Institution: University of Manchester

Unit of Assessment: 11 (Computer Science and Informatics)

Title of case study: SpiNNaker – enabling brain-inspired AI

Period when the underpinning research was undertaken: 2002 – December 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed:
Stephen Furber	Professor	1990 – present
James Garside	Senior Lecturer	1991 – present
David Lester	Senior Lecturer	1990 – 2020
Oliver Rhodes	Lecturer (2019 – present), Research Fellow (2016 – 2019)	2016 – present

Period when the claimed impact occurred: October 2013 – December 2020

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

University of Manchester research within the Department of Computer Science led to the creation of SpiNNaker – a novel computer chip architecture. SpiNNaker has had extensive impact on the domain of brain-inspired computing. A novel computer chip, computer architecture and software stack were developed, enabling:

- Economic impact via sales of 10 boards to non-academic and 39 to academic institutions worldwide, generating royalties of GBP150,714 to Cogniscience Ltd.
- New business activities for MindTrace Ltd (which relies on SpiNNaker). MindTrace received GBP1.3Million from Advanced Digital Ventures and Mercia Technologies (through the Northern Powerhouse Fund), creating 6 jobs in Manchester.
- The creation of approximately 22 jobs in Germany, due to a EUR8Million investment by the Saxony government.

2. Underpinning research

SpiNNaker (a contraction of Spiking Neural Network Architecture) has been 20 years in conception and 15 in construction. The "SpiNNaker" name is used to collectively describe:

- a novel computer chip architecture inspired by the workings of the brain;
- the chip that embodies that architecture (the SpiNNaker chip);
- circuit boards incorporating a number of those chips (SpiNNaker boards); and
- machines comprising one or more connected boards (SpiNNaker machines).

Originally developed with EPSRC funding (combined total over GBP3,300,000), the million-processor SpiNNaker machine at the University of Manchester (UoM) is the world's largest neuromorphic computing platform (as of July 2020) and a core node in the EU H2020 Future Emerging Technologies flagship Human Brain Project EBRAINS infrastructure.

A SpiNNaker machine (Figure 1) is a massively parallel computing platform, using a novel inter-processor communication technology based on a novel efficient multicast infrastructure inspired by the very high degree of connectivity found between neurons in the brain. The key component of the communications infrastructure is a (patented) bespoke multicast router that is able to replicate small packets (each of which carries a neuron's action potential, or "spike"), where necessary, to implement the multicast function associated with sending the same packet to many different destinations.

The concept of the *SpiNNaker* machine was proposed by Furber in the early 2000s as a high-performance computing solution to the Grand Challenge of modelling the brain. The architecture was evolved at UoM over the subsequent few years, with the major design decisions published in 2013. This includes the development of the novel massively-parallel computer architecture [1], the design of the microchip at the heart of this architecture [2], the construction of a million-processor machine and the development of techniques to make it reliable, and the development of a novel software stack to map problems onto the machine [3].

The unique capabilities of the machine have been demonstrated through subsequent research. This includes several outputs showing the application of the machine to model neurological processes in real-time, e.g. [4], which demonstrates the credibility of SpiNNaker in addressing the needs of the neuroscience community. Equally, SpiNNaker's applicability to a broader class of problems has been validated, including AI algorithms requiring event-based simulation and low-precision arithmetic [5]. This showed the potential of the architecture for industrial AI applications, and stimulated investment, as described below. The first 20 years of the project have been documented in an Open Access book [6].

Figure 1. The million-processor SpiNNaker machine at the University of Manchester

3. References to the research

This research has been funded through EPSRC grants (EP/D07908X/1 and EP/G015740/1, totalling over GBP3,300,000), and is part of the EU H2020 Future Emerging Technologies flagship Human Brain Project (FP7-604102, H2020-720271, H2020-785907 and H2020-945539, totalling over GBP5,000,000). Citations are from Google Scholar (December 2020).

[1] Furber, S., Lester, D., Plana, L., Garside, J., Painkras, E., Temple, S., and Brown, A. (2013) Overview of the SpiNNaker System Architecture, *IEEE Transactions on Computers* **62**(12), 2454-2467, DOI: 10.1109/TC.2012.142 [527 citations]

[2] Painkras, E., Plana, L., Garside, J., Temple, S., Galluppi, F., Patterson, C., Lester, D., Brown, A., and Furber, S. (2013) SpiNNaker: A 1-W 18-core system-on-chip for massively-parallel neural network simulation, *IEEE Journal of Solid-State Circuits* **48**(8), 1943-1953, DOI:10.1109/JSSC.2013.2259038 [243 citations]

[3] Rhodes, O., Petrut, B., Brenninkmeijer, C., Davidson, S., Fellow, D., Gait, A., Lester, D., Mikaitis, M., Plana, L., Rowley, A., Stokes, A., and Furber, S. (2018) sPyNNaker: A Software Package for Running PyNN Simulations on SpiNNaker, *Frontiers in Neuroscience*. **12**, 816, DOI: 10.3389/fnins.2018.00816 [22 citations]

