BRAIN CO-PROCESSORS

A MOONSHOT NEUROSCIENCE PROJECT IN INDIA

itihaasa
Research and Digital

Contents

Foreword

As the country marches towards India@100 and strives to become self-reliant and vibrant, research, science and technology, and innovation have a crucial role in achieving that goal. These are the areas that I decided to fully support, after my retirement from Infosys.

Brain science is an important next frontier of human knowledge. In particular, there are two areas to explore – brain-inspired computing, and understanding how the brain ages and disorders that arise due to ageing. I strongly believe that the some of the next disruptions in computing will come from our understanding of how the brain works. Also, we will have a better understanding of and develop affordable and India-customised solutions for diseases such as Alzheimer's, dementia, Parkinson's and other neurological disorders.

Keeping this in mind, through Pratiksha Trust, I support brain research centres at IISc (Brain, Computation and Data Science group) and IIT Madras (Centre for Computation Brain Research - CCBR), which hosts six distinguished visiting chairs in brain science in India. The idea behind this model is to seed capability in the leading Indian educational institutions with the help of endowed Chairs, occupied by world-class multidisciplinary scientists. Over a period of time, a number of papers in reputed international journals, several research projects, knowledge-dissemination computational tools and infrastructure have been created. This model has helped create significant knowledge base and capability around brain sciences in the country.

I am happy to also support the Centre for Brain Research, an autonomous, non-profit research organization at IISc, focused on aging brain and age-associated brain disorders. CCBR, IIT Madras is developing a high throughput computational and experimental pipeline to study cellular architecture, connectivity and molecular architecture in human brains.

I am delighted that the researchers at IISc have conceptualized a grand challenge project called "Brain Co-processors". I am hopeful that such long-term, big-scoped projects will successfully bring together academia and industry, across multiple disciplines, in India and the world.

Kris Gopalakrishnan

Co-founder, Infosys and Chairman, itihaasa Research and Digital

Brain Co-Processors –

A moonshot project under IISc –
Pratiksha Trust initiative

At the workshop on Brain, Computation and Learning, BCL-2023, organized by Indian Institute of Science (IISc) and the Pratiksha Trust and held between January 9-13, 2023, the researchers at the Brain, Computation and Data Science group at IISc announced their moonshot project on **Brain Co-Processors**.

"Brain co-processors" are a new technology that use AI to augment or restore brain function.[1] This project aims to develop invasive (implantable) and non-invasive brain co-processors to enhance or restore brain functions like memory, attention, vision, motor skills and the like. Such co-processors involve decoding activity from neural recordings, processing it with an AI algorithm implemented in software or hardware, and re-encoding signals back into the brain, either directly with neural stimulation/neurofeedback or by actuating external devices, such as prosthetic arms.

A simplified view of a brain co-processor and its use-case of brain-computer interface is shown in Figure 1.

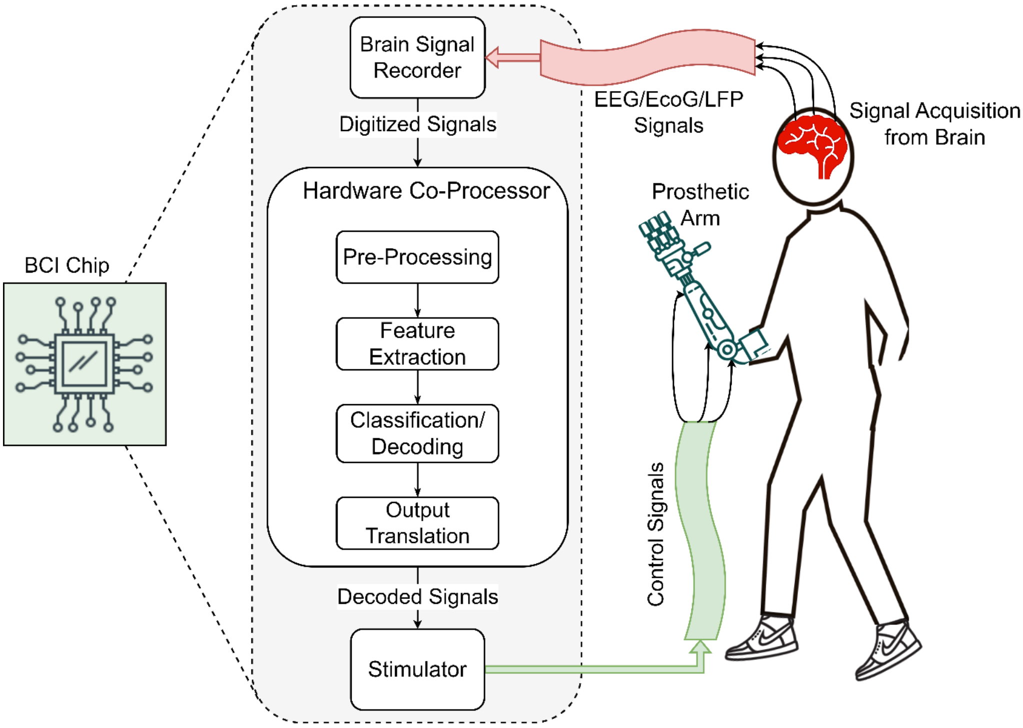

Figure 1: Use-case of brain-computer interface (Source: IISc)

