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Report on my 2018 stay at the Yukawa Institute for Theoretical Physics, Kyoto, Japan

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Abstract. In this report, I summarize some aspects and outcomes of the discussions during my one-month stay as Distinguished Visiting Professor at the Yukawa Institute for Theoretical Physics in October 2018. This visit was supported by the International Research Unit of Advanced Future Studies, Kyoto University, Japan.

Keywords: cognitive information processing, information processing paradigms beyond machine learning, complex systems, interdisciplinary and transdisciplinary science

Personal Note

I feel deeply indebted to Professor Masatoshi Murase for his wonderful hospitality, his kindness, inspiration and support during my stay at YITP as a Distinguished Visiting Professor. Prof. Murase's strive towards connecting researchers coming from different backgrounds and disciplines, including the sciences and the humanities, is an inspiration and allows for creating truly inter- and transdisciplinary interactions.

I would also like to thank the YITP and the International Research Unit of Advanced Future Studies for their support of my visiting professorship.

Moreover, I would like to thank its director Prof. Sinya Aoki and the colleagues at YITP and the International Research Unit of Advanced Future Studies for their hospitality and inspiring discussions.

Finally, I would like to thank all the YITP staff for their kindness and their invaluable administrative help.

It has been a pleasure to work at YITP and to interact with its faculty and staff, making it a very inspiring and fruitful period for me.

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Ingo Fischer

1. Scientific Activity

My research as a Distinguished Visiting Professor at the International Research Unit of Advanced Future Studies was conducted during the month of October 2018 in collaboration with Professor Masatoshi Murase.

During my stay, I enjoyed fruitful discussions and interactions with Prof. Murase on topics at the interface of his and our own work. This entailed aspects of interdisciplinary and transdisciplinary research on complex systems in general, and more particularly on cognitive processes involving analog cognitive computing beyond standard machine learning approaches and beyond the standard thinking, and their potential and ethical implications.

I participated and contributed to the *2018 Kyoto University International Forum on Advanced Future Studies* organized as a Parallel Session of the *International Conference on Applied Physics and Mathematics 2018*, held at the Narita Radisson Hotel, with a talk entitled *"Optical implementations of neuro-inspired information processing and its applications"*.

Moreover, I gave an outreach presentation entitled *"A computer working with light"* for high school students and the interested public in the prestigious clock tower room at Kyoto University. The interaction with these young students, experiencing their curiosity and self-driven initiative to understand nature and technology, was a pleasure and inspiration.

1.1. Context

Cognitive computing and neuro-inspired information processing have been gaining significant interest in recent years due to the development of novel computing concepts and, in particular, the implementations of cognitive computing using different kinds of analog hardware. Increasing demands on computing requirements with respect to the quantity of data to be processed, as well as the quality of data processing, problems to maintain Moore's Law much longer, and the need for higher energy efficiency, have been driving the developments of novel computational concepts. Moreover, driven by the growing problem of energy requirements for computing, it has been shown that many tasks require finite precision. This has resulted in a revival of analog computing. Employing analog hardware allows to design computational systems with high bandwidth and lower energy consumption. The idea behind this approach is to realize systems with the required computational precision for the given tasks using the best-matching hardware, without having to pay more than necessary for higher precision.

In our institute IFISC, we have been following a minimal design approach, and implementing our designs in electronic, optoelectronic and all-optics hardware, allowing for hardware efficiency, high speed, low energy consumption and compatibility with the corresponding experimental infrastructure.

The ideas driving this general development originate from machine learning and artificial intelligence in general, and neuroscience, complex systems, computational complexity, quantum computing and nonlinear photonics. From the viewpoint of machine learning, we have been witnessing the immense success of deep learning and related concepts in tasks deemed humanly or very difficult to achieve (Silver, 2017). We are witnessing how tools developed in these fields are entering our everyday lives, such as AI-based digital assistants, smart homes, Internet of Things, cyber-physical systems, medical self-tracking, diagnostics and Big Data analytics. But even these very popular and successful approaches are ultimately only realizing complex input-output functions, based on simple learning concepts. They do not mimic the still little understood human information processing, and neither can they be considered representations of Artificial General Intelligence (AGI). It will require many further steps in exploring advanced information processing paradigms, learning concepts, and their smart implementations.

We feel that there is much room to improve and for fundamental insights to be gained. This feeling is fueled by the fact that a biological brain is capable of performing a large variety of tasks in an ever-changing environment and of learning very efficiently, although it only requires 20-25W to operate.

Even fundamental aspects regarding how the brain encodes information, routes information, stores, retrieves (memorizes) and connects information, evade a thorough understanding so far.

