

# Performance Factors of Deep Learning and Shallow Network Applications: A Beginners Guide

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**Abstract**—Machine Learning is probably the most present topic of computer science in general media. This popularity only increased over the recent years through widely publicly known applications ranging from DeepBlue to IBM Watson and AlphaGo. Because of these successes Machine Learning is sometimes viewed as an omnipotent solution to every imaginable problem. This is most certainly not the case, based on our studies we can conclude that their capabilities depend on done design and engineering work. In this paper we want to give an short introduction into the most performance influencing factors to performance, during the most time intensive phase, the training.

## I. INTRODUCTION

Machine Learning seems to be everywhere around us. With the recent success of Neural Networks, and other Machine Learning tools, especially in general media well reported learners like AlphaGo or IBM Watson, these technologies are experiencing a kind of renaissance. Their usage has spread from industrial(e.g. self-driving cars, which rely on autonomous interpretation of camera feed and sensor output using machine learning) to retail. Also in modern automation and research, machine learning becomes a greater tool for managing to find more efficient ways to achieve better results in many cases.

In this paper we want to observe and identify the most performance influencing factors of these networks while designing and implementing them for specific applications, with both small and large scale deployments. We expect that this study will provide help for readers interested in learning about the the initial design of neural networks, requirements for managing data, and operations of an efficient neural network.

During our study we found no comprehensive study touching this thema not being based on the comparison of frameworks or on an experimental execution on different platforms or frameworks. This paper is based on these publications.

At first we attend to the choice of neural network and the impact of this decision. Afterwards we have a look, on one hand, at small scale neural networks running on a single machine without large data sets and on the other hand, large scale neural networks operating with more layers and nodes, large data sets and a distributed system to handle the computational power required by the neural network training algorithms to be completed in reasonable time. We divide our survey into, the choice of neural network, the choice of processing units, including basic data distribution strategies for multi-processing, a discussion of the challenges in running small and large scales.

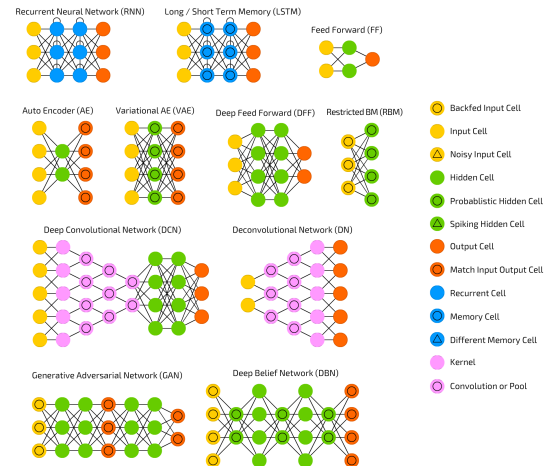


Fig. 1. "A mostly complete chart of Neural Networks" by "The Asimov Institute" extract of only in this paper referenced networks [1]



Fig. 2. Popularity in % of the term "deep learning" on Google in relation to maximum peak, plotted with the Google Trends tool provided by Google

The topic of considering the performance of neural networks and the influencing factors, has been covered in many studies like in "Benchmarking state-of-the-art deep learning software tools" [16] and "Paleo: A performance model for deep neural networks" [17]. In our study we hope to offer a collected view, which could serve as an entry point for developers seeking to work with these tools.

## II. BACKGROUND AND RELATED WORK

In this section we introduce some commonly used models, we consider some performance factors and we refer readers to related work in evaluating performance factors of these models. For this we begin by showing some of the history of Deep Learning followed by clarification of the distinction between what we define as small and large scale networks.

The term "Deep Learning" itself is just a rebranding of the since the 80s existing concept of multilayered perceptrons. Its basic idea is to simply use more than 1 layer in a neural network to increase the accuracy of the learned model [2]. A good definition of Deep Learning is delivered by Deng in his 2014 book "Deep learning: methods and applications" [3]: "A class of machine learning techniques that exploit many layers of non-linear information processing for supervised or unsupervised feature extraction and transformation, and for pattern analysis and classification". Additionally to the reuse of multilayer perceptrons the ideas of Deep Belief Networks and unsupervised pretraining have been introduced.