itihaasa Research and Digital (www.itihaasa.com), which studies the evolution of technology domains in India and has previously published a landscape study of brain research in India[2], met the IISc researchers to better understand the moonshot project and other key developments in the neuroscience domain.

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Interview with
Dr. Sridharan Devarajan, IISc

Sridharan Devarajan is an Associate Professor and Swarna Jayanti Fellow at the Centre for Neuroscience and an Associate Faculty of Computer Science and Automation at IISc. He studies the neural mechanisms of selective attention in humans with a combination of brain imaging, neurostimulation and computational modelling. Sridharan is also the co-convenor of the Brain, Computation and Data Science (BCD) Initiative at IISc and is one of the Principal Investigators (PIs) participating in the Brain Co-processor project.

itihaasa Research and Digital met with him to understand his research interests and perspectives on the Indian Brain Co-processor initiative. Below is an edited version of the interview between Sridharan Devarajan, IISc and Krishnan Narayanan, itihaasa.

KN: Can you explain a little bit about the moonshot project, the Brain Co-Processor?

SD: This project is being developed and piloted under the aegis of the BCD initiative at IISc, generously supported by the Pratiksha Trust. The idea is to come up with implantable or non-invasive technologies that can augment or restore brain function. When some part of brain function is lost because of pathology, whether it is due to stroke or due to accidents like trauma, the idea is to come up with an AI enabled device that will make up for that loss of that part of the brain. This can be in the form of a chip or an external device, to which the information from the brain is sent and routed back into the brain wirelessly. Essentially, this co-processor will be doing a computation which the damaged part of the brain would otherwise have done.

KN: What are the major challenges in this research work?

SD: One challenge is to read information from the brain, from the damaged area that would have received the information; and the second challenge is to put information back into the brain, i.e., to those parts of the brain where the damaged part could be sending out instructions, for example to muscles that control the eyes or the limbs.

If you read the brain, you have to decode that information and understand what is happening there. Putting information back into the brain is yet another level of complexity, because you have to put it back in a form which that part of the brain understands. The Brain Computer Interfacing (BCI) technology is in early days. Even if what we put in is not the exact neural code, the brain is intelligent enough to adapt, even to noisy signals.

KN: What are the broad research streams in this project?

SD: The project is broadly divided into two streams. One is the sensory and cognitive stream, where we are focusing on vision and attention. So, we are basically asking if can we decode the stimulus a person had or saw, based on activity recordings in different brain areas, especially visual areas. And can we also decode the person's visual attention, i.e., where in space or to what object are they paying attention? Think of this as the input stream. The vision and the attention researchers are working primarily on primate models, that is human and non-human primates (macaques).

The other stream is where we are looking at choices in actions. When someone makes behavioural decisions, say about wanting to go here versus there and so on, how are they making those decisions and what is driving those decisions? And how do those motor actions themselves work – i.e., once you have made a choice, you may have to physically move some actuator, say push a button or open a door to go somewhere. One interesting research focus in this task is called foraging – if you have multiple choices of options, how do you decide when to stop exploiting one option and start exploring other options? Think of this as the output stream. The choice and the decision researchers initially will be working on rodent models, and would later move to primate models.

KN: What stage is the moonshot project right now?

SD: We have submitted a preliminary proposal to the Scientific Advisory Committee and the Chair professors associated with the IISc-Pratiksha Trust BCD Initiative, and received their feedback. We plan to organize the proposal into two phases. In the first phase (years 1-5) – MindReader – we seek to develop technologies for recording neural activity at high densities from different brain regions, and decoding mental states – perceptual, cognitive and motor – by developing customized AI algorithms in software and hardware. In the second phase (years 6-10+) – MindHacker – we will develop technologies for re-encoding signals back into the brain using a combination of recording and neurostimulation technologies.

We are currently in year zero (pilot year) of the project. The goal is to develop a synergistic proposal and pitch this idea to external funding agencies to obtain funding at scale to develop a state-of-the-art Brain Co-Processor.

