



DEPARTMENT OF INFORMATICS

TECHNISCHE UNIVERSITÄT MÜNCHEN

Master's Thesis in Data Engineering and Analytics

# **Analyzing Bottlenecks in Hivemind**

Adrian David Castro Tenemaya





DEPARTMENT OF INFORMATICS

TECHNISCHE UNIVERSITÄT MÜNCHEN

Master's Thesis in Data Engineering and Analytics

# **Analyzing Bottlenecks in Hivemind**

## **Analysieren von Engpässen in Hivemind**

Author:	Adrian David Castro Tenemaya
Supervisor:	Prof. Dr. Ruben Mayer
Advisor:	M. Sc. Alexander Isenko
Submission Date:	September 18, 2022



I confirm that this master's thesis in data engineering and analytics is my own work and I have documented all sources and material used.

München, September 18, 2022

Adrian David Castro Tenemaya

## Acknowledgments

I was 4 years old and a half when I first arrived in Italy. Now, 20 years later (wow), I am completing my journey. Thanks to everyone who tagged along on my academic journey. Special thanks to my wonderful and supportive parents Laura and José; my “sore” Valeria, and my girlfriend Iris. Also, thanks to everyone who has believed in me and who didn’t make me quit (you know who you are).

# Abstract

The amount of computing resources required to train state-of-the-art deep neural networks is steadily growing. Most institutions cannot afford the latest technologies, which are sometimes needed to keep up with today’s demanding deep neural network research. Access to powerful devices is therefore limited to few research institutions, slowing down research.

In [RG20a] they propose a novel concept for decentralizing deep neural network training using large amounts of consumer-grade hardware. The training algorithm described in the paper is called “Decentralized Mixture-of-Experts” (DMoE) and employs a combination of decentralized and Mixture-of-Experts [Sha+17] techniques. This allows thousands of computing devices to join forces and train a single neural network model together. DMoE achieves this by splitting the target neural network model into different parts called partitions, similarly to model parallelism. Each partition is then replicated across a subset of workers participating in the training. Next, a gating function is used to select which workers can perform the next operation on the given input. After the workers have been selected and located using a Distributed Hash Table (DHT), the input data is sent to the workers, and a forward pass is performed. A similar algorithm is applied during the backward pass. DMoE proved that scaling model training to thousands of heterogeneous compute nodes is possible, thus enabling large-scale community research projects.

Although DMoE is robust against training latency, it also requires large amounts of data to be exchanged between every participant worker. We may assume, however, that most participants in the network will not have datacenter-grade network connections and bandwidth. Therefore, the communications needed to perform training may saturate a worker’s network. An approach suggested by [RG20a] to reduce the network load is to compress and convert tensors to a lower precision before transfer.

From the combination of features and findings of [RG20a; Rya+21], Hivemind was created. Hivemind [tea20] is an open-source framework that enables collaborative model training using a large number of heterogeneous devices from universities, companies, and volunteers. Every device participating in the computation may differ in its characteristics, featuring different architectures and network speeds.

In Hivemind interactive demonstration [tea20], 40 devices jointly trained a modified DALL-E [Ram+21] neural network model over 2.5 months. The reported results,

however, do not include the participant’s device information and metrics. Without this type of information, it’s not possible to perform an independent analysis of the effects of different configurations on training. In this paper, we intend to reproduce the results of [tea20] on our cluster using different device configurations to identify the impact of key system metrics on Hivemind.

Over the last years, research and software libraries like Hivemind have been focused on reducing and optimizing deep neural network model training times with techniques such as data and model parallelism. In [Xin+21] however, the authors show that as much as 45% of total training time may be spent on preprocessing tasks alone. Despite this, the impact of preprocessing pipelines is often ignored in current research. Therefore with this paper, we propose to explore the impact of preprocessing pipelines in [tea20].

As noted by [Ise+22], it is crucial to find and analyze bottlenecks during computation to maximize performance. In their work, they also detail several possible improvements that can be applied in preprocessing pipelines, increasing throughput under certain circumstances. Intuitively, given the high amount of communications and data loading that DMOE needs, the preprocessing pipeline may be subject to inefficiencies. Using the techniques and findings showcased in [Ise+22], this paper further aims to find bottlenecks in the Hivemind preprocessing pipeline.

