



# Deep Learning on SpiNNaker: Report

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**Abstract**

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# 1 Introduction

According to the SpiNNaker project's website:

SpiNNaker is a novel massively-parallel computer architecture, inspired by the fundamental structure and function of the human brain, which itself is composed of billions of simple computing elements, communicating using unreliable spikes (SpiNNaker Team, 2020).

SpiNNaker is a digital neuromorphic computer architecture, designed to model the human brain. This is rather a gross simplification of what SpiNNaker was designed for. Understanding the human brain is one of the biggest frontiers of science and there are many ideas on how one can model a complex and still mostly unknown structure such as the human brain. Therefore, there are many different proposed neuromorphic computer architectures and ideas on how to model the human brain, from early analogue approaches for vision systems like presented in Mead (1989) to large scale digital architectures like Blue Brain (Markram, 2006); all aiming to implement different types of neurons and models of the human brain efficiently (Furber and Temple, 2007).

SpiNNaker is an architecture for the large scale and real-time modeling of spiking neural networks (Furber et al., 2006a,b; Furber and Temple, 2007). Maass (1997) describes spiking neural networks as the third generation of neural networks. Unlike the second generation neural networks—which we will deal with in the dissertation project here reported on in the form of deep learning neural networks—spiking neural networks incorporate a concept of time in their action potentials (spikes). Neural networks of the second generation do not have a concept of time and fire every time they are activated. Spiking neural networks are derived from evidence collected from biological neural systems; they are therefore more closely representing neural systems of biological life than deep learning neural networks (Maass, 1997).

The SpiNNaker chip is a ARM multiprocessor chip having 18 cores, with a Network-on-Chip system for communication between cores (Furber and Temple, 2007; SpiNNaker Team, 2020). Each core can model up to 1000 spiking neurons. The spiking neurons in the neural network communicate with spike events (Furber and Temple, 2007). Spike events are—like their biological counterpart—inherently unstable and small. This is represented in the interconnection hardware. Small packets (40 or 72 bits) can be sent, without guarantee of successful arrival. Even without this guarantee, one can still perform meaningful computations on SpiNNaker and fault detection and recovery mechanisms are implemented (SpiNNaker Team, 2020). One can connect many SpiNNaker chips together, to build a massively parallel and energy efficient supercomputer that is able to run up to a billion spiking neurons in real time (Furber and Temple, 2007). Photos of the SpiNNaker hardware can be found in Appendix A.

SpiNNaker is targeted at three main areas of research: (i) neuroscience: understanding the human brain, (ii) robotics: low power hardware for implementing neural decision systems and (iii) computer science: new approach to supercomputing and massive parallelism (SpiNNaker Team, 2020). The dissertation project, which this paper reports on, will concern itself with (iii) and one of the research areas of computer science, which has emerged as a driving force behind advancements in many fields and for many tasks like speech and image recognition, drug discovery and genomics: deep learning (LeCun et al., 2015).

While deep learning is a promising field and deep neural networks at the center of important advancements, like described above, they face a major problem: the sheer amount of computation needed for training them. Researchers at OpenAI have estimated, that the amount of computation needed for training state of the art deep neural networks increases exponentially, doubling every 3.4 months (Amodei et al., 2019). In order to cope with such unprecedented amounts of computation and energy needed, the search for specialized

hardware is well underway. Current state of the art hardware for accelerating the training of deep neural networks are ASICs like TPUs and general purpose GPUs (Jouppi et al., 2017; Mittal and Vaishay, 2019).

The goal of the dissertation project that is introduced in this paper, will be to analyze if SpiNNaker could be an energy efficient, scalable and fast alternative to the above mentioned hardware. Since deep neural networks are derived from the human brain and nerve system (Goodfellow et al., 2016) and SpiNNaker was designed to model the human brain, it seems rather probable, that SpiNNaker will be a good target for accelerating the training of deep neural networks.

This paper concerns itself with the dissertation project: “Deep Learning on SpiNNaker”, which will be conducted in the period from May 2019 to August 2019 as the final work of the author to achieve his Master of Science in High Performance Computing with Data Science from the University of Edinburgh. The report is mostly a summary of the preliminary work conducted in the months before the actual work on the dissertation will be conducted.