One area of synergy is developing a generic co-processor that can decode information from any part of the brain associated with any cognitive process. We have started a few collaborations. The core team in the moonshot project is from IISc and IIT Kanpur (Arjun). Each of the PIs have other collaborators and we have a team of 10 researchers right now, including a clinician (neurosurgeon) from Ramaiah Hospital (Shabari). We also want to build additional collaborations on the clinical front.

We want to bring this project to the next level where institutes / universities across the country are working towards a common, scientific grand challenge. For example, if the goal is sensory decoding, rather than narrowly defining the problem statement as a particular type of decoding, we will define it at a broader level so that an auditory neuroscience researcher can participate, as well as researchers working on speech and language.

A note on the evolution of the moonshot initiative team structure

The moonshot project has evolved rapidly in the initial stages in terms of how it is structured to ensure greater synergies and efficiencies. For instance, the project initially envisaged 5 sub-themes and after deliberations converged on 3 sub-themes. **See Table 1 and Table 2.**

In the first six months of the project (October 2022-March 2023), PI-s met regularly to update progress in preliminary data collection for the 5 sub-themes or verticals (Vision, Attention, Decisions, Motor, Neuromorphic). These updates were organized as weekly meetings where each of the 5 groups presented its research per week.

Following these discussions, the team decided to apply for a joint grant to scale up the proposal's outcomes. The goal of such a grant would be to identify a common medical application that could be a relevant target for the co-processor. Based on discussions, the PI-s converged on **developing a co-processor for cognitive rehabilitation of stroke patients.**

The rationale was that, in such patients, multiple cognitive capacities as well as visuomotor function gets impaired because damage to any major artery results in widespread insult across the brain. In this sense, stroke patients would be a good model for exploring rehabilitation across all 5 verticals.
Then the teams performed a review of literature to understand what type of co-processor was feasible in such stroke patients. It became clear that:

- Co-processors for stroke developed so far were primarily of the non-invasive type, and rarely of the closed-loop type. Even with FDA-approved recording implants (e.g. Utah arrays), stimulation was generally never fed back directly into the (spared) cortex.
- Nearly all co-processors developed so far, whether invasive or non-invasive, were for restoring motor control. Even this was primarily in quadriplegic/paraplegic patients.
- Another type of co-processor explored was one that induced neuroplasticity with (invasive) epidural neurostimulation. But even this was currently in the experimental stage

In general, they agreed that the field was wide open for developing <u>non-invasive co-processors</u> for stroke for cognitive (non-motor) rehabilitation (e.g. attention, decisions); no previous effort had developed such a cognitive co-processor. They also agreed that a potential fallback strategy was to test <u>invasive co-processors</u> in comatose patients to enable decoding of their mental states, or for two-way communication. Such invasive co-processors for stroke patients require extensive development and preliminary testing in animal models before these can be translated to humans. In this regard, PI-s working on animal models could play a major role.

The PI-s, therefore, decided to organize into 3 teams, each of which would tackle one facet of the project, with some immediately realizable goals. The long-term goal would continue to remain developing and deploying implantable brain co-processors in stroke patients.

Table 1: Details of Brain Co-Processor Project (5 Sub-themes)

SUB-THEME	DESCRIPTION
1. **Decoding Vision** **Team** – Supratim Ray, SP Arun, Chandra Murthy, Chandrasekhar Seelamanthula – all from IISc	• The objective is to decode the identity of a visual stimulus by observing signals from a sensory area of the brain. • In the project, a subject will be shown natural images, and from the brain signals alone, the image that the subject was looking at will be reconstructed. It will be implemented in a monkey brain. • One unique aspect of the project is that it aims to generate a cohesive dataset from 4 brain areas.
2. **Decoding Attention** **Team** – Sridharan Devarajan, Ambedkar Dukkipati, Chandra Murthy – all from IISc	• The objective is to decode attention – both spatial and feature based – based on real-time neural recordings. And understand precise neural mechanisms by which attention works in the human brain. • The project aims to develop capabilities: ○ for real-time recording and analysis of EEG and fMRI brain signals, ○ for rapid and efficient data compression and reconstruction, and ○ state-of-the-art machine learning and deep learning models for decoding subjects' attention state.
3. **Decoding Decisions** **Team** – Arjun Ramakrishnan (IIT Kanpur), Kaustubh Deshpande (Eywa Neuro)	• The objective is to decode decision making in dynamically changing environments. For example, in foraging for food: choosing between a known option with an expected reward or exploring an unfamiliar one with an unknown and possibly greater reward value. • The project involves development of implants for neural recording and stimulation of brain regions of interest. • It also aims to build neurocomputational process models to assess optimality of decision making and determine the role of working memory and reinforcement learning in foraging.
4. **Decoding Actions** **Team** – Hardik Pandya (IISc), Deepak Nair (IISc), Shabari Girishan (MS Ramaiah)	• The objective is to understand and examine the neurophysiological origins of motor signals using indigenously developed implantable devices. • The project focuses on developing ○ implantable cortical microarrays and flexible neural interfaces for the regions of a rat's motor cortex; ○ an associated electronic system for studying a rat's motor signals from an awake rat; ○ decode movement intention from these recordings.
5. **Decoding in Real-time** **Team** – Chetan Singh Thakur (IISc)	• The objective is to develop a state-of-the-art decoder system using digital architecture for deployment in large-scale BCI applications, such as vision, attention, decisions and motor control. • In phase 1, the project will design and develop a hardware co-processor chip with hardware-optimized decoder algorithms, to process EEG, ECoG or fMRI brain recordings in real-time. • In phase 2, the processed output will be re-encoded to the brain either through neurofeedback or by actuating external devices such as prosthetic arms.