In this paper, we will analyze the impact of Hivemind’s different possible scenarios on preprocessing pipelines. As we test the software and its limitations, we might find possible areas of improvement in Hivemind. Whenever possible, we will further contribute using the knowledge gathered through our experiments by improving the Hivemind [tea20] source-code. Our contributions can be summarized as follows:

- We analyze the challenges of optimizing preprocessing pipelines in decentralized distributed training and provide insights on possible improvements
- We verify the effectiveness of Hivemind for different peer hardware configurations concerning preprocessing pipelines
- We use the gained knowledge and insights to contribute to the Hivemind open-source library.

# Contents

Acknowledgments	iii
Abstract	iv
1 Introduction	1
2 Fundamentals	5
3 Setup	6
List of Figures	7
List of Tables	8
Bibliography	9

# 1 Introduction

It is safe to say that the internet paved the way of many things for humanity. Media such as images, video and audio can be shared across websites and applications, knowledge can be stored in faraway servers and retrieved with ease in text format using mobile devices, and products and services can be bought with the click of a button or a tap on a screen. Interactions, media and information make up for massive amounts of data that flow through complex computer systems, which in turn generate even more data and information.

Researchers have found ways to leverage the magnitude of data that is being produced every second by countless systems all around the world. One of the most recent and most popular uses of this huge variety and quantity of data is machine learning (ML). Machine learning can be defined as a set of techniques that use data to improve performance in a set of tasks. Today, for example, we feed data to machine learning models to calculate what is the probability that a webpage visitor will buy certain products, or the chances that it is going to rain in a few days or to generate elaborate text and stunning, never-before-seen pictures.

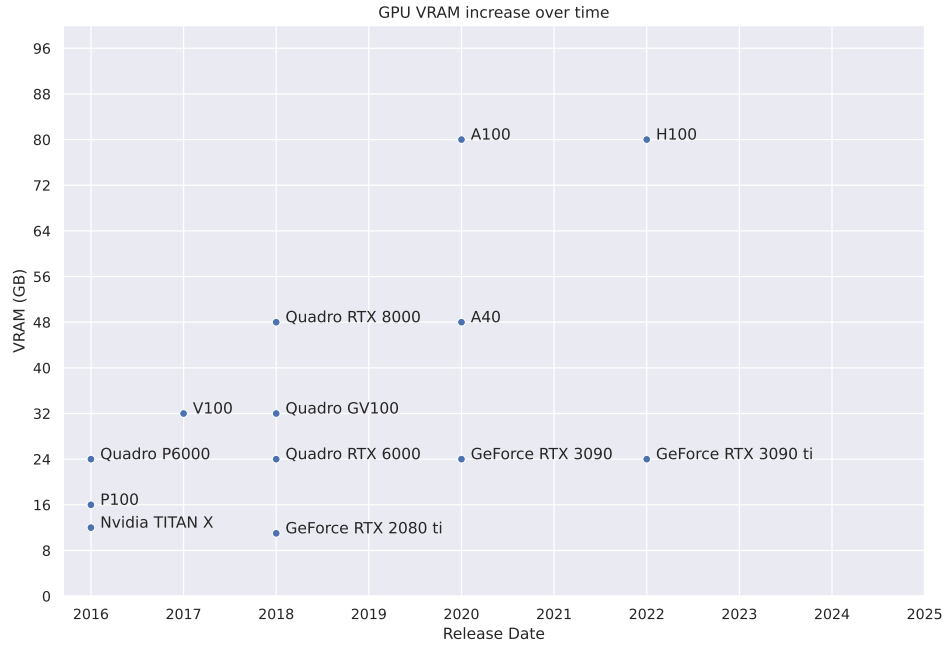
Recently, models such as BERT [Dev+18], DALL-E [Ram+21], GPT-3 [Bro+20] and others have become incredibly popular thanks to their outstanding results and endless possibilities. DALL-E for example can generate high-quality realistic images and art starting from a text description written in natural language. These models however require massive amounts of data as well as very expensive computational resources, such as graphical processing units and tensor processing units (TPUs). In recent years, the size of neural network models has been steadily increasing exponentially, as shown by Figure 1.2. A simple calculation shows that the neural network model Megatron-Turing-NLG 530B [Smi+22] would take roughly  $530 \times 4 = 2120\text{GB}$  of memory to simply hold its 530 billion weights.