The findings of the preliminary work and the changes made to the original project scope are the focal point of this report. The original title of the dissertation project was “A Tensorflow Backend to SpiNNaker”, but the preliminary work conducted to this point show, that the scope will be redirected from implementing a backend for tensorflow—a library for running fast linear algebra operations on distributed, heterogenous systems, mainly designed for implementing computationally demanding machine learning algorithms like deep learning in a fast manner (Abadi et al., 2015)—to an approach focused on implementing deep learning directly on SpiNNaker. Because of SpiNNaker’s specialized design, which works rather contrary to that of tensorflow and current hardware trends for building accelerators for deep learning, interfacing between SpiNNaker’s runtime and tensorflow was deemed too difficult and not beneficial. Instead, this dissertation aims at implementing deep learning directly on SpiNNaker, probably providing an interface designed in the likes of the well known deep learning library Keras (Chollet et al., 2015). Mario Antonioletti and Alan Stokes (2019) shows the original dissertation project’s scope.

This paper starts with presenting the final project proposal, in particular focusing on the benchmark to be conducted in Section 2. Afterwards related work is presented in Section 3. The main focus lies on presenting papers with benchmarks we can compare our implementation against. The paper continues by giving a work plan in Section 4, before presenting a risk analysis in Section 5. Afterwards the preliminary findings outlined above are discussed in more depth in Section 6. At last Section 7 will contain a review of a related dissertation project done in 2018: “Deep Learning Performance on Different Architectures” by Spyro Nita (Nita, 2018).

## 2 Final Project Proposal

This section will begin by giving an outline of the initial project proposal. The preliminary findings given in Section 6 led us to abandon the initial project proposal. The updated project proposal is given. The benchmark with which we will compare our deep learning implementation on SpiNNaker with other hardware platforms and deep learning libraries is presented.

The final project proposal will differ from the initial one in two meaningful ways: (i) we will implement deep learning algorithms and layers directly on SpiNNaker, instead of implementing a tensorflow backend (see Section 6) and (ii) a different benchmark to measure the performance of SpiNNaker. While at first, implementing a tensorflow backend in order to enable deep learning on SpiNNaker seemed wise: low level

linear algebra operations based on which deep learning algorithms run, instead of having to implement them directly. The discrepancy between tensorflow’s architecture and SpiNNaker’s was deemed too big to overcome and to get a working deep learning neural network running in the limited amount of time for doing the dissertation was estimated to be impossible. Concerning (ii), the benchmark proposed by the initial proposal was to benchmark our native deep learning implementation against the snn toolbox (Rueckauer et al., 2017). The snn toolbox allows taking pre-trained deep neural networks and convert them to spiking neural networks, which then can be deployed on SpiNNaker. The problem with this benchmark is the fact, that only pre-trained deep neural networks can be used and only inference would be possible on SpiNNaker. We do not aim at doing the rather inexpensive inference (at least compared to the training), rather we want to use SpiNNaker where it would be needed more: training a deep neural network—a computationally very costly operation (see Section 1).

Instead of benchmarking against the snn toolbox, we intend to go for a much more ambitious benchmark. We want to benchmark the performance of our implementation on SpiNNaker against other state of the art hardware and software libraries for deep learning based on a model for computer vision—a very popular problem domain for deep learning, providing many good benchmarks we can compare against (see Section 3).

Currently, the most famous and probably biggest challenge for benchmarking computer vision models is the ImageNet Large Scale Visual Recognition Challenge (ILSVRC), based on the ImageNet dataset. The ImageNet dataset consists of more than 14 million images, organized according to the WordNet hierarchy into over 21 thousand so called synsets (synonym sets) (Russakovsky et al., 2015; Miller, 1995). The ILSVRC is an annual competition running since 2010. It has produced many famous models, e.g. AlexNet, VGG16 or ResNet-50 (Krizhevsky et al., 2012; Simonyan and Zisserman, 2014; He et al., 2015). We intend to benchmark by training the most complex of these three models: ResNet-50. The benchmark will be to train ResNet-50 with 1000 categories (1.28 million images) of the ImageNet dataset (setting of the ILSVRC 2012) and measure the time it takes to finish the training. The top-1 accuracy of the model is evaluated on 50,000 test images and should be at least 74.9%, in order to compare it to the other benchmarks presented in Section 3.

In conclusion, our final project proposal will be implementing deep learning algorithms directly on SpiNNaker, instead of providing a backend to tensorflow. We will benchmark this implementation and SpiNNaker against other benchmarks based on state of the art deep learning libraries and accelerators for fast training of neural networks, instead of benchmarking our implementation against the snn toolbox. For this benchmark we will train the famous ResNet-50 model based on the settings described above and compare our results against the results others generated with the same setting but with different libraries and hardware, which are presented below.