Table 2: Details of Brain Co-Processor Project (3 Sub-themes)

SUB-THEME	DESCRIPTION
A. Stereo EEG in epilepsy patients **PI-s:** Sridharan Devarajan, SP Arun, Chandra Murthy – all from IISc	• Goal 1: Collaborating with clinicians to develop a comprehensive sEEG database. As a first step toward understanding the role of different brain regions in diverse cognitive functions (e.g. attention, decision making). • Goal 2: Exploring ways to combine different imaging modalities (e.g. dMRI, fMRI, scalp EEG) to develop a tool to enable better localization of epileptogenic networks • Goal 3: A tertiary goal is testing the effect of intracortical stimulation on neural activity and behaviour. • These goals will pave the way for developing invasive co-processors in stroke patients.
B. Non-invasive brain co-processors for stroke patients **PI-s:** Arjun Ramakrishnan (IIT Kanpur), Sridharan Devarajan (IISc), Chetan Singh Thakur (IISc)	• Goal 1: Collecting scalp EEG recordings from healthy participants/stroke patients and developing models for decoding cognitive functions (e.g., attention or decision-making) • Goal 2: Developing passive controllers (includes prosthetic devices e.g., switch that turns on or off based on decoding attention) and active neurofeedback systems (includes integrated neurostimulation e.g., tACS devices) • Goal 3: Integrating these into a neuromorphic device with a small form factor as wearable technology. • These goals can be piloted in healthy participants and then tested with stroke patients to understand challenges unique to such patients. This will require the involvement of clinicians who deal with stroke patients and with non-invasive rehabilitation. • This goal will also pave the way for hybrid or minimally invasive co-processors for stroke patients.
C. Invasive brain co-processors for stroke patients **PI-s:** Hardik Pandya (IISc), Supratim Ray (IISc), Arjun Ramakrishnan (IIT Kanpur), Chetan Singh Thakur (IISc)	• Goal 1: Building algorithms for decoding and re-encoding activity in the animal brain with existing, approved technologies (e.g. Utah arrays). As a first step, this could involve decoding activity in visuo-motor tasks because these are considerably simpler to train than cognitive tasks in either primate or rodent models. • Goal 2: Building low-cost, invasive electrodes for decoding and/or re-encoding activity back in animal brains. This will include development of biocompatible electrodes as well as novel, multi-contact electrode technologies for simultaneous recording and stimulation. • Goal 3: Building and testing invasive neuromorphic co-processors in animal models. Combining the deliverables of Goals 1 and 2, a neuromorphic co-processor will be developed for testing in animal models. Because the ultimate aim is to translate the deliverables to human patients, in the long term, this theme will necessarily involve both animal and human (patient) work.

KN: Can you elaborate on the work that you are doing with clinicians?

SD: We have actively reached out to neurologists and neurosurgeons across multiple hospitals in India. These institutes record neural activity directly from the brains of epilepsy patients by performing minimally invasive stereo-EEG (Electroencephalogram) and subdural ECoG (Electrocorticography) grid implantation procedures. In standard scalp EEG, clinicians put some sensors on the scalp and record, but the signal quality is very poor with such recordings because sensors are far from the brain. In stereo SEEG, the clinicians directly record from electrodes implanted inside the brain to localize seizures in epilepsy patients.

We had a workshop in October 2022 with clinicians from 6-7 hospitals in India. The objective of our collaboration with the clinicians is to study normal brain activity in these epilepsy patients when they are not having seizure episodes. During these times, when patients are resting, we can ask them to do some simple vision, attention and motor tasks, similar to those proposed in the moonshot project. When the patients do these tasks, we will have an unprecedented window into the human brain recordings.

Speakers of the IISc-BCD Stereo-EEG workshop at the Centre for Neuroscience, IISc

KN: Why are clinicians motivated to collaborate with you in this project?