It is our conviction that qualitative advances on understanding biological information processing can only emerge from a truly multidisciplinary and ultimately transdisciplinary approach.

1.2. Cognitive computing beyond standard methods

The notion that we need in order to apply a multi-perspective approach to advance in the challenge of understanding the human brain and, more generally biological information processing, had already bared fruits during my stay in October 2017 (Fischer, 2018). Projects, conferences, workshops and meetings covering multi-disciplinary approaches to information processing, or being devoted to it, are increasing in number, and more researchers from the best Universities and Institutions are joining this endeavour. Even the industry is meanwhile starting to recognize the potential of this approach (Nakajima, 2018). However, we are often still limited by the boundaries of disciplines that prevent real synergies due to the lack of the ability to truly exchange insights and ideas.

In the following, I will address some of the advances based on the stimulating discussions I have had with Professor Masatoshi Murase and colleagues during my stay at the Yukawa Institute of Kyoto University in October 2018. This is work in progress. The aspired advances of our research are to gain an extended understanding of cognitive processes in general, and to further support the paradigm shift towards a perspective of cognition as an emerging dynamical process. Besides these fundamental aims, we have been identifying minimal requirements for the implementations of cognitive computing systems in recent years, and we are now applying them to real-world applications. I will only outline the general approach here and will leave the detailed descriptions for more technical publications.

1.3. Minimal information processing concepts and its applications

At my home institute IFISC, we have been pursuing a minimal design approach of complex dynamics - based systems capable of performing tasks usually deemed complex. This already brought on technical challenges.

Our approach to practical information processing systems is inspired by the reservoir computing method (Jaeger, 2001), (Maass, 2002). The appeal of this method is that it combines the properties of fading memory for contextual information processing with low constraints on the network and easy training methods based on linear regression.

We have simplified the concept dramatically by using the simplest possible dynamical system allowing for a high-dimensional nonlinear mapping of the input onto a high-dimensional state space. This simple system can only comprise a single nonlinear node and a delayed feedback loop (Appeltant, 2011). We have time-multiplexed the input information during one delay time by multiplying the input with a mask or input matrix, generating nonlinear transients. Various nonlinearities, including those being of Mackey-Glass type (Appeltant, 2011), Ikeda-type (Larger, 2012), or of semiconductor laser type (Brunner, 2013) have all proven successful in this approach. Remarkably, we have found that the ring-like topology of the delay-dynamical system works as well as large random networks with many nodes. Based on different implementations, tasks such as nonlinear prediction and dynamical pattern classification have been successfully demonstrated (Soriano, 2015).

1.4. Application of an all-optical minimal information processing system for message recovery

Using telecommunication-compatible hardware, namely a semiconductor laser as nonlinear node and an optical fiber as optical delay line, we have implemented reservoir computing and extreme learning machine concepts, and first demonstrated their attractive features in benchmark tests including classification tasks and nonlinear prediction.

The real-word technological challenge we have been tackling then is, how to classify ultra-fast signals from fiber-optical communication systems that have been distorted due to in-fiber propagation. Fiber communication systems are range-limited due to these transmission impairments limiting speed, complicating the communication infrastructure, and costing additional energy. Moreover, for extended transmission distances, standard bit recovery techniques fail completely. Using our all-optical minimal information processing approach, we are able to overcome this limitation by transforming the bit classification problem into a pattern recognition problem. The scheme of how this was achieved is depicted in Figure 1.

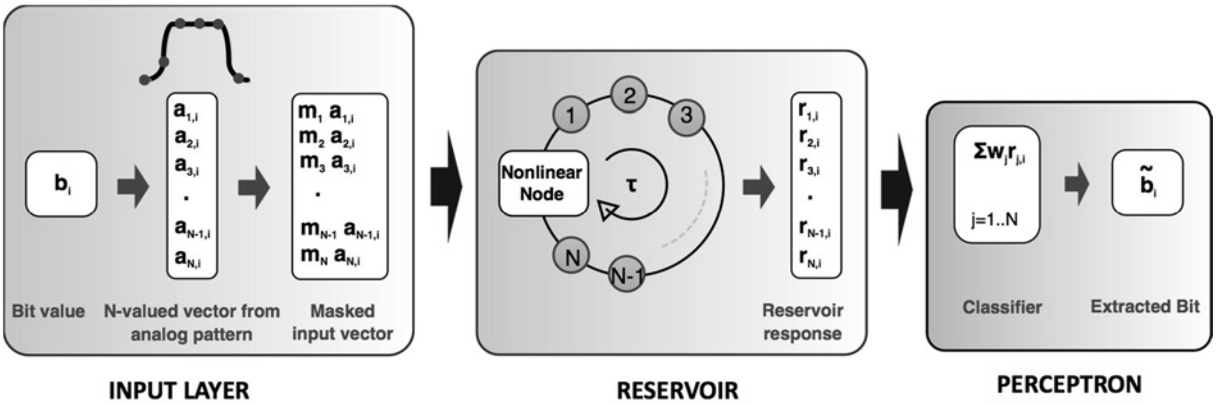

Figure 1: Minimal all-optical reservoir computing system transforming the bit classification problem into a pattern recognition problem.