### 3 Related Work

This section will focus itself with related work important for the final project proposal of “Deep Learning on SpiNNaker”. The main focus lies on benchmarks, with which we can compare our implementation on SpiNNaker with state of the art libraries and—more importantly—hardware. Further literature of importance for this project, e.g. He et al. (2015), Goodfellow et al. (2016) or Russakovsky et al. (2015), can be found in the References.

The benchmark settings described in the previous chapter are the image classification benchmark for training deep learning models of the recently launched MLPerf benchmark project. The MLPerf benchmark was

paper	processor/accelerator	#	library	time
He et al. (2015)	Tesla P100	8	caffe	29 hours
Goyal et al. (2017)	Tesla P100	256	caffe2	1 hour
Smith et al. (2017)	TPU pod	1	tensorflow	30 minutes
Akiba et al. (2017)	Tesla P100	1024	chainer	15 minutes
You et al. (2017)	Xeon Phi KNL	2048	caffe	14 minutes
Jia et al. (2018)	Tesla P40	2048	tensorflow	6.6 minutes
Mikami et al. (2018)	Tesla V100	2176	NNL	3.7 minutes

Table 1: Selected timings from benchmarks other than MLPerf with a similar setting. None can beat the fastest system from the MLPerf benchmark, which is not surprising, given the fast pace of improvements in both hardware and software for deep learning and the fact, that the MLPerf benchmark results are the most recent.

proposed, to ensure fair performance comparisons between various hardware and software libraries for deep learning (Mattson et al., 2019). We intend to stick to the rules of the MLPerf benchmark. If the dissertation project will succeed as planned, we will submit our timing results to the MLPerf Training benchmark v0.7, which is due on the 21st of February 2020. The results of MLPerf Training v0.6 can be found at <https://mlperf.org/training-results-0-6/>. Currently the fastest system for the image classification benchmark is based on tensorflow and 1024 TPUs. It is able to finish in 1.28 minutes. Besides the MLPerf benchmark, which is quite new, there are a few older papers which use a similar setting for benchmarking their systems. These papers and their results are listed in Table 1.

## 4 Work Plan

This section will describe the time table for the actual dissertation period. The dissertation period starts on Monday the 25th of May 2020 and will end on Friday the 21st of August 2020. This covers 13 weeks, calendar week 22 to calendar week 34 inclusively.

There are three distinct main tasks to do for the dissertation project, which all can be further broken down into more fine-grained subtasks:

- Implementing ResNet-50 on SpiNNaker
  1. Dense layer forward pass (Inference) (see Goodfellow et al., 2016)
  2. Stochastic gradient descent with dense layer backward pass (SGD) (see Goodfellow et al., 2016)
  3. Convolutional layer and ReLu layer (Conv) (see Goodfellow et al., 2016)
  4. Pooling layer (Pool) (see Goodfellow et al., 2016)
  5. Residual learning (RL) (see He et al., 2015)
  6. Optimize implementation (Optimize)
- Benchmarking
- Dissertation writing

CW Task \	22	23	24	25	26	27	28	29	30	31	32	33	34
<b>Implement</b>													
Inference	Green												
SGD		Green	Green										
Conv				Green	Green								
Pool						Green							
RL							Green						
Optimize								Green	Green	Green			
<b>Benchmark</b>								Red	Red	Red			
<b>Writing</b>													
Background	Blue	Blue	Blue	Blue	Blue								
Log						Blue	Blue	Blue	Blue				
Benchmark										Blue	Blue		
Conclusion											Blue		
Proof reading						Blue					Blue	Blue	

Table 2: Gantt chart displaying the work plan for the dissertation period.

- Background
- Log
- Benchmark
- Conclusion
- Proof reading

There are a few dependencies between the subtasks. Benchmarking obviously depends on a finished implementation. Optimizing the implementation and benchmarking will depend on each other and will be done iteratively to the final benchmark. The background for the dissertation can be written independently from implementing and benchmarking. The log section and the benchmark section will depend on the implementation and benchmarking efforts. The conclusion section of the report depends on the log and the benchmark section of the dissertation. The subtasks of implementing ResNet-50 are enuerated, because they are done in succession, in the order they are presented. Only optimizing will depend on the benchmark, all else is independent from the rest.

The Gantt chart presented in Table 2 is derived from these dependencies and displays the work plan for the dissertation period. The most challenging week will be calendar week 32 with four tasks to do in parallel. It will be the week the final benchmark must be finished and the writing of the benchmark section will begin. For the background section of the dissertation is a lot of time allocated. Not all of the time will be necessary, or just a little time per week will be dedicated to the writing of this section. The last week before the deadline will solely be spend on proof reading. Calendar week 33 could be used as a buffer week, if the benchmark will not be finished after calendar week 32.