SD: Clinicians do not routinely perform stereo EEG unless there is enough evidence that it is going to lead to a positive outcome. Also, the implants are expensive. If we as basic researchers can give the clinicians better pointers and information regarding the seizure focus from those recordings using our models and analyses, they will also find it more meaningful to do implantations, with potentially better outcomes for patients as well. So, clinicians are eager to work with us. This is one example of basic research directly contributing to a translational goal.

KN: What is the translational potential of the moonshot project?

SD: The algorithms and technologies developed as part of this proposal may have significant impact for restoring or rehabilitating sensorimotor and cognitive functions in patients with neuropathologies.

The brain co-processor is essentially like a chip that you can either implant inside or leave outside. So, the neuromorphic chip itself is one outcome. For example, say someone's lost their motor function and they want to switch off a fan. The chip would help decode their intention to do this action and assist in completing the intended task.

Then, the technologies that allow us to record the brain signals, read and transmit them, these are electrodes. Those are also outcomes. These electrodes should be biocompatible, should not cause damage to the brain, can record from many channels, should be low-cost, low-power solutions.

One aspect to consider with respect to translation is that, without demonstration of proof of concept in animal models, it is challenging to get clearance for direct implantation in humans. Another aspect is that a grand challenge like this requires researchers with expertise in different topics working together. I don't think a single company will have the scale to address a challenge of this nature. We will see a number of startups in the future. Elon Musk's NeuralLink is one example, although their approach is different. Arjun (Ramakrishnan), one of the PI-s of this project, has startups in the domain of electrodes (Eywa Neuro in India, CogWear Technologies in the US).

KN: Are there any global references for this moonshot project?

SD: Yes, there are other initiatives on AI-augmented neuroscience in the world. Prof. Rajesh Rao, Pratiksha Chair professor, himself has led several such initiatives (his research at the University of Washington is on computational neuroscience and Brain-Computer Interfaces) and he has shared his thoughts on our proposal.

Our moonshot project is unique in its breadth of objectives and scale. Although the number of stereo EEG implants for epilepsy are limited today, India can become the leading country in the world in terms of number of implantations, with ultimately better outcomes for patients. Also, the knowledge that is gained through these sEEG implantations can also aid developing co-processors for stroke patients by restoring lost brain function in specific areas.

Interview with

Dr. Rajesh Rao, University of Washington

Rajesh Rao is the CJ and Elizabeth Hwang Professor at the Paul G. Allen School of Computer Science & Engineering and co-Director of the Center for Neurotechnology at University of Washington (UW). His areas of interests include computational neuroscience, artificial intelligence, and brain-computer interfaces. He studies how the brain learns models of the world from observations and actions, how the brain makes decisions based on noisy sensory information, and how brain signals and AI can be combined to build brain co-processors for restoring and augmenting neural function. Rajesh is also the Pratiksha Trust Distinguished Chair Professor at IISc.

itihaasa Research and Digital met with him to understand his research interests, perspectives on the Indian Brain Co-processor initiative and the state of neuroscience in the country. Below is an edited version of the interview between Rajesh Rao, UW and Krishnan Narayanan, itihaasa.

KN: You, along with Dana Ballard, are credited with proposing the predictive coding model of brain function. What does it entail?

RR: Yes, this was right after my PhD thesis. This was a time when I was trying to understand how to get computer vision algorithms and AI to recognize objects and emulate the brain. But I was failing to do that. This was in the pre-deep learning era, there were no computational resources, no data resources, like we do now. We were still using neural networks but we didn't really have the capacity to build very large neural networks. So that's when I got fascinated by the brain and pivoted to see how it solves the problem.

Dana Ballard was my PhD advisor, and he encouraged me to look into cognitive science, brain science. Then we came up, as part of my thesis, with this model of how the brain, at least the visual cortex, may be processing information and this is called the predictive coding model. It was a very radically different way of looking at how we may solve the vision problem, which is that the brain builds a model of the world and it constantly predicts what it actually sees.

In the traditional model of vision, when you have something (an image) in your eyes, in the retina, it goes through a sequence of processing stages. Similar to how a deep learning network works, going from one layer to the next. In the traditional model, you have more and more complex processing going from one stage to the next. Eventually, it gets to the higher order of consciousness and you recognize an object.

What the predictive coding model says is that's the wrong way of looking at it. Instead, you are constantly constructing a hypothesis of what's going to happen and you are constantly testing the hypothesis, just like in a scientific experiment. And whenever there's a mismatch between what you expect and what comes in, you get an error or mismatch signal, which is sent back up. So, the errors are sent instead of raw signals like in feed forward neural networks in deep learning.