Since then Deep Learning has experienced an almost exponential growth in popularity as seen in Figure 1, where the popularity steeply increases around 2014.

As a small scale neural network applications we define a network with few and because of this rather limited size it. Most of the time such a network is run on a single machine.

On the other hand as a large scale neural network applications we define a network with a large number of nodes which can, because of the complexity of the resulting connections take a large amount of time to complete training if computed on one processing unit. Therefore it requires a system capable of running the training parallel in a single processing unit, a system containing multiple processors in one node, or a multinode system. Or in other words a system capable of parallelization, since this is of highest concern in large scale networks.

The most commonly used shallow Neural Networks are Feed Forward, Auto Encoders and Restricted Boltzmann Machines, which all have only a single layer of hidden nodes and therefore are quite restricted in what they can compute based on the input data.

Feed Forward Networks(FFN) simply connects input, hidden and output layers with an all to all connection between the layers with the number of outputs being equal or smaller to the number of hidden nodes.

Auto Encoders(AE) are of an similar build but the hidden layer compresses the input information into fewer nodes while these are later again decompressed to output nodes that match the previously given input nodes, therefore AE can be classified as a generative network.

Restricted Boltzmann Machines(RBM) only have an input and an output layer with an all to all connection between these. This RBM has in comparison to the normal Boltzmann Machine a better training behaviour which leads to a faster trained network.

A more advanced architecture is to increase the number of hidden layers to enlarge the application possibility of these networks for more complex models these are then called Deep Networks. The more commonly used ones are Variational Auto Encoders, Deep Belief Networks, Generative Adversarial Networks, Recurrent Neural Networks, e.g. Long short-term memory networks, Deep Convolutional Neural Networks, Deconvolutional Networks, and Recursive Neural Networks.

Variational Auto Encoders(VAE) consists of an encoder, sampler and decoder and are able to generate output based on specification given to the VAE.

Deep Belief Networks(DBN) are a combination of RBM and FFN in which the RBM are used to pretrain the network with the initial training data and the FFN to adjust the learned values slightly to improve the result. The pretraining is done in an unsupervised manner enabling the network to learn structural features of the input in each layer. These networks are at the core of the renaissance of neural networks, stemming from the work of Hinton 2006 [4].

Generative Adversarial Networks(GAN) like the VAE create random output based on the model found in the given training data. VAE are a specialization of GAN because of the restrictions that can be set for the output which is not possible in a GAN.

Deep Convolutional Networks(DCN) are based on Convolutional Nodes compressing the incoming information into the needed base model and then calculating the required output. [5] They are used to abstract input information into more general models. These networks especially are being used to process images.

Deconvolutional Networks(DN) [6] are less surprisingly the opposite of DCN in the idea that input information is first spread to a larger amount of nodes and then processed by the following Nodes to be used by the output.

Long short-term memory(LSTM) [7] are a variant of Recurrent Neural Networks(RNN) including additionally memory cells and gates that control the content of the cells, that are able to remember patterns in sequential data. This model has been able to improve learning process of RNN and results.

The reason why the training of neural networks is so expensive can be traced back to the algorithm used to train all commonly used networks, which is backpropagation. Backpropagation is based on the idea that we first calculate the deviation of the output values from the actual result and then use this backwards through the layers of the net to calculate a correction, based on the error of the node and the learning rate, for each connection weight until the input layer is reached [8]. Some Networks like DBN use a slightly diverged "Gentle" Backpropagation, which relies on a learning rate after the initial values have been found from the training data with the help of the pretrained RBM [5].

Another performance influencing factor besides the actual neural net and the learning algorithm, is the amount of data required for the net to be trained and the size of each training example. While this is mostly important for large scale applications, it can also be hindering for smaller ones. For example if we use a Convolutional Neural Network to classify the content of a greyscale picture we get for small  $512 * 512$  sized images 262144 inputs that each need to be transferred to the processing unit, CPU or GPU, for each example.