The input signal is simply multiplied by a random mask, before it is injected into the all-optical reservoir computing system. Here, even the dimension of the state space of input and reservoir response are the same. Nevertheless, when training the system to recover the transmitted bit stream via linear regression, we could experimentally demonstrate an improvement of the bit error rate of two orders of magnitude, compared to the system without the nonlinear reservoir or competing methods (Argyris, 2018). We interpret the good performance to be due to a more complex representation of the transmitted bit pattern in the presence of the reservoir as compared to results obtained in its absence.

The bit classification performance we achieved is a significant breakthrough since we can recover data at high speed that otherwise cannot be recovered. Challenges regarding a real-time implementation remain, but we are pursuing strategies already to research how these challenges can be overcome.

This example shows that conceptual simplification is not only an advantage to gain a better understanding of information processing systems, but that those simplified concepts could even be of high technological relevance.

2. Presentations in affiliation with the International Research Unit of Advanced Future Studies

During my stay, I contributed to several seminars and workshops, as follows:

- Invited talk entitled *"Optical implementations of neuro-inspired information processing and its applications"*, presented at the *2018 Kyoto University International Forum on Advanced Future Studies*, organized as a Parallel Session of the *International Conference on Applied Physics and Mathematics 2018* and held at the Narita Radisson Hotel.
- Public outreach presentation entitled *"A computer working with light"* for students from high schools and the interested public in the prestigious clock tower room at Kyoto University.

3. Conclusion and Outlook

After my first visit in 2017, I was able to continue the intense and fruitful interaction with Prof Masatoshi Murase on topics including cognitive information processing, extended concepts and ethical implications of AI systems in general and potential AGI concepts in the future. The ethical implications are becoming more and more pressing. Besides the positive potential of better AI personal assistants, better health care, smart cities etc., we also need to be aware of the risks related to AI-controlled weapons and warfare, invasion of privacy, ethical and legal consequences of autonomous cars, manipulation of elections, etc. Initiated by AI researchers, we are now witnessing the creation of organizations such as the *Future of Life Institute* (https://futureoflife.org), raising awareness for the required ethical and political questions to be addressed. During my visit at YITP we discussed ideas of Mr. Hideto Ishihara to inherently build ethical principles into AI and AGI systems.

Regarding the minimal system approach to cognitive computing, we will in the near future explore the extension of our concepts in two ways. First, we will further adapt the photonic reservoir computing systems to their practical applications in optical fiber communication systems. Second, we will move beyond the reservoir computing concept, in order to achieve unsupervised learning and create a scaling approach that is adapted to the properties of the system and a dimensionality analysis.

A key goal is to learn about the interplay of information processing, self-organized information routing and the robustness of such systems based on different computing substrates and scaling approaches. The way biological systems, and the human brain in particular, cope with these challenges, and how these systems/organisms emerged in evolution will be major sources of inspiration and will help to obtain a better understanding.

In addition to my interactions with Prof. Masatoshi Murase, Prof. Murase also initiated joint discussions with Prof. Johann Hohenegger from the University Vienna (Austria), who has been working on complex systems in the research field of paleontology. The aspect, how intelligence and the ability to cope with the environment have evolved, represents yet another promising perspective to gain further insight into biological information processing, and this might inspire extended or novel concepts and their implementation.

The work and discussions at Kyoto University were complemented by lively and inspiring discussions on more technical advances, fundamental earlier works and questions on what we can expect from cognitive computing in the future with colleagues and friends outside Kyoto University, in particular with Dr. Peter Davis (Kyoto), who hosted me as a postdoctoral researcher 19 years ago, and Prof. Kensuke Ikeda (Ritsumeikan University) who has pioneered and inspired the research on delay-dynamical systems.

4. Future collaboration possibilities with Kyoto University

It is a very worthwhile venture to further explore a formal and longer-term collaboration between the YITP and the IFISC in physics in the areas of Complex Systems and Advanced Future Studies. This collaboration could entail joint research activities and the joint organization of seminars, workshops and conferences as well as mutual visits.

I have greatly benefited from Professor Murase's generosity and hospitality, and his inspiring openness to share his ideas. I would be delighted to have the opportunity to further build upon the insightful interactions with him and to continue this fruitful collaboration.

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