For example, when you learn to walk, you pay a lot of attention to your body and how it moves and so on. But later, you don’t have to pay attention and you can walk, even while speaking on the phone or coming down a flight of stairs. But, if there is an increased gap in one of the steps, you sense it immediately. That is because there is a mismatch between expectation and reality. Same thing with you becoming aware if there is a sudden sound or a strong smell when you enter a room. Initially there is a mismatch, but then your brain adapts to the error signal.

KN: This is similar to what Jeff Hawkins suggested?

RR: Yes, he builds on these ideas. If you read his first book, On Intelligence, he says that he was inspired by a few researchers including me. His second book, A Thousand Brains, in turn inspired me to update our old model, in an article I posted on bioRxiv in December (2022).[3] This updated version is called active predictive coding, and acknowledges the important role of actions; the older model was purely about visual perception.

The predictive coding model came out in 1999, but not many in the neuroscience community paid attention to it then. Then, around 2009-10, when the tools became available to test these kinds of theories and evidence for predictions, and prediction errors started coming in, more neuroscientists got interested. That was when I started noticing the Google Scholar citations for our 1999 paper shooting up!

KN: Can you tell a little about your computational neuroscience research work?

My research work too has evolved – after my Ph.D. in computer science from the University of Rochester, I did a postdoc at the Salk Institute in San Diego, where I learned more neuroscience. And then I got my faculty position at the University of Washington, Seattle. I continued doing research in computational modelling of the brain but also started working a lot more in the brain machine interface and brain computer interface research.

For instance, in 2013, at UW, we performed what we believed to be the first proof-of-concept non-invasive human-to-human brain interface. I was able to send a brain signal via the Internet to control the hand motions of my fellow researcher (Andrea Stocco)[4].

(See box below for a summary of Rajesh Rao's work at UW.[5])

Prof. Rajesh Rao's Research Focus – Computational Neuroscience and Brain-Computer Interfaces

The primary goal of Rajesh's research is to discover the computational principles underlying the brain's remarkable ability to learn, process and store information, and to apply this knowledge to the task of building AI systems and brain-computer interfaces (BCIs).

- How does the brain learn efficient representations of objects and events occurring in the natural environment?
- What are the algorithms that allow useful sensorimotor behaviours to be learned?
- What computational mechanisms allow the brain to adapt to changing circumstances and remain fault-tolerant and robust?
- How can the knowledge gained through computational studies of the brain be used in biomedical applications such as BCIs for the disabled?

KN: I read about your work on humanoid robots that learn from humans. It was described like "just like how babies learn". Can you tell us more about this project? Did it involve techniques like reinforcement learning?

RR: This was in collaboration with a developmental psychologist, Prof. Andy (Andrew) Meltzoff, also at the University of Washington. Andy had shown that babies learn by imitating even after they're just born – there's some amount of facial imitation; for example, if they see you stick your tongue out, they will also start to do that. We got funded by the National Science Foundation for a project that looked at that relationship between how babies learn and how those results could be applied to robotics. We tested our ideas on a humanoid robot.

With respect to reinforcement learning (RL), it's trial and error learning. And it takes a long time. In video games, RL takes millions of trials. The system tries all possible actions, and the ones that are rewarded are reinforced. Whereas when humans watch somebody do something, they get a lot of clues on how to solve a task and are able to learn very quickly. For example, when a child sees someone turn a door knob and open a door, it will try to do the same thing. So, in the humanoid project, we tried to emulate such a brain-inspired, human-inspired imitation learning framework to speed up learning.

KN: A quick clarification. The robot has some sort of computer vision. But it should also have some understanding of concepts like "door knob" and "turning". How do you factor in those concepts into the humanoid robot?

RR: Babies learn through what's called 'body babbling' – the baby, even in the womb, is moving its body and learning a model of how its body behaves. "When I make an action, I see if I move my muscle this way, then I'll hit this part of my mother's womb inside". This is how it feels because it has proprioceptive and tactile signals going back to its brain. It's all about learning the consequences of your actions. This is sometimes called learning a forward model of the world. If I push this cup, it'll fall – that's the physics of the world; I can learn the physics of the world through my interactions with the world.

In the case of the robot, we suggested that there was a progression of learning capacity, from simple mimicry like facial imitation to goal inference and goal-based imitation. This is how the child learns. This was new thinking in robotics. Traditionally, people said, "you have to do motion capture", "you have to track the trajectory of the arm" and so on. But we suggested that the robot need not blindly mimic what the human is doing. Instead, it should extract the goal, say, of opening the door. Once it infers the goal, it can perform some action – use one hand or two hands or even one hand and one leg to turn the knob – to achieve the goal.

KN: You have worked on the idea of brain co-processors as part of your research. How has that influenced the moonshot initiative in India?

RR: In 2019, I wrote a paper on this idea, and called it "neural co-processors".[6] Sridhar (Sridharan Devarajan, IISc) and team were inspired by this paper and they took it to the next level in the form of this moonshot project.