This large amount of data can, for one, take some time to be transferred, if for example this data package is required by an external processing unit like a GPU other units cannot receive new data and therefore the performance drops due to

them being idle. Also if too much data is needed in relation to the actual output the data storage can achieve enduring performance loss will occur.

Further can the required training data exceed direct accessible memory from the processing unit, enhancing the problem of delivering data to all processing units.

Furthermore if the training data exceeds the memory for the processing unit, the problem of delivering data to all units becomes more pressing.

The next major performance influencing factor will be the choice of the actual processing unit. This decision is the most computation time influencing. This decision can have the biggest influence on computation time. We divide our processing unit into three groups starting with the CPU, which have a greater memory capability because they can be equipped with additional RAM sticks but possess a smaller parallelization limitation than GPUs because of their different architecture, then the GPU, with a much larger architectural focus on multithreading than CPUs, and following GPU Clusters, being simply a group of GPUs either in a single node or spanning multiple nodes, like they are used in supercomputers.

The most common neural network frameworks which we, because of their wide popularity, have found in performance studies are Tensorflow [9], Caffe [10], Torch [11], CNTK [12], deeplearning4j [13], Keras [14], and MXNET [15].

Next will follow the choice of neural network and its influence on performance.

### III. PERFORMANCE IMPACTING CHOICES

The first important choice is to what neural network is going to be used. This decision is heavily reliant on the application that is to be implemented. Such decision influences all further actions and has to be carefully made.

To assist this decision we offer some general guidelines for when to use shallow vs. deep networks, and what specializations of certain networks could be advantageous for specific tasks.

#### A. Choice of Neural Network

1) *Shallow Networks*: Simple task can be done by a network which is not deep, like a FFN or a RBM. They are faster to train and even larger training sets can be completed in a reasonable time without multithreading or usage of GPUs. But their limited depth can decrease the accuracy of the model when the learned task is more complex than expected. In other words, these models have a risk to overfit the training data. Accordingly, to use them, careful validation is required.

2) *Deep Networks*: More complex tasks often require a deep neural network that can learn a more complex model than shallow networks and offer a greater accuracy while doing this. The major downside of these networks is that they require a larger amount of time to train and can be oversized for the actual learning task and might add unnecessary computation time. Large scale applications mostly contain deep networks because of their larger training sets and more complex models underlying the actual task.

We can not offer a clear answer about when to use which kind of network, every problem must be individually analyzed and based on the information, and complexity, as well as the acceptable error rate of the final network the decision has to be made. For cases that are unclear a shallow network can first be constructed, because of their short training time, and if the result is unsatisfying a more complex network can be considered. Also it is advisable to use a deep network if the learning task involves image or audio understanding, or the task needs to include recurring changes over time of an input signal [5].

An also important choice is the setting of the initial values of connection weights, here it is advisable to start at low values like 0.1 to prevent straying too far from the optimal solution, since algorithm like backpropagation mostly find a local optimum initial values too far from the global optimum will deliver worse results.

#### B. Shallow network node amount

If a shallow network shall be used the next choice will be the amount of nodes in the hidden layer. This is of course dependent on foremost the number of inputs and outputs, the number of hidden nodes should deviate to strong from them. How strong this deviation really is is dependent on the chosen neural network, for example a feed forward network profits when the number is equal or larger than the number of inputs, while an auto encoder probably has fewer hidden nodes. For a shallow network this decision can be if too far from the optimum less fatal than for a deep network, while a shallow network may lose some accuracy or gain additional training time a deep network can experience these effects at a greater scale.

#### C. Deep networks node amount

Like in shallow networks the amount of nodes to be used is an important value that determines the final ability of the network to fulfill its task in the required accuracy and speed. The actual number of nodes chosen at the end is of course a bit more complex in deep networks for example networks like DCN require a special node configuration based on their basic idea (step by step decreasing of nodes per layer until desired compression reached), or DN (opposite of DCN). So how the node configuration looks like is strongly dependent on the net chosen.

