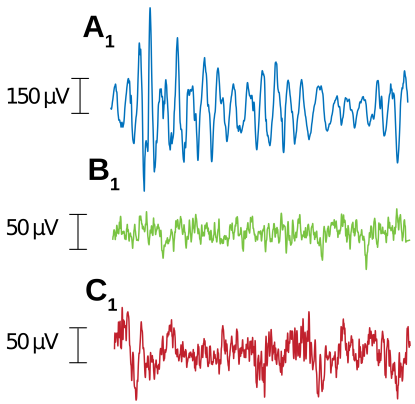
APPLICATIONS II: CLINICAL DIAGNOSIS

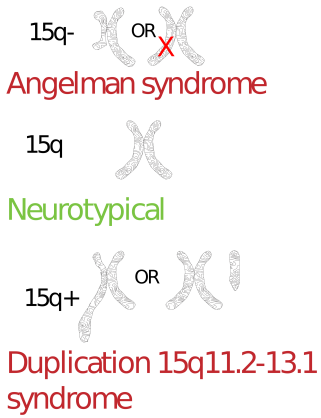
RARE GENETIC DISEASES

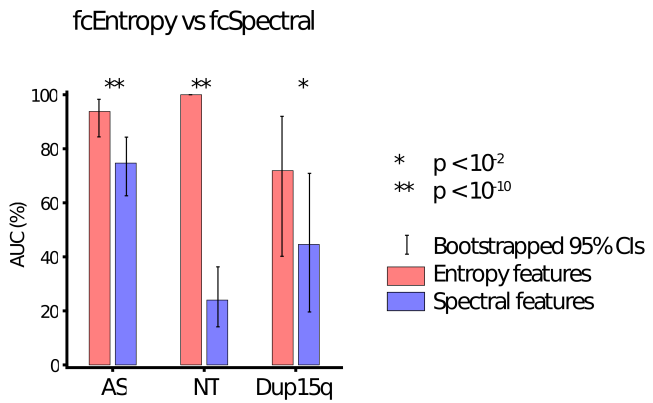


- Angelman syndrome: rare genetic disorder with severe effects.

Classifiers with entropy-based features generalise better than previous alternatives.







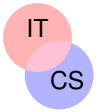
Joel Frohlich

Martin Monti

UCLA

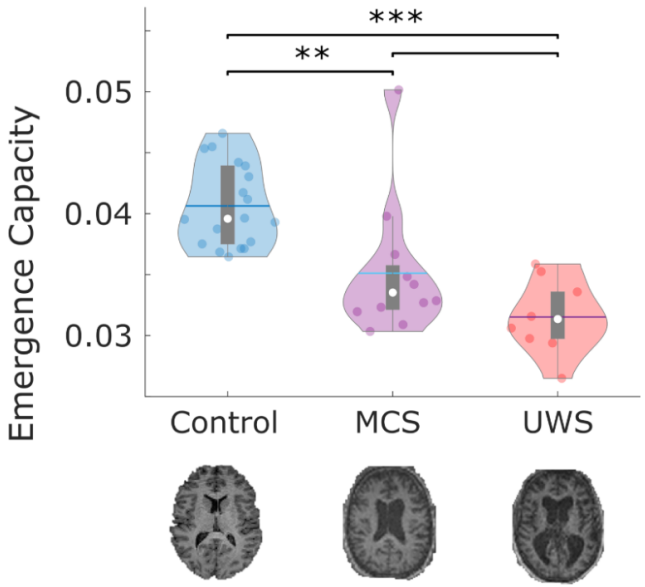
APPLICATIONS II: CLINICAL DIAGNOSIS

COMA



- Some patients have *covert consciousness*, hindering diagnosis.

Emergence-based tools predict unresponsive wakefulness syndrome.



Andrea Luppi

Fernando Rosas

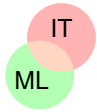
Daniel Bor

Emmanuel Stamatakis

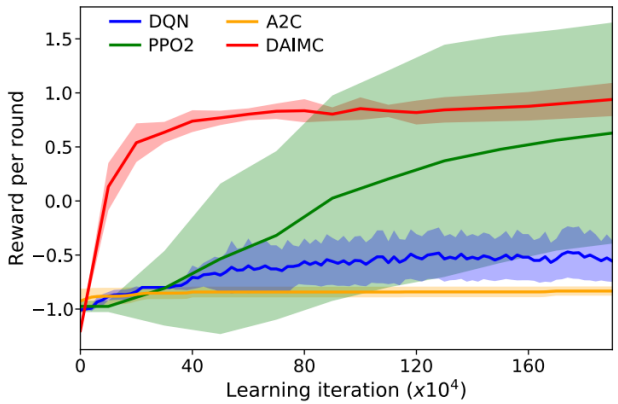
Imperial College London

UNIVERSITY OF CAMBRIDGE

CLOSING THE LOOP: BACK TO ML



RL agent based on information theory learns faster.