In the paper, the idea was to combine neural networks with brain interactions, and use an artificial neural network as a way to replace biological neural networks. Something like back propagation in deep learning networks and yet different. If you're stimulating the brain, there is a whole sequence of things that happen before you see the effect of the stimulation, such as moving the hand. You cannot use the traditional backpropagation learning method because you don't really know the transformation from the stimulation (in brain circuits) to what actually causes you to move to the muscles. In the paper, I suggested that you can come up with a second neural network that acts like an emulator, and emulates that transformation. (See the box below for the highlights of the paper.)[7]

Towards neural co-processors for the brain: combining decoding and encoding in brain–computer interfaces

- Bidirectional brain–computer interfaces (BBCIs) combine neural decoding and encoding within a single neuroprosthetic device.
- BBCIs have been used to control prosthetic limbs, induce plasticity for rehabilitation, reanimate paralyzed limbs and enhance memory.
- Neural co-processors for the brain rely on artificial neural networks and deep learning to jointly optimize cost functions with the nervous system.
- Neural co-processors can be used to achieve functions ranging from targeted neuro-rehabilitation to augmentation of brain function.

The brain coprocessor is a type of bi-directional interface but it's suggests using AI as a way to mediate that bi-directional interaction. It is a device that can both read the brain and write to the brain, but in between the two, you have to have some intelligence. And that is where AI comes in. (See figure below that provides a simple illustration of a traditional BCI and brain co-processor.[8])

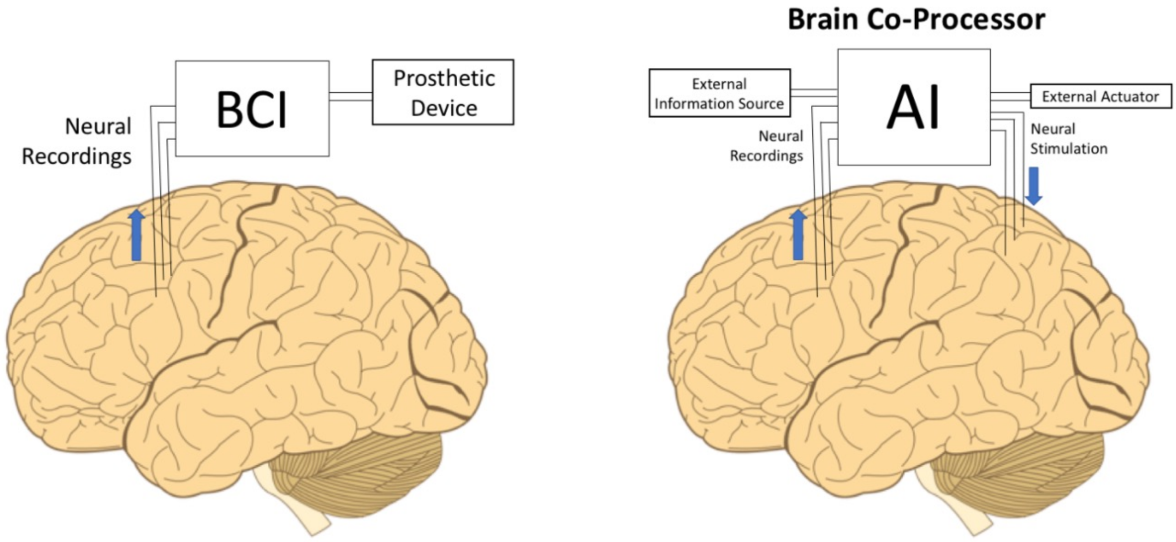

Figure 2: Simple illustration of a traditional BCI and brain co-processor

KN: The brain seems to have a capacity to process lots of information even though it is noisy. So, why do you need AI? Why not just allow the brain to process the information on its own?

RR: That is the big debate that we've had in the field and in our group also. There are two ways in which you can build brain interfaces. In one, you feed information directly to the brain, and let the brain adapt to it and figure out how to accomplish a task, such as controlling a cursor. And that method has been successful for simple kinds of protocols or information being sent to the brain. One difficulty with it is that it takes a long time and it takes a lot of practice for the brain to learn. It's like learning any new skill. In some cases, it may plateau, and the learning may never improve beyond a particular point.

In the second way, you allow the AI to adapt to the brain while the brain itself is adapting. We call this a co-adaptive system. It can speed up the learning process involving the brain and the interface trying to achieve a goal. As an analogy, if you give a student a very hard mathematics book, he/she may take a long time to learn the concepts in it. But if you have a good teacher who adapts to what the student understands, the teacher can then deliver the information appropriately and enable faster learning.

KN: As the Pratiksha Trust Chair at IISc, you advise the moonshot project. How important and unique is this project in the context of Indian neuroscience?