## 5 Risk Analysis

This section will look at risks for the successful completion of the dissertation and how they can be overcome. There are three main risks that will endanger the progress of the dissertation:

- Alan Stokes dies
- Hardware destruction
- Failure to implement ResNet-50 on SpiNNaker

Alan Stokes is one of the dissertation's supervisor and part of the core team of SpiNNaker developers. He is the main source of information concerning the SpiNNaker hardware and runtime. His death would put the dissertation in grave jeopardy. A death of a person is always coupled to mental difficulties and traumas for the bereaved. Also, a lot of necessary knowledge needed for this dissertation would be lost. Psychic help in form of a psychiatrist would hopefully help with overcoming a trauma following Alan Stoke's death. Concerning the second point—knowledge about SpiNNaker—there exists a Google group with most of the people using SpiNNaker in it, including the members of the SpiNNaker core team. The google group already is the second point of contact concerning SpiNNaker and would therefore be upgraded to first.

There is a SpiNNaker board (see Appendix A for a picture of a SpiNNaker board) allocated for work on this dissertation. A SpiNNaker board is a costly piece of hardware. While the destruction of the board would put the author into financial problems, the destruction of the board is not endangering the successful completion of the dissertation, since there is the supercomputer in Manchester (see Appendix A for a picture of the supercomputer) where the work on the dissertation can be done on. The benchmarks will be run on the supercomputer anyways. Only the implementation phase could take longer, because rapid prototyping on a dedicated piece of hardware would not be possible, since the supercomputer must be shared with other researchers.

## 6 Preliminary Findings

## 7 Deep Learning Performance on Different Architectures: Review

This section will concern itself with a review of the dissertation of Spyro Nita, which he did for earning his Master of Science in High Performance Computing with Data Science at the University of Edinburgh: “Deep Learning Performance on Different Architectures” (Nita, 2018). First, a summary of his dissertation will be given, before the review of his work is presented. The review will start by looking at how well the context of the dissertation is explained and how well the scope of the dissertation’s problem is defined. The last part of the review will be the consideration of the dissertation’s layout and formatting. After the review, the importance of the dissertation for “Deep Learning on SpiNNaker” will be discussed and evaluated.

Nita (2018) concerns itself with measuring the computational performance of two different approaches for training deep neural networks: (i) distributed training using GPUs and (ii) distributed training using CPUs. The dissertation is a work derived of the efforts of Team EPCC at the Student Cluster Competition at the International Supercomputing Conference 2018, held in Frankfurt, where Team EPCC competed against other teams by building a small supercomputing cluster and running various benchmarks on it, to see which team

built the best supercomputing cluster. One of these benchmarks concerned itself with measuring the performance of training a deep neural network on the clusters, which is picked up in Nita (2018) and represents the benchmark for approach (i).

The benchmark is based on the famous ImageNet dataset, like the ILSVRC (see Section 2). Contrary to the ILSVRC, the benchmark for the Student Cluster Competition only concerns itself with the throughput of images during training and not with the accuracy of the trained models. The throughput is measured in images per second. Only if two teams should have the same throughput during training is the training accuracy taken into account as the secondary criterion for tie-breaking. The teams participating in the Student Cluster Competition had to train the VGG16 deep neural network—a famous model architecture introduced in the ILSVRC 2014 by researchers from Oxford University (Simonyan and Zisserman, 2014)—on 1000 synsets containing 1.2 million images. The main limitation for the clusters were their power budget of 3kW and—for the ImageNet benchmark—a maximum runtime of three hours (Nita, 2018).

Nita (2018) compares the throughput of the supercomputing cluster of Team EPCC for the performance of a distributed GPU system against Cirrus—a supercomputer hosted by the EPCC—for the performance of a distributed CPU system (EPCC, 2020).

Concerning the results of Nita (2018), two major problems were encountered: (i) cluster damage and failure of the Team EPCC cluster shortly before the competition and (ii) the fact that the CPU benchmark on Cirrus could not be distributed over multiple backend nodes. Fortunately benchmarks were done on the Team EPCC cluster, before its failure and Nita (2018) presents the results of using the first node of the cluster with six NVIDIA V100 GPUs. Concerning (ii), Nita (2018) presents the results for a single backend node and assumes that Cirrus would be able to linearly scale to multiple backend nodes, when comparing the two clusters. The single node of the Team EPCC cluster with its six NVIDIA V100 GPUs generates a throughput of 2,052 images per second, while a single backend node of Cirrus (two Intel Xeon E5-2695 processors, each with 18 physical cores) can generate a throughput of just 18 images per second. Assuming linear scaling over multiple backend nodes of Cirrus, 21 nodes would be needed for the throughput of a single NVIDIA V100 GPU. Nita (2018) concludes that GPUs offer a significant advantage compared to CPUs, when it comes to training deep neural networks.