Furthermore, training a neural network model requires even more memory. Intermediate computation outputs such as gradient and optimizer states sometimes require 2 or 3 times as much memory than just the model parameters, making GPU memory one of the main bottlenecks in training huge neural network models. While some of these issues can be tackled using clever techniques such as parameter quantization, pruning and compression, they must not be considered one-fits-all solutions. Some models are simply too big to be trained on a single device. This problem is exacerbated by factors



such as GPU prices and much slower growth of their memory size. Figure 1.1 shows how GPU memory has been increasing from 2016 to 2022.

Figure 1.1: GPU VRAM over the past 4 years. The growth is mostly linear, doubling



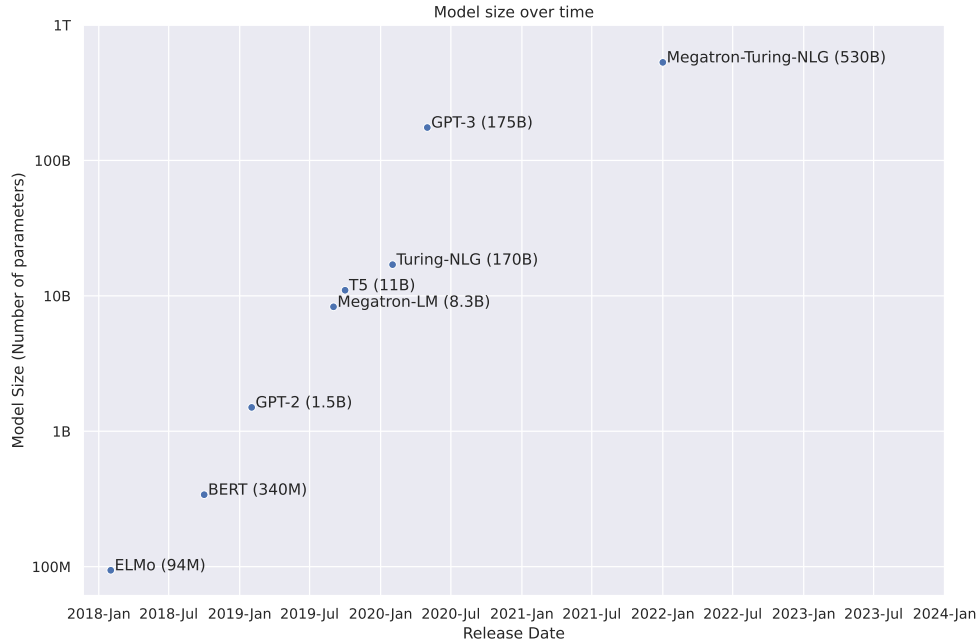
The characteristics of the latest GPU released by NVIDIA earlier in 2022, the H100 with 80GB of memory, an amount that hasn't changed since its direct predecessor A100.

To tackle this problem, practitioners studied and developed distributed computing techniques to train models that do not fit entirely in a single GPU's memory, distributing the training load to potentially thousands of devices.

These techniques can be briefly categorized as follows:

- *Data parallelism*. Given a set of  $n$  devices, an instance of the model is trained on each one of the devices. Usually, gradients obtained during backpropagation are then aggregated across all the devices using techniques such as *AllReduce*. This technique however does not work very well with models that exceed a single device's available memory and is therefore used in applications with low-memory devices such as *Federated Learning* [Li+19].
- *Model parallelism*. A deep neural network is conceptually split into  $n$  partitions

Figure 1.2: Model size over the past 4 years: ELMo [Pet+18], BERT [Dev+18], GPT-2 [Rad+19], Megatron-LM [Sho+19], T-5 [Raf+19], Turing-NLG [Mic20], GPT-3 [Bro+20], Megatron-Turing-NLG [Smi+22]