RR: One of the attractive aspects of the moonshot project is that it brings about this combination of state-of-the-art engineering, of devices and other electrodes, with cutting edge neuroscience. I think not many people in the world are looking at things in the way the brain co-processor project has been conceptualised. At this point in time, even NIH (National Institutes of Health, US) is mainly funding more traditional brain computer interface projects rather than ones on brain co-processors.

The moonshot project brings together talents in many different areas to share a common vision – there's AI, device development, electrode development, the animal aspects, neuroscience and the human clinical aspect. And in India, we have the resources, both on the engineering and the sciences side.

With sustained progress and funding, the moonshot project could eventually reach humans. The project is using epilepsy as a stepping stone to test the decoding algorithms and so on. Eventually, it could address other degenerative diseases such as stroke, Parkinson's, and spinal cord injuries.

KN: Is there any other area in neuroscience where India can take the lead in the world?

RR: India may not have the latest, most expensive, experimental resources but India does have a lot of talented young and ambitious scientists and engineers. I think there's an opportunity for scientists and engineers in India to come up with new comprehensive unified theories of the brain. Like how Einstein, working in a patent office, came up with the theory of relativity. (Einstein described the patent office as his 'worldly cloister', where he 'hatched [his] most beautiful ideas'.[9])

Theoretical neuroscience has been around for quite some time, but it has been quite narrow. We need it to become much broader. In one of my talks, I mentioned that there seem to be striking patterns in brain architecture, in areas like the cortex or the cerebellum. It seems that the same module is being repeated multiple times across many areas. Now, if you can make sense of them, we may be able to explain a lot of data coming from many different labs.

There will be more data coming in the next 10 years with new technology – optogenetics, optical imaging, many thousands of neurons being imaged at the same time. So, we will have data and access to the data. Researchers can use mathematics, computer models, AI to analyse this data and come up with theories of the brain consistent with this and other known data about the brain. For this work, you don't need big labs or much equipment. You could run computer simulations even on your laptop. India is well positioned because we have people with really strong backgrounds in mathematics, engineering and the sciences.

KN: You have been spending some time with the Indian neuroscience community. What do you make of the neuroscience interest and capability in the country?

RR: I did my first sabbatical in India in 2007-08 at IISc where I worked with Prof. Rangarajan's group in Mathematics on applications of time-series analysis to neural engineering. In 2012, we conducted one of the first workshops in neural engineering in India. We had leading neuroscientists, like John Donoghue from Brown University and Nitesh Thakor from John Hopkins, participate in the workshop. We had invited researchers in neural engineering and brain computer interfaces, and a number of students across India to come to Bangalore.

At that time, we could see that we were in the early days of neuroscience and neural engineering in the country, and the students were not quite at the stage where they could fully understand. In the decade since, I see a lot of growth. At the recent BCL workshop, we had many faculty members presenting cutting-edge research in neuroscience, and the students who participated were very adept and knowledgeable. I believe that there were over 900 to 1000 responses to the call for participation to the workshop, from which only a 100 or so were short-listed. There is a lot of interest in the country when it comes to the brain sciences, neural engineering and brain computer interfaces, and I think it's only going to grow. This is the right time to have such initiatives in India.

KN: What is your advice to an under-graduate student about learning about neuroscience? Is it too early?

RR: No, it is never too early! Being an undergraduate is a great time to start a career ineuroscience and neural engineering. I tell all my students that there are multiple ways to get into this field, which relies on techniques from AI, computer science, neuroscience, and cognitive science. They can enter it from a field of their liking, be it computer science, engineering or biology. Additionally, there is so much information that is available on the Internet. For example, I love watching YouTube lectures of other professors and students to learn about their research. There are papers available only a click away on bioRxiv and aRxiv. So, this is a great time to get involved in neuroscience and neural engineering – there are going to be lots of exciting developments in the next 10 to 20 years, and you can be part of it!

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About itihaasa Research and Digital

itihaasa Research and Digital (*www.itihaasa.com*) is a non-profit Section 8 company that aims to understand the evolution of technologies and innovation in India. We have published reports on the landscape of AI / ML research and brain science research in India. We have worked as a knowledge partner for the U.S. - India Artificial Intelligence (USIAI) initiative of the Indo-U.S. Science and Technology Forum (IUSSTF).

Kris Gopalakrishnan, co-founder Infosys, is the founder and Chairman of itihaasa Research and Digital. Our flagship project is itihaasa history of Indian IT, a first-of-its-kind free digital museum that recounts the history of Indian IT since the 1950s. This makes the incredible history of Indian IT accessible to an audience across the world and is available on (*https://itihaasa.com/History*) We have also published the book Against All Odds: The IT Story of India.

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