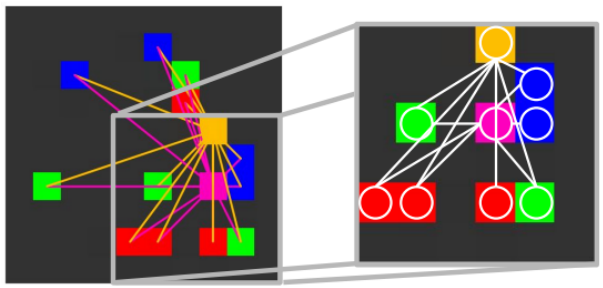


Zafeirios Fountas

Noor Sajid

Karl Friston

Modelling agent interactions helps us understand *and* train multi-agent systems.



Neil Rabinowitz

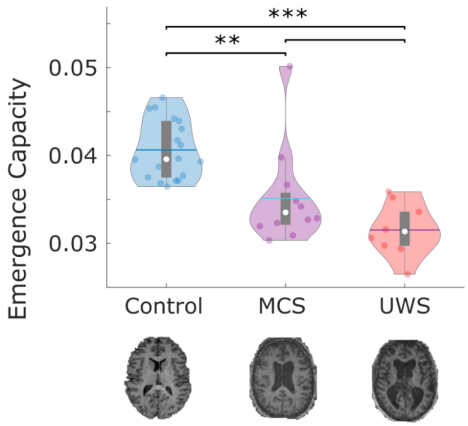
Andrea Tacchetti

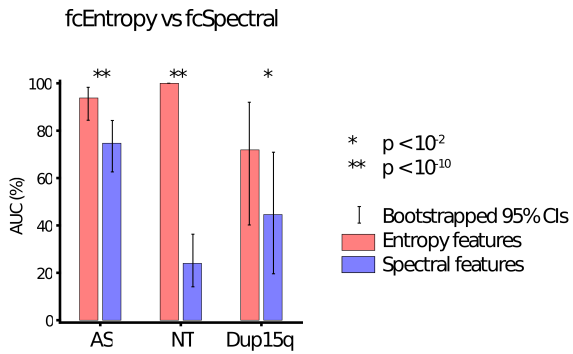
Francis Song

INTERIM SUMMARY

PRACTICE

- ✓ Demonstration of novel theories implemented and applied on real data.
- ✓ Powerful open-source algorithms for complex systems analysis.
- ✓ New insights on real-world problems: neurological diagnosis and mental health treatment.





WHAT'S NEXT

RESEARCH VISION

Future research goals:

- ✓ **Closer alignment** between ML and neuroscience models.
- ✓ Deepen the links between **synergy and learning**.
- ✓ **Clinical applications** in mental health, with direct benefit to patients (e.g. depression).
- ✓ **More diverse applications** (e.g. economics, social networks).

FUNDING SOURCES

Multidisciplinarity brings a **diversity of funding streams**.
→ E.g. Engineering, life & physical sciences, mental health.

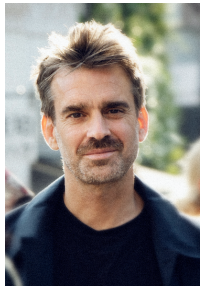
- Ongoing and upcoming applications:

wellcome	JOHN TEMPLETON FOUNDATION	MRC Medical Research Council	EPSRC Engineering and Physical Sciences Research Council
£ 640,000	$ 230,000	£ 625,000	£ 640,000