#### D. Specific deep networks

Based on the content of the task a few networks can be more fitting than others to fulfill it. To deliver a short overview of it we use a classification by Patterson [5] for the basis of our advice.

If the task includes the generation of data to be output a GAN, VAE or RNN/LSTM. Which of these to choose is strongly dependent of the specific parameters of the task. For example if we want to generate random new data following the model of our training data the closest to this would be a GAN because it is by design designated to fulfill such tasks.

But if new data which is not completely random is to be generated a VAE can be considered which offers by design this possibility. In practice there are lots of generation examples available using these networks for example image generation with GAN [18] (corresponding paper [19]) or text generation with LSTM [20] (paper describing base approach [21]).

If the task includes classification or interpretation of visual data deep neural networks, like CNN or DBN, can be used. For once CNNs are a straightforward choice since they are able to compress data and therefore abstract smaller data like the content of an image from the original image. But DBN also offer a possibility to complete the task with the major advantage of being able to first roughly guess values based on the training data and then train unsupervised in the fine-tuning phase as shown by Zhong 2016 [22].

If the task includes the classification or interpretation of incoming data over time the ability of RNN and LSTMs to data that is of sequential nature comes in handy. For example voice recognition is possible to implement with the help of LSTMs as shown by Soltan 2016 [23].

Finally, if the task has been covered in the literature, it is worthwhile to use existing publically available networks like AlexNet, GoogleNet and others.

To further optimize training time we will next touch the topic of processing units which can be used.

#### E. Choice of Processing Units

The next important choice is the choice of the actual operating calculation unit. We distinguish them into three main models, CPU, GPU, Multi-GPU and GPU-Clustering.

#### F. CPU

As the first most naive option we have a look on the CPU for training of the neural net with the simple single thread and more complex multi-thread calculation.

1) *Single-thread*: The most naive implementation is the single-thread CPU calculation, because oft this more brute force approach and sequential execution and calculation this is also the slowest and with a larger number of connected nodes simply unfeasible because of the excessive calculation time required. But as can be thought of this does not utilize the full capacity of the CPU and therefore results in performance loss in comparison to multithread usage (Table I).

2) *Multi-thread*: A more complex approach consist of utilizing the multi-core characteristics of modern CPUs, by splitting of training calculation with only requirements to already calculated values. This is for example preferable when training with the help of a *Backpropagation* algorithm. The effect continues to grow by using more threads but reaches it limits when using more threads than physical cores available.

Though this approach is limited by the actual core number available and should not overstep the number of physical cores, like with intel *hyper-threading* technology, which can lengthen the required calculation time because of a more inefficient usage [16].

Framework	1 Thread	2 Threads	4 Threads	8 Threads
Caffe	1.324	0.790	0.578	15.444
Tensorflow	7.062	4.789	2.648	1.938
Torch	1.329	0.710	0.423	na

TABLE I

TRAINING TIME(IN S) FOR A MINI-BATCH OF SIZE 64 OF A FULLY CONNECTED NETWORK(FCN) TRAINED WITH SYNTHETIC DATA ON A I7-3820 WITH 4-PHYSICAL CORES USING 3 DIFFERENT COMMONLY USED DEEP LEARNING FRAMEWORKS [16]

#### G. GPU

A more advanced implementation is to use the shared memory, multi-core environment of modern GPUs. For example with the help of NVIDIAs CUDA this can be done efficiently and result in a speed-up of calculation of up to 3 times the CPU-based approaches performance for deep learning algorithms over optimized floating-point baseline [16]. Almost all recent neural net learning frameworks support GPUs because of its excellent performance rating for neural networks.

Problems lie in the tightly restricted memory of graphic cards that may not be able to contain all nodes with their corresponding weights as well as training dataset. This leads to some communication overhead depending on the communication strategy chosen.