[4] Rhodes, O., Peres, L., Rowley, A., Gait, A., Plana, L., Brenninkmeijer, C., and Furber, S. (2019), Real-time Cortical Simulation on Neuromorphic Hardware, *Philosophical*

Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, **378**, DOI:10.1098/rsta.2019.0160 [9 citations]

[5] Fonseca Guerra, G., and Furber, S. (2017) Using Stochastic Spiking Neural Networks on SpiNNaker to Solve Constraint Satisfaction Problems. *Frontiers in Neuroscience*. **11**, DOI:10.3389/fnins.2017.00714 [25 citations]

[6] Furber, S.B. and Bogdan, P. (eds.) (2020) SpiNNaker – a spiking neural network architecture. Now Publishers. DOI:10.1561/9781680836523 (Open Access)

4. Details of the impact

Pathway to impact

The SpiNNaker concepts began to emerge from an EPSRC ROPA (Realising Our Potential Awards) grant in the late 1990s through an internal proposal [6, chapter 1] to detail design work under EPSRC funding in collaboration with the universities of Southampton, Cambridge and Sheffield. The first full SpiNNaker1 silicon was delivered in 2011 and positioned the UoM group to contribute to the Human Brain Project (HBP) Flagship proposal and join the HBP in October 2013. Within the HBP, the UoM group worked with TU (Technische Universitat) Dresden to develop a second-generation chip design, SpiNNaker2, taking advantage of silicon process advances to increase the number of cores from 18 to 152. SpiNNaker2 is strongly based on the architectural principles developed at Manchester in SpiNNaker1, but also brings in significant TU Dresden IP (intellectual property). SpiNNaker2 small-scale prototypes are supporting ongoing research; the full SpiNNaker2 chip will be fabricated in 2021.

The impacts described below are based upon either the sales (Cogniscience Ltd) or use (Mindtrace Ltd) of SpiNNaker1, or on government and industry commitment to research and development (R&D) using SpiNNaker2 (TU Dresden collaborations), all within this REF period. None of these would be possible without the underpinning research at UoM.

Impact summary

SpiNNaker has been in development since 2000, with sales and licenses starting in 2015. SpiNNaker has generated economic impact worldwide, including:

- Generation of at least GBP150,714 in royalties to Cogniscience Ltd
- Enabling a UK business (MindTrace) to generate new IP (1 patent awarded, 1 pending) described as "*unique in the commercial world"*, offering "*substantial cost, energy efficiency and speed advantages over competitive approaches"*
- GBP98,000 in UK government investment (Innovate UK)
- EUR8,000,000 of investment by the Saxony government to support German industry
- EUR60,000,000 of industry research commitment (e.g. Infineon, BMW, Bosch)
- Creation of at least 28 jobs to date

As of December 2020, SpiNNaker systems are on every continent except South America and Antarctica, in a total of 44 academic and commercial R&D organisations (Figure 2).

Generated revenue and profit for a University spin-out company

Cogniscience Ltd, a UoM spinout, owns key SpiNNaker IP. Since sales of SpiNNaker technology started in 2015, 12 boards have been sold to non-academic organisations and 36 boards to academic institutions worldwide. Cogniscience Ltd has received GBP150,714 in royalties, with GBP31,000 in royalties to other IP suppliers including ARM, Cadence, Synopsys and Mentor [A]. To date, a total of 48 boards have been sold at GBP7,500 per board for academic purchasers (across 20 institutions worldwide) and GBP10,500 per board for commercial sales (4 organisations worldwide).

Most sales are single-board machines (each board containing 48 SpiNNaker chips), where each board is in an acrylic case laser cut at UoM. A few sales are multi-board machines in a cased card frame. A further 20 are on loan to academic partners worldwide.

Generated sales for supply-chain businesses
SpiNNaker chips are manufactured to the UoM design by UMC in Taiwan. [Text removed for publication]. The packages are then assembled onto circuit boards by Norcott Ltd in Warrington, and supplied to UoM, who carry out board tests, component black-listing, and machine assembly and commissioning.

In 2020, negotiations commenced to license the Chinese Academy of Sciences to build a 600-board machine. This should generate a further GBP300,000 royalties to Cogniscience Ltd.