The dissertation starts with an introduction, which includes a description of the dissertation’s layout. The second chapter concerns itself with a description of convolutional neural networks for image classification, describing ImageNet and VGG16 as a special convolutional neural network. Chapter three describes everything concerning the Student Cluster Competition, including the benchmarks, rules and various features of the Team EPCC cluster, including the used hardware, operating system and other important software libraries. It also describes the difficulties and hardware damage to the cluster and—concerning the ImageNet benchmark—how the images were preprocessed and reformatted to the TFRecord format (Abadi et al., 2015). Chapter four concerns itself with the optimization of the VGG16 neural network, mainly through different parameters which are passed to tensorflow, which is used for implementing VGG16. It thoroughly describes how one can distribute training across multiple GPUs. The benchmark for the Student Cluster Competition is described and analyzed, as is the benchmark for Cirrus. The chapter ends by comparing both. Nita (2018) concludes by summarizing the results presented in chapter four and gives an outline for future work, which could shed more light on the performance of GPU and CPU clusters for training deep neural networks. The two main points of emphasis for future work presented are: (i) scaling training to hundreds of CPU nodes (see e.g. You et al., 2017, for distributing training onto multiple CPUs) and (ii) comparing power consumption of CPU nodes against GPU nodes.

The best thing to say about Nita (2018) is how well the whole experience of the Student Cluster Competition

is communicated by the author. Nita (2018) does not simply give a description of everything that is important for the benchmark, but gives a very conclusive and elaborate review of the whole competition. It serves as a red line throughout the whole dissertation.

Chapter four contains the benchmark and its results. It is a conclusive chapter and well annotated with useful references. The difficulties of the environment are clearly described and while there were failures and the benchmarks on both the cluster of Team EPCC and Cirrus are not optimal, these difficulties are discussed openly and the presented results are sensible.

Overall, Nita (2018) describes the context and problem scope well. Its only problem is, it does not make it easy for the reader to see that. The layout can only be described as cluttered and a few passages and paragraphs are simply unnecessary. For example, Chapter 3.4 does not belong in the chapter that concerns itself with the Student Cluster Competition, if it belongs into the dissertation at all. While the chosen data format could be seen as an optimization and therefore should be described in chapter four, problems during the download before the competition are irrelevant to the benchmark. Also chapter three and two could be swapped, which would have made for an easier introduction to the dissertation, where one is first confronted by the whole context and rather gentle chapter about the Student Cluster Competition, instead of by a description of convolutional neural networks and ImageNet. The first paragraph of the introduction to the dissertation is just weird and seems to pay homage to Goodfellow et al. (2016), which also starts with a similarly weird introduction about Greek mythology and the craving of humankind for thinking machines; absolutely irrelevant for both: benchmarking deep neural networks and deep learning in general.

A second point of critique could be the absence of a chapter on related work, which gives a rough overview of other, comparable benchmarks. Some other benchmarks, like You et al. (2017), are referenced in the dissertation, but the reader does not get a general overview over what else is out there.

Nita (2018) and “Deep Learning on SpiNNaker” overlap in their problem scope, in the sense that both concern itself with benchmarking the training speed of deep neural networks. Both focusing on image recognition based on the ImageNet dataset. While probably not directly important for the benchmark conducted as part of “Deep Learning on SpiNNaker”, since Nita (2018) benchmarks the VGG16 model and “Deep Learning on SpiNNaker” will focus on ResNet-50 (see Section 2), Nita (2018) still provided a great first point of reference for the literature review done so far.