#### H. Multi-GPU

To further improve performance during training multiple GPUs can be used to train the neural net. This shortens training time but also requires new actions like synchronizations of GPUs and splitting of data and/or neural network.

A main advantage of Multi-GPU is of course the increased computation power available during the training phase, reducing training time by 35% when doubling the number of GPUs in CNTK and MXNET, 28 % in Caffe and 10 % in Torch and Tensorflow [16].

Another advantage is the greater availability of memory somewhat easing the restrictions of the memory restricted GPUs structure. While this is an advantage it is not efficient if used as the single goal of multiple GPU usage because of the high price connected to acquiring them.

Figure 2 visualizes this improvement showing the reduction of training time steadily with the increasing of amount of GPUs used. Although costly this leads to a constant improvement. Higher Numbers of GPUs can be again slower or offer no significant improvement if used the same as smaller amounts because of an increasing communication overhead and bottleneck in the CPU, which is responsible for managing separate GPUs.

1) *Parallelism between GPUs*: There are two kind of parallelism approaches applicable to the problem, first there is data parallelism which splits the training data into multiple sets, mostly used when the training set is splittable into multiple subsets. This can be done by dividing the data by case or by feature. Second model parallelism in which the net is divided into separately runnable parts which later can be joined together again, this method is fitting for single system

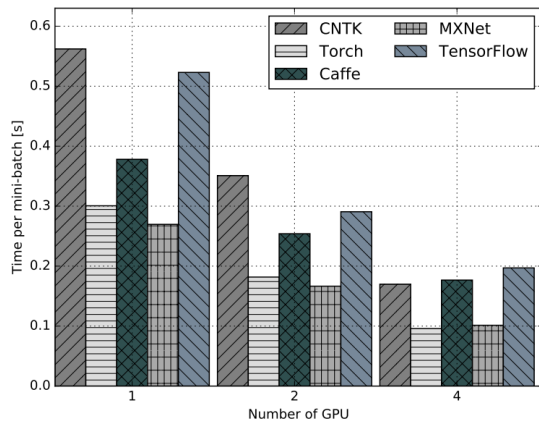


Fig. 3. Time per mini-batch in s compared between different amount of GPUs used [16]

distribution in which the GPUs share one PCIe bus, but lead to the result being more vulnerable to calculation failures [24].

2) *Synchronization between GPUs*: For synchronizing Multi-GPU setups like in Figure 4 there are theoretically two choices. One being the synchronous method in which after a value is calculated they are shared with every other GPU. This method is applicable to all Multi-GPU configuration and delivers an acceptable result [25]. The update of values for all GPUs occurs only after the updated values have been send by each of them. Until a large amount of over 40 GPUs are used this mehtod can be used without limitation [24]. There is also the possibility to run the GPUs asynchronously, by letting them use different versions of the values and only updating them periodically by sending an update request to the CPU. This can lead to a slight improvement of the training speed but is not guaranteed depending on the training model [25].

### I. GPU-Clusters

The next logical step is to use multiple Multi-GPU systems further reducing training time but also creating new challenges, because of the decentralized nature of the Cluster, like communication overhead. This is mostly used in large scale applications and is most of the time not needed in small scale.

1) *Multiple GPU-Clusters*: Taking a step further it is possible to connect multiple Clusters of GPUs to compute a single task. In doing this we again increase raw computation power, but also increase the total amount of communication required. Similar to multiple GPUs this leads at the beginning with 2 or more Clusters to a stronger improvement than later on with 8 to 16 Clusters as seen in (Figure 3)

2) *Parallelism of multiple GPU-Clusters*: Like the Multi-GPU setup this can be done by creating either data or model parallelism. Combination are also possible when using GPU-Clusters, for instance in a setup consisting of multiple Clusters and one single communication server a model parallelism can be used to distribute the model on the different clusters, but they internally use data parallelism to split work [25].