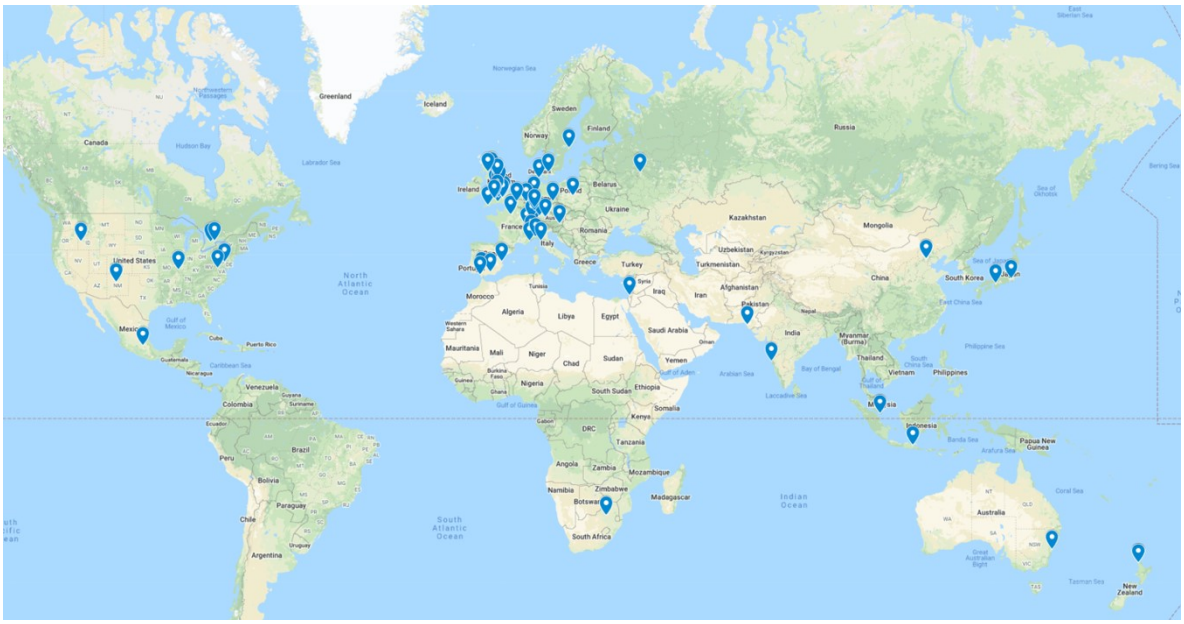

Figure 2. Geographic location of current SpiNNaker machines.

Contribution to UK business and innovation in AI systems
Mindtrace Ltd was established in 2017 (independently from the University) to develop event-based AI systems, following a Venture Capital seed investment of GBP1,300,000 from Advanced Digital Ventures and Mercia Technologies. Mindtrace identified SpiNNaker as the best option available and used SpiNNaker as its primary development platform [B]. Head of Research, and co-founder at Mindtrace Ltd, confirms:

> "*the advantages of using SpiNNaker accrue from its being designed to support spike-based neural networks […] as a result of its use of software neuron and synapse models. This was not available in other 'neuromorphic' architectures we explored"* [B]

This is a direct consequence of the research described in [4,6].

In 2018, the company purchased six 48-chip SpiNNaker boards for GBP72,000 [B]. They have confirmed "*SpiNNaker has been pivotal in the early development of Mindtrace Ltd*" and attribute several developments to their use of SpiNNaker, including [B]:

- securing a GBP98,000 Innovate UK grant (awarded in 2017)
- creation of 6 R&D jobs to support development on SpiNNaker
- award of US patent (10,510,001) with all algorithm development based on SpiNNaker
- development of proprietary event-based AI algorithms for massively parallel visual processing, which have further ensured the viability of the business

- development of proprietary Deep Learning algorithms (UK patent pending) for fast visual object recognition

Mindtrace Ltd have described the novel developments as "*unique in the commercial world"*, offering "*substantial cost, energy efficiency and speed advantages over competitive approaches"* [B].

Stimulation of new investments by an EU government.
In 2019, the Saxony Science Ministry announced an EUR8,000,000 investment awarded to TU Dresden to construct SpiNNcloud, a large-scale datacentre service for German industry, which is based on SpiNNaker-2, a second-generation of the SpiNNaker architecture [C]. TU Dresden have confirmed that "*SpiNNcloud would not have been possible without the SpiNNaker-1 IP, first developed at the University of Manchester*" [D]. The SpiNNaker-2 architecture is based on the research developed for SpiNNaker, including the relevant patents [D].

Stimulation of new investments by EU industry, enabling highly skilled jobs.
SpiNNaker has directly stimulated industry-funded research, with an estimated total value of EUR60,000,000 across the following projects: KI-ASIC (Infineon, BMW EUR7,000,000), Scale4Edge (Infineon, Bosch, EUR17,000,000), WINFDSOI (Global Foundries, approximately EUR6,000,000) and Tempo, Andante (Infineon & various aerospace companies, EUR30,000,000) [D]. Infineon, a world leader in semiconductor solutions, is centralising all AI activities in Dresden and approximately 10 staff are now working with the current SpiNNaker2 prototypes, a number that is expected to increase significantly when SpiNNcloud is deployed. Therefore, since the Saxony Science Bid was awarded in 2019, 22 new jobs have been created on SpiNNaker2/SpiNNcloud projects [D], with confirmation this number will increase once SpiNNcloud is deployed.

In addition to these industry collaborations, EUR600,000 seed funding has been secured from the federal German 'Agentur für Sprunginnovationen' for TU Dresden to spin-out an AI company (with contributions from the University of Manchester) to further develop industrial applications of SpiNNaker2 and related technologies [D].

5. Sources to corroborate the impact

[A] Letter from Apicius Ltd, re Cogniscience Ltd royalty income (January 2021)
[B] Letter from Head of Research (and Co-founder) at MindTrace Ltd (June 2020)
[C] Press announcement of the Saxony Science Ministry EUR8,000,000 grant
[D] Letter from Head of Group at TU Dresden (July 2020)