## References

Martín Abadi, Ashish Agarwal, Paul Barham, Eugene Brevdo, Zhifeng Chen, Craig Citro, Greg S. Corrado, Andy Davis, Jeffrey Dean, Matthieu Devin, Sanjay Ghemawat, Ian Goodfellow, Andrew Harp, Geoffrey Irving, Michael Isard, Yangqing Jia, Rafal Jozefowicz, Lukasz Kaiser, Manjunath Kudlur, Josh Levenberg, Dandelion Mané, Rajat Monga, Sherry Moore, Derek Murray, Chris Olah, Mike Schuster, Jonathon Shlens, Benoit Steiner, Ilya Sutskever, Kunal Talwar, Paul Tucker, Vincent Vanhoucke, Vijay Vasudevan, Fernanda Viégas, Oriol Vinyals, Pete Warden, Martin Wattenberg, Martin Wicke, Yuan Yu, and Xiaoqiang Zheng. TensorFlow: Large-scale machine learning on heterogeneous systems, 2015. URL <https://www.tensorflow.org/>. Software available from tensorflow.org.

Takuya Akiba, Shuji Suzuki, and Keisuke Fukuda. Extremely large minibatch SGD: training resnet-50 on imagenet in 15 minutes. *CoRR*, abs/1711.04325, 2017. URL <http://arxiv.org/abs/1711.04325>.

- Dario Amodei, Danny Hernandez, Girish Sastry, Jack Clark, Greg Brockman, and Ilya Sutskever. AI and Compute. <https://openai.com/blog/ai-and-compute/>, 2019.
- François Chollet et al. Keras. <https://keras.io>, 2015.
- EPCC. Cirrus, 2020. URL <https://www.cirrus.ac.uk>.
- S.B Furber, Steve Temple, and Andrew Brown. On-chip and inter-chip networks for modelling large-scale neural systems. In *Proceedings - IEEE International Symposium on Circuits and Systems*, pages 1945–1948, 2006a. ISBN 0780393902.
- Steve Furber and Steve Temple. Neural systems engineering. *Journal of the Royal Society, Interface / the Royal Society*, 4:193–206, 05 2007. doi: 10.1098/rsif.2006.0177.
- Steve Furber, Steve Temple, and Andrew Brown. High-performance computing for systems of spiking neurons. 2, 01 2006b.
- Ian Goodfellow, Yoshua Bengio, and Aaron Courville. *Deep Learning*. MIT Press, 2016. <http://www.deeplearningbook.org>.
- Priya Goyal, Piotr Dollár, Ross B. Girshick, Pieter Noordhuis, Lukasz Wesolowski, Aapo Kyrola, Andrew Tulloch, Yangqing Jia, and Kaiming He. Accurate, large minibatch SGD: training imagenet in 1 hour. *CoRR*, abs/1706.02677, 2017. URL <http://arxiv.org/abs/1706.02677>.
- Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. Deep residual learning for image recognition. *CoRR*, abs/1512.03385, 2015. URL <http://arxiv.org/abs/1512.03385>.
- Xianyan Jia, Shutao Song, Wei He, Yangzihao Wang, Haidong Rong, Feihu Zhou, Liqiang Xie, Zhenyu Guo, Yuanzhou Yang, Liwei Yu, Tiegang Chen, Guangxiao Hu, Shaohuai Shi, and Xiaowen Chu. Highly scalable deep learning training system with mixed-precision: Training imagenet in four minutes. *CoRR*, abs/1807.11205, 2018. URL <http://arxiv.org/abs/1807.11205>.
- Norman P. Jouppi, Cliff Young, Nishant Patil, David A. Patterson, Gaurav Agrawal, Raminder Bajwa, Sarah Bates, Suresh Bhatia, Nan Boden, Al Borchers, Rick Boyle, Pierre-luc Cantin, Clifford Chao, Chris Clark, Jeremy Coriell, Mike Daley, Matt Dau, Jeffrey Dean, Ben Gelb, Tara Vazir Ghaemmaghami, Rajendra Gottipati, William Gulland, Robert Hagmann, Richard C. Ho, Doug Hogberg, John Hu, Robert Hundt, Dan Hurt, Julian Ibarz, Aaron Jaffey, Alek Jaworski, Alexander Kaplan, Harshit Khaitan, Andy Koch, Naveen Kumar, Steve Lacy, James Laudon, James Law, Diemthu Le, Chris Leary, Zhuyuan Liu, Kyle Lucke, Alan Lundin, Gordon MacKean, Adriana Maggiore, Maire Mahony, Kieran Miller, Rahul Nagarajan, Ravi Narayanaswami, Ray Ni, Kathy Nix, Thomas Norrie, Mark Omernick, Narayana Penukonda, Andy Phelps, Jonathan Ross, Amir Salek, Emad Samadiani, Chris Severn, Gregory Sizikov, Matthew Snelham, Jed Souter, Dan Steinberg, Andy Swing, Mercedes Tan, Gregory Thorson, Bo Tian, Horia Toma, Erick Tuttle, Vijay Vasudevan, Richard Walter, Walter Wang, Eric Wilcox, and Doe Hyun Yoon. In-datacenter performance analysis of a tensor processing unit. *CoRR*, abs/1704.04760, 2017. URL <http://arxiv.org/abs/1704.04760>.
- Alex Krizhevsky, Ilya Sutskever, and Geoffrey E. Hinton. Imagenet classification with deep convolutional neural networks. In *NIPS*, 2012.
- Yann LeCun, Y. Bengio, and Geoffrey Hinton. Deep learning. *Nature*, 521:436–44, 05 2015. doi: 10.1038/nature14539.