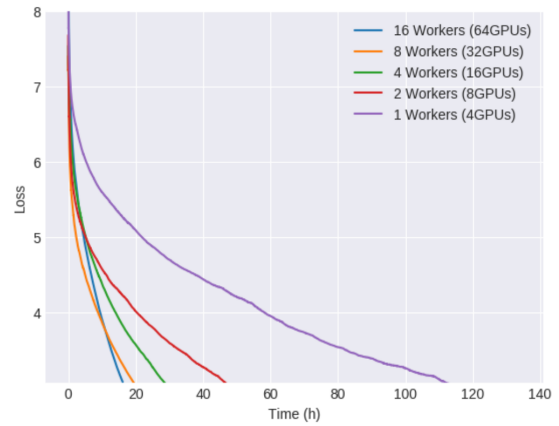


Fig. 4. Time (in h) of different asynchronous configurations until reaching destined error rate(loss) [24]

3) *Synchronization of multiple GPU-Clusters*: Similar to parallelism the synchronization of GPU-Clusters can be undertaken either with the synchronous or asynchronous like in Multi-GPU configurations. Again these tactics can be combined to create a mixed-asynchronous strategy, using an asynchronous training on inter-clusters level and cluster internal synchronous training [24]. This creates the best performance on large configurations with many clusters [25]. Which challenges this and other characteristics of this incur will be explained in the next section.

## IV. LARGE SCALE CHALLENGES AND SMALL SCALE CHALLENGES

Dependent on the choice of scale each one has its own challenges to be considered during design and implementation of the neural network.

### A. Small scale challenges

First and foremost it is important to notice that the biggest restrictions of small scale applications is the limited computation power available during the initial training process, later during usage of the net this is less impeding because either the net is completely pretrained and not changed later or the only change is some optimization when the network receives a query.

This leads to the focus lying on the design to find the best fit of complexity to fit the desired model. Otherwise longer training time or less accuracy of the resulting network will conclude.

Further small scale applications are relatively free of performance related complications, because of their relative simplicity and fast modern computer hardware enabling operations which are not optimal to be resolved in a non less desirable time.

### B. Large scale challenges

Opposing to small scale applications large scale ones do not have the actual processing power as their highest pending restriction but the communication and data transfer between

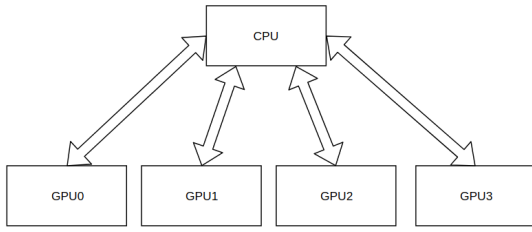


Fig. 5. One example configuration consisting of a CPU and 4 connected GPU units for training the neural network.

all acting processing units. This problem occurs because a larger data flow has to be managed to more processing units compared to small scale applications.

The *data flow* is a problem on multiple fronts. For one the transfer of the training data from main memory to GPU memory can be the first bottleneck restricting faster processing speeds from being realized. For example if the GPU only receives data if no calculation is currently active this slows down the training process unnecessarily. To increase the speed of the calculation data can be fetched during the processing of already present data, this is called data prefetching as described and implemented by Yang 2010 [26]. This solution can solve the problem partially but reaches its limits if used with multiple GPUs for example configuration (Fig. 3), which leads that the CPU will become a bottleneck if the training data of each individual GPU is too large to fit in the GPU memory, since the CPU can only manage transfer to the GPUs one at a time. For example a GPU equipped with PCI-Express 4.0 with a x16 Throughput can at best receive 31.5 GB/s, if we assume that all training data can be fit into main memory, that way if we need to refresh the complete memory of a modern GPU like NVIDIA GTX 1080, we need 0.253968 s, so to refresh all GPUs memory without including any overhead produced by switching operations between the GPUs we have an absolute transfer time of 1.015873 s, and for 3 units 0.7619 s, so if our GPU completes the desired calculation faster, for example 0.5 s, we have an 0.2619 s period in which our GPU idles every iteration, assumed that we can transfer all data during the calculation time. Therefore we have an effective calculation computation time each phase of 65.62 %. This problem only enlargens if the main memory is too small to fit the complete training data since connections to solid state disk are too slow and hard disk do physically do not reach the required throughput.