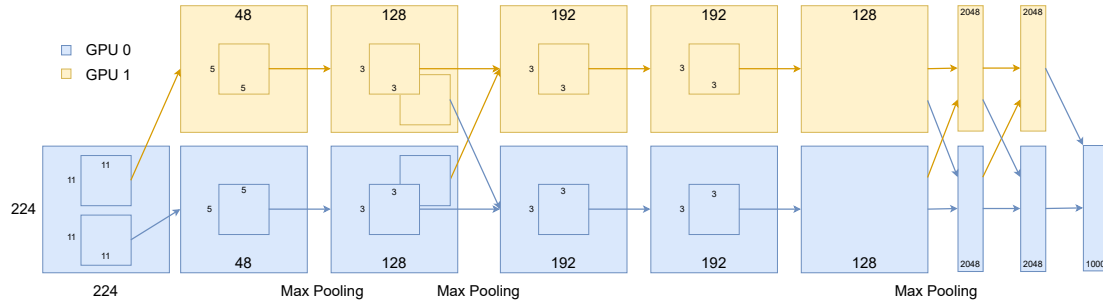
across  $n$  devices, each hosting a different partition and set of weights. An early notable example of model parallelism is AlexNet [KSH12], where the authors decided to split the computation of some of the layers across two GPUs with 3GB of ram each, a concept illustrated in Figure 1.3. This technique relieves the burden of a single node to host all of the weights of a model but is also more sensitive to issues with communication across nodes.

- *Pipeline parallelism.* A combination between model parallelism and data parallelism. Introduced by [Hua+18], pipeline parallelism consists in splitting a batch into micro-batches across the available computing devices, leading to fewer dead wait times.
- *Tensor parallelism.* Tensor operations for huge neural network models can become a bottleneck, as they can require more memory than the host's device can handle and can become slow in general. Tensor parallelism can alleviate a single node's

computational burden by splitting a tensor operation across many devices. This technique has been first introduced in neural network models in [Dea+12] with a framework called DistBelief.

- *Mixture-of-Experts*. Instead of conceptually splitting a model, we construct multiple, different models. Each of them specializes in a different subset of the complete set of training cases, helped by a gating function. This has been first introduced in 1991 by [Jac+91] but has recently gained traction due to its attractiveness in numerous tasks.

Figure 1.3: AlexNet [KSH12] architecture shows one of the first examples of model parallelism. The training of convolutional layers is split across two GPUs, as the size of the model during training exceeded the available memory of a single GPU.



Most of the frameworks and papers built on top of these techniques approach the issues that we have discussed before by employing tremendous amounts of expensive, top-of-the-art and heterogeneous technologies. However, universities, small companies and hobbyists that want to train the models described in these papers do not necessarily have access to a such vast amount of resources, limiting possibilities and research directions.

Hivemind [RG20b] is a framework that aims to [...]

Our contributions are as follows:

- We analyze the challenges of optimizing preprocessing pipelines in decentralized distributed training and provide insights on possible improvements
- We verify the effectiveness of Hivemind for different peer hardware configurations concerning preprocessing pipelines
- We use the gained knowledge and insights to contribute to the Hivemind open-source library.

## 2 Fundamentals

Neural networks (NNs) have been one of the main focuses of research in the past decade. They were first conceptualized back in

## 3 Setup

## List of Figures

1.1	GPU VRAM over the past 4 years. The growth is mostly linear, doubling	2
1.2	Model size over the past 4 years: ELMo [Pet+18], BERT [Dev+18], GPT-2 [Rad+19], Megatron-LM [Sho+19], T-5 [Raf+19], Turing-NLG [Mic20], GPT-3 [Bro+20], Megatron-Turing-NLG [Smi+22] . . . . .	3
1.3	AlexNet [KSH12] architecture shows one of the first examples of model parallelism. The training of convolutional layers is split across two GPUs, as the size of the model during training exceeded the available memory of a single GPU. . . . .	4