- Wolfgang Maass. Networks of spiking neurons: The third generation of neural network models. *Neural Networks*, 10(9):1659 – 1671, 1997. ISSN 0893-6080. doi: [https://doi.org/10.1016/S0893-6080\(97\)00011-7](https://doi.org/10.1016/S0893-6080(97)00011-7). URL <http://www.sciencedirect.com/science/article/pii/S0893608097000117>.
- Mario Antonioletti and Alan Stokes. A Tensorflow Backend to SpiNNaker, 2019. URL <https://www.wiki.ed.ac.uk/display/hpcdis/A+TensorFlow+BackEnd+to+SpiNNaker>.
- Henry Markram. The blue brain project. *Nature Reviews Neuroscience*, 7:153–160, 2006.
- Peter Mattson, Christine Cheng, Cody Coleman, Greg Diamos, Paulius Micikevicius, David Patterson, Hanlin Tang, Gu-Yeon Wei, Peter Bailis, Victor Bittorf, David Brooks, Dehao Chen, Debojyoti Dutta, Udit Gupta, Kim Hazelwood, Andrew Hock, Xinyuan Huang, Bill Jia, Daniel Kang, David Kanter, Naveen Kumar, Jeffery Liao, Guokai Ma, Deepak Narayanan, Tayo Oguntebi, Gennady Pekhimenko, Lillian Pentecost, Vijay Janapa Reddi, Taylor Robie, Tom St. John, Carole-Jean Wu, Lingjie Xu, Cliff Young, and Matei Zaharia. Mlperf training benchmark, 2019.
- Carver Mead. Analog vlsi and neural systems. 1989.
- Hiroaki Mikami, Hisahiro Saganuma, Pongsakorn U.-Chupala, Yoshiki Tanaka, and Yuichi Kageyama. Imagenet/resnet-50 training in 224 seconds. *CoRR*, abs/1811.05233, 2018. URL <http://arxiv.org/abs/1811.05233>.
- George A. Miller. Wordnet: A lexical database for english. *Commun. ACM*, 38(11):3941, November 1995. ISSN 0001-0782. doi: 10.1145/219717.219748. URL <https://doi.org/10.1145/219717.219748>.
- Sparsh Mittal and Shraiyyh Vaishay. A survey of techniques for optimizing deep learning on gpus. *Journal of Systems Architecture*, 08 2019. doi: 10.1016/j.sysarc.2019.101635.
- Spyro Nita. Deep learning performance on different architectures. 2018. URL [https://static.epcc.ed.ac.uk/dissertations/hpc-msc/2017-2018/Spyro\\_Nita-dissertation-spyro-nita.pdf](https://static.epcc.ed.ac.uk/dissertations/hpc-msc/2017-2018/Spyro_Nita-dissertation-spyro-nita.pdf).
- Bodo Rueckauer, Iulia-Alexandra Lungu, Yuhuang Hu, Michael Pfeiffer, and Shih-Chii Liu. Conversion of continuous-valued deep networks to efficient event-driven networks for image classification. *Frontiers in Neuroscience*, 11, 12 2017. doi: 10.3389/fnins.2017.00682.
- Olga Russakovsky, Jia Deng, Hao Su, Jonathan Krause, Sanjeev Satheesh, Sean Ma, Zhiheng Huang, Andrej Karpathy, Aditya Khosla, Michael Bernstein, Alexander C. Berg, and Li Fei-Fei. ImageNet Large Scale Visual Recognition Challenge. *International Journal of Computer Vision (IJCV)*, 115(3):211–252, 2015. doi: 10.1007/s11263-015-0816-y.
- Karen Simonyan and Andrew Zisserman. Very deep convolutional networks for large-scale image recognition. 09 2014.
- Samuel L. Smith, Pieter-Jan Kindermans, and Quoc V. Le. Don’t decay the learning rate, increase the batch size. *CoRR*, abs/1711.00489, 2017. URL <http://arxiv.org/abs/1711.00489>.
- SpiNNaker Team. SpiNNaker Project, 2020. URL <http://apt.cs.manchester.ac.uk/projects/SpiNNaker/project/>.
- Yang You, Zhao Zhang, Cho-Jui Hsieh, James Demmel, and Kurt Keutzer. Imagenet training in minutes, 2017.

