IITB-Monash Research Academy

Indian Institute of Technology Bombay | MONASH University

An Indian-Australian research partnership

Project Title:	**The Arrow of Sophistication in Biological Self-Organization**	
Project Number	**IMURA0827**	
Monash Main Supervisor (Name, Email Id, Phone)	Adeel Razi, adeel.razi@monash.edu	*Full name, Email*
Monash Co-supervisor(s) (Name, Email Id, Phone)		
Monash Head of Dept/Centre (Name,Email)	Kim Cornish, kim.cornish@monash.edu	*Full name, email*
Monash Department:	Psychological Sciences	
Monash ADGR (Name,Email)	Nellie Georgiou-Karistianis Nellie.Georgiou-Karistianis@monash.edu	*Full name, email*
IITB Main Supervisor (Name, Email Id, Phone)	Manoj Gopalkrishnan, manoj.gopalkrishnan@gmail.com	*Full name, Email*
IITB Co-supervisor(s) (Name, Email Id, Phone)		*Full name, Email*
IITB Head of Dept (Name, Email, Phone)	B G Fernandes, head@ee.iitb.ac.in	*Full name, email*
IITB Department:	Electrical Engineering	

Research Clusters: / Research Themes:

Highlight which of the Academy's CLUSTERS this project will address? *(Please nominate JUST* ***one.*** *For more information, see www.iitbmonash.org)*		**Highlight which of the Academy's Theme(s) this project will address?** *(Feel free to nominate more than one. For more information, see www.iitbmonash.org)*	
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2	*Energy, Green Chem, Chemistry, Catalysis, Reaction Eng*	2	*Infrastructure Engineering*
3	*Math, CFD, Modelling, Manufacturing*	3	*Clean Energy*
4	***CSE, IT, Optimisation, Data, Sensors, Systems, Signal Processing, Control***	4	*Water*
5	*Earth Sciences and Civil Engineering (Geo, Water, Climate)*	**5**	***Nanotechnology***
6	*Bio, Stem Cells, Bio Chem, Pharma, Food*	**6**	***Biotechnology and Stem Cell Research***
7	*Semi-Conductors, Optics, Photonics, Networks, Telecomm, Power Eng*	7	*Humanities and social sciences*
8	*HSS, Design, Management*	8	Design

The research problem

Atoms come together to form molecules. Molecules self-organize to form crystals, and stars, and planets, and galaxies, and living systems. Living systems self-organize to display a wealth of sophisticated behavior, leading to the evolution of marvels such as the human brain. What algorithmic processes drive this **arrow of sophistication** in self-organization? Can we explain this process mathematically? Can we get a computer to replicate such processes?

Project aims

Some appealing theoretical hypotheses have been put forward to explain this arrow of sophistication. These include the idea of a Markov blanket leading to emergent self-organization by Karl Friston, ideas of variational inference by Sanjoy Mitter, and connections to Bayesian statistics and machine learning theory. The aims of this project are to:

1. Survey, engage with and master this literature;

2. Attempt a synthesis of these various ideas, pose new mathematical questions, and attempt to resolve them;

3. Instantiate the abstract ideas in these hypotheses through concrete and simple examples, both of a mathematical and algorithmic nature;

4. Implement these simple examples on a computer, and empirically study their behavior, in an attempt to discover new laws concerning the arrow of sophistication;

5. Ask new algorithmic questions about the speed of biological self-organization, and explore these questions in our models;

6. Attempt to leverage the learnings obtained through such study to more concrete situations, like solving Machine Learning problems, understanding situations in neuroscience, or designing systems for molecular programming and synthetic biology applications.

Expected outcomes

1. To obtain a novel synthesis of the laws governing an emergence of an arrow of sophistication in nature, and a better understanding of the resulting biological self-organization;

2. To create a library of simple synthetic examples of biological self-organization. These examples are intended to provide pedagogical tools for teaching the abstract ideas undergirding this subject, to inspire further study of this subject, and to facilitate possible application of these ideas;

3. To gain a better understanding of the workings of some among various self-organization systems and processes like the brain, artificial neural networks, molecular self-assembly, financial markets, evolution, the immune system, heart rhythms, etc.

How will the project address the Goals of the above Themes?

Advanced computational engineering, simulation and manufacture: This project engages with the fundamental question of computer science, “What is it about the laws of nature that allow the emergence of learning and self-organizing systems?” This is a question that many pioneers of computer science like Alan Turing (pattern formation), John von Neumann (cellular automata), and Marvin Minsky (origin of intelligence) have engaged with. Progress on this question will impact many areas of computer science. For the sake of illustration, consider artificial neural networks, which are inspired by the human brain, and have led to remarkable advances in Machine Learning in recent years. We have a poor understanding of the laws that have led atoms and molecules to self-organize into systems as sophisticated as the human brain. A better understanding of these laws can lead to a better understanding of the workings of brains and artificial neural networks, as well as suggest new directions for Machine Learning.

Nanotechnology: In Richard Feynman’s famous talk “There is plenty of room at the bottom,” which is widely credited with launching the field of Nanotechnology, he pointed out that the ability of systems at the nanoscale to self-organize is one of the reasons that makes the nanoscale such a fascinating length-scale for study. Biological systems exhibit behaviors at the nanoscale that are many orders of magnitude more sophisticated than what we can synthesize, even after tremendous progress in nanotechnology. The next big advance in nanotechnology is likely to come from a coupling of mathematical and information science ideas, leading to a better understanding of the self-organization processes that enable biological systems.

Biotechnology and Stem Cell Research: One of the PIs on this project (MG) has been actively involved with the DNA computing and molecular programming community, and is hopeful of ideas from this project translating into advances in that domain.

Capabilities and Degrees Required

1. Inclination towards Mathematics and Physics, along with a willingness to engage with mathematically-written research papers
2. Coding skills
3. Some familiarity with Machine Learning, Information Theory, Statistics, Statistical Mechanics
4. Willingness to engage with research ideas in Biology as required
5. Exposure to basic ideas in theoretical computer science at the level of Sipser's book on Theory of Computation, Papadimitriou's book on Computational Complexity Theory, and Dasgupta and Vazirani's book on Algorithms.

Potential Collaborators

Karl Friston, University College London

Select up to **(4)** keywords from the Academy's approved keyword list **(available at http://www.iitbmonash.org/becoming-a-research-supervisor/)** relating to this project to make it easier for the students to apply.

Data Science,optimisation,algorithms 6
Maths 8
BioScience 11
Systems Analysis and Control 31