Additional data flow is created when *synchronizing GPUs* with each other, by approaches described beforehand in "Choice of Processing Units", they each have their own advantage but can limit efficiency in certain situations. But both create an communication overhead because during transmission of values the GPU cannot operate on the neural network training.

Synchronous training, while being recommended for setups that have 40 GPUs or less, can create idling time if one unit is slower than others, since all updates have to be sent to the

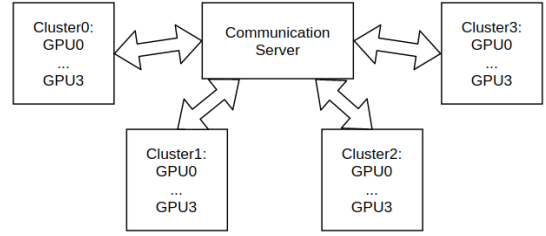


Fig. 6. One example configuration consisting of a communication server and 4 connected GPU-Clusters each containing 4 GPUs.

server before the next iteration can be undertaken this slows down all other units. This problem becomes more probable the more units are used. Also more GPUs lead to more communication if synchronization is required after every step, so they increase the amount of data managed by the CPU or communication server. This applies to configuration like Figure 4 and Figure 5.

If an *asynchronous training* approach is used problems may occur influencing the result, if updates are too sporadic and different versions of values drift too far apart. To avoid this problem GPU-Cluster configurations do not rely on complete asynchronous training strategies, but on the already described mixed-asynchronous minimizing this problem while still reducing possible communication overhead.

To ease the effect of *GPU to GPU communication*, by relieving the CPU of managing them, technologies like GPUDirect from NVIDIA [27] can be used allowing direct GPU to GPU communication if they are connected to the same PCIe bus, so this is only applicable within a GPU Cluster or a single system and does not remove all communication overhead. Also shared memory between GPUs can come in place saving synchronization between them.

*Memory limitation* is another issue that appears while training if the training data is too large to fit in memory. Then time expensive disk accesses to either very slow HDDs or faster but still relatively slow SSDs are required. For example a fast available SSD SAMSUNG 960 PRO can reach up to 3.5 GB/s which is still relatively slow compared to the maximum 31.5 GB/s possible through an PCIe x16 interface. To further increase speed a RAID 0 setup can be created consisting of multiple M.2 SSDs with the potential of parallel access and data transfer reaching for instance with 5 960 PRO that could transfer at maximum of around 17 GB/s.

*Cluster communication* becomes only more and more concerning if more GPU-Clusters are used, because the connection between them may be slower than the interfaces of RAM, GPU and storage used therefore creating a new bottleneck. This problem can be reduced if training data is stored by the cluster, which has the downside of further increasing the cost of these setups.

## V. CONCLUSION

During our survey we observed that the most influencing factors are the basic choice of neural network to be used,



this includes its complexity as well as the actual architecture the network is build of. Further the processing unit that is chosen has a strong influence on the quality and speed the final network that lies within acceptable error limits will be reached. Based on the choice of this other factors came into consideration influencing the process, like communication between processing units and parallelism of data between them. They are not quite as influential as the first two but can lead to a strong improvement or worsening. We observed that even in example systems that handle communication efficiently about 35 % of the calculation time is sacrificed to it.

Especially data transfer time and alike carries a potential to lengthen the training time of an significant amount. To ease this technology like GPUDirect [27] and data prefetching [26] can be used. It may be possible to decrease the effect of the data flow further by introducing a direct memory transfer unit which can indepently organize synchronization and can handle parallel transfers to and from multiple GPUs. This could decrease the calculation time to a bare minimum but would require additional hardware and maybe modification of the used GPUs. Although this could break some security limits because of unauthorized memory accesses.

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