# Appendices

## A Photos of SpiNNaker

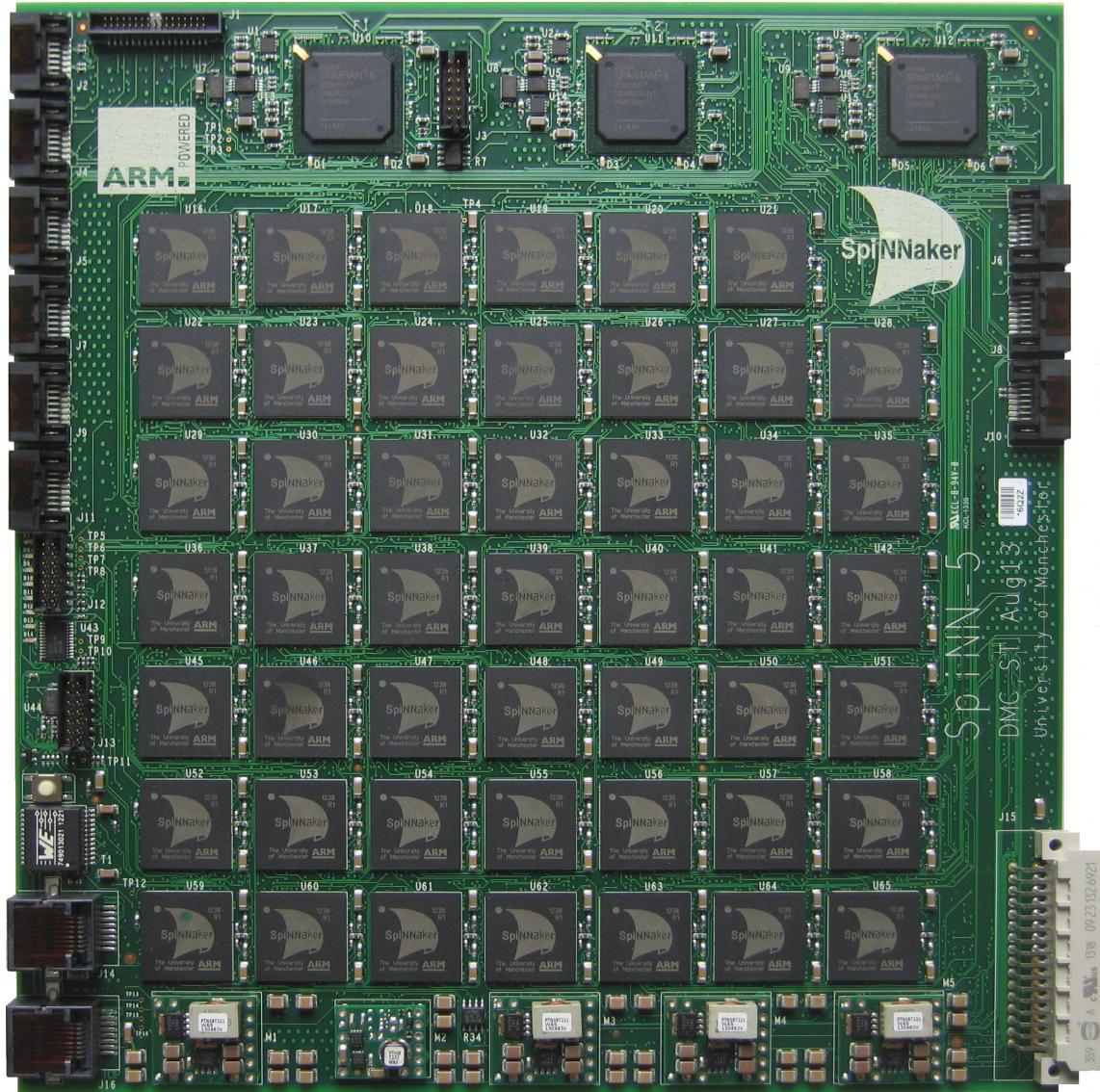


Figure 1: A single SpiNNaker board with 48 SpiNNaker chips. Each chip has 18 cores.



Figure 2: The one million core machine in Manchester. It is capable of running up to one billion spiking neurons in real-time.