POSSIBLE INTERNAL COLLABORATIONS

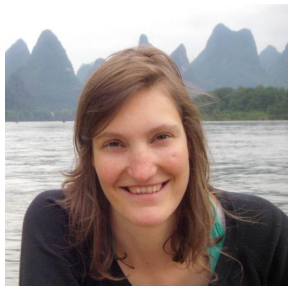
IMPERIAL

Henrik Jensen
Department of Mathematics
Complexity science



David Erritzoe
Department of Brain Sciences
Mental health treatment

Tim Evans
Department of Physics
Complex network analysis



Claudia Clopath
Department of Bioengineering
Computational neuroscience

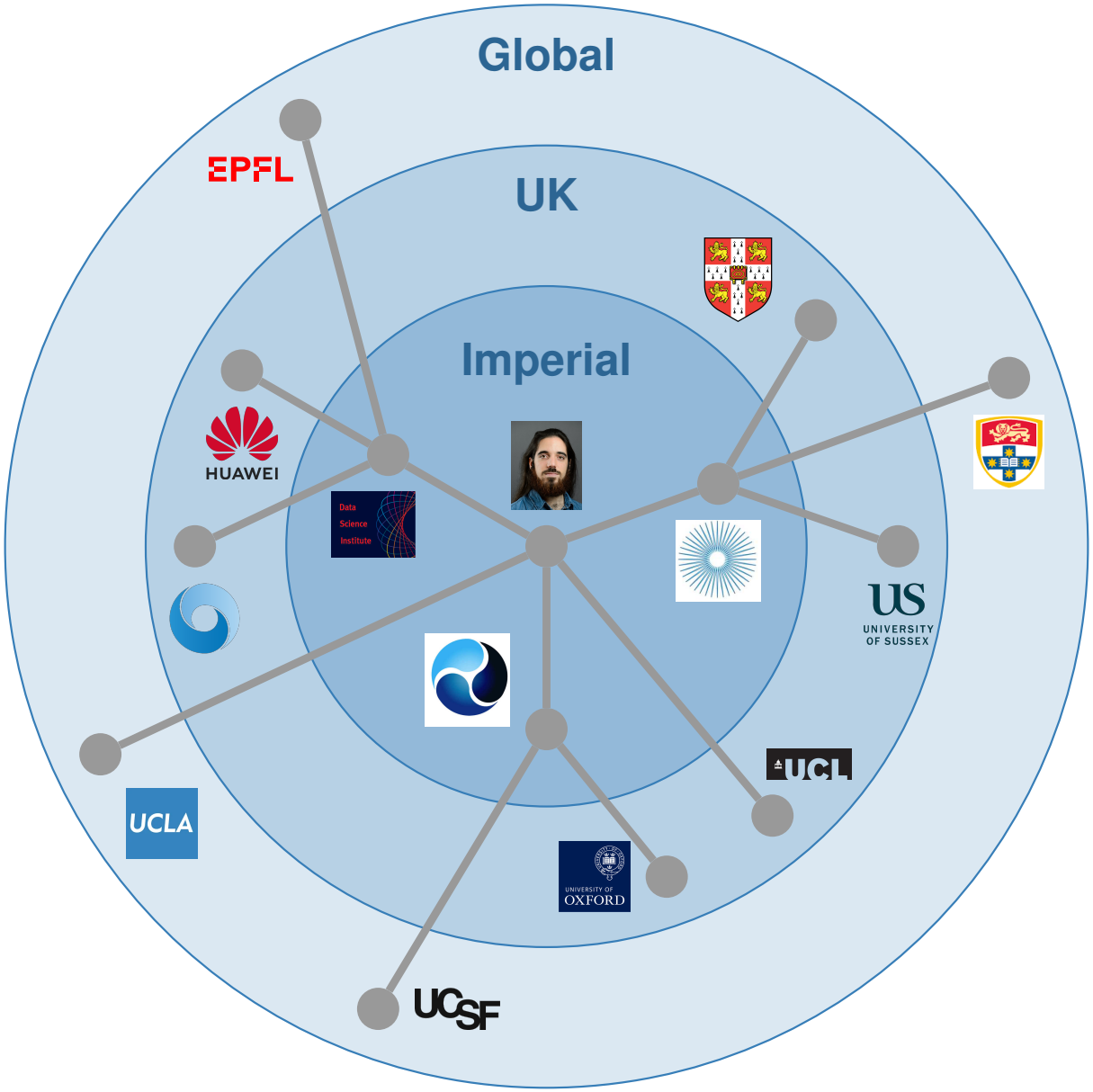
POSSIBLE INTERNAL COLLABORATIONS

DOC

Possible collaborative projects:

- ML for neurological diagnosis (BioMedIA)
- Non-Boltzmann entropies for complexity and ML (Yingzhen Li)
- Group dynamics during agent evolution (Antoine Cully)
- Causal emergence and abstraction (Alessandra Russo)
  $\rightarrow$ More on this in proposed grant application.

IMPERIAL & ME


Global
UK
Imperial
EPFL
HUAWEI
Data Science Institute
US UNIVERSITY OF SUSSEX
UCL
UCLA
UNIVERSITY OF OXFORD
UCSF

WHY DOC? WHY ME?

? Why does my research belong in DoC?

- ✓ **For the rigour and relevance** in computing applications to real-world problems.
- ✓ **For the students**, who enjoy multidisciplinary projects and courses.
- ✓ **For the required skills**, which rely heavily on computing, mathematics, and statistics.
- ✓ **For the opportunities for DoC** in terms of funding and collaboration.

Wrap-up

WRAP-UP

- ✓ Multidisciplinary computing research spanning information theory, ML, and computational neuroscience, with impactful empirical results.
- ✓ Great research potential, used by several MSc and PhD projects.
- ✓ New funding opportunities beyond usual DoC channels.
- ? **Interested?** Learn more at:

`https://pmediano.gitlab.io`

`plogp@pm.me`

Thank you for listening!

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REFERENCES

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