## List of Tables

# Bibliography

- [Bro+20] T. B. Brown, B. Mann, N. Ryder, M. Subbiah, J. Kaplan, P. Dhariwal, A. Neelakantan, P. Shyam, G. Sastry, A. Askell, S. Agarwal, A. Herbert-Voss, G. Krueger, T. Henighan, R. Child, A. Ramesh, D. M. Ziegler, J. Wu, C. Winter, C. Hesse, M. Chen, E. Sigler, M. Litwin, S. Gray, B. Chess, J. Clark, C. Berner, S. McCandlish, A. Radford, I. Sutskever, and D. Amodei. “Language Models are Few-Shot Learners.” In: *CoRR* abs/2005.14165 (2020). arXiv: 2005.14165.
- [Dea+12] J. Dean, G. S. Corrado, R. Monga, K. Chen, M. Devin, Q. V. Le, M. Z. Mao, M. Ranzato, A. Senior, P. Tucker, K. Yang, and A. Y. Ng. “Large Scale Distributed Deep Networks.” In: *NIPS*. 2012.
- [Dev+18] J. Devlin, M.-W. Chang, K. Lee, and K. Toutanova. “BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding.” In: *CoRR* abs/1810.04805 (2018). arXiv: 1810.04805.
- [Hua+18] Y. Huang, Y. Cheng, D. Chen, H. Lee, J. Ngiam, Q. V. Le, and Z. Chen. “GPipe: Efficient Training of Giant Neural Networks using Pipeline Parallelism.” In: *CoRR* abs/1811.06965 (2018). arXiv: 1811.06965.
- [Ise+22] A. Isenko, R. Mayer, J. Jedele, and H.-A. Jacobsen. “Where Is My Training Bottleneck? Hidden Trade-Offs in Deep Learning Preprocessing Pipelines.” In: *Proceedings of the 2022 International Conference on Management of Data*. SIGMOD ’22. Philadelphia, PA, USA: Association for Computing Machinery, 2022, pp. 1825–1839. ISBN: 9781450392495. DOI: 10.1145/3514221.3517848.
- [Jac+91] R. A. Jacobs, M. I. Jordan, S. J. Nowlan, and G. E. Hinton. “Adaptive Mixtures of Local Experts.” In: *Neural Computation* 3.1 (1991), pp. 79–87. DOI: 10.1162/neco.1991.3.1.79.
- [KSH12] A. Krizhevsky, I. Sutskever, and G. E. Hinton. “ImageNet Classification with Deep Convolutional Neural Networks.” In: *Advances in Neural Information Processing Systems*. Ed. by F. Pereira, C. J. C. Burges, L. Bottou, and K. Q. Weinberger. Vol. 25. Curran Associates, Inc., 2012.



- [Li+19] Q. Li, Z. Wen, Z. Wu, S. Hu, N. Wang, X. Liu, and B. He. “A Survey on Federated Learning Systems: Vision, Hype and Reality for Data Privacy and Protection.” In: *CoRR* abs/1907.09693 (2019). arXiv: 1907.09693.
- [Mic20] Microsoft. *Turing-NLG: A 17-billion-parameter language model by Microsoft - Microsoft Research*. <https://www.microsoft.com/en-us/research/blog/turing-nlg-a-17-billion-parameter-language-model-by-microsoft/>. May 2020.
- [Pet+18] M. E. Peters, M. Neumann, M. Iyyer, M. Gardner, C. Clark, K. Lee, and L. Zettlemoyer. “Deep contextualized word representations.” In: *CoRR* abs/1802.05365 (2018). arXiv: 1802.05365.
- [Rad+19] A. Radford, J. Wu, R. Child, D. Luan, D. Amodei, and I. Sutskever. “Language Models are Unsupervised Multitask Learners.” In: (2019).
- [Raf+19] C. Raffel, N. Shazeer, A. Roberts, K. Lee, S. Narang, M. Matena, Y. Zhou, W. Li, and P. J. Liu. “Exploring the Limits of Transfer Learning with a Unified Text-to-Text Transformer.” In: *CoRR* abs/1910.10683 (2019). arXiv: 1910.10683.
- [Ram+21] A. Ramesh, M. Pavlov, G. Goh, S. Gray, C. Voss, A. Radford, M. Chen, and I. Sutskever. “Zero-Shot Text-to-Image Generation.” In: *CoRR* abs/2102.12092 (2021). arXiv: 2102.12092.
- [RG20a] M. Riabinin and A. Gusev. “Learning@home: Crowdsourced Training of Large Neural Networks using Decentralized Mixture-of-Experts.” In: *CoRR* abs/2002.04013 (2020). arXiv: 2002.04013.
- [RG20b] M. Riabinin and A. Gusev. “Learning@home: Crowdsourced Training of Large Neural Networks using Decentralized Mixture-of-Experts.” In: *CoRR* abs/2002.04013 (2020). arXiv: 2002.04013.
- [Rya+21] M. Ryabinin, E. Gorbunov, V. Plokhotnyuk, and G. Pekhimenko. “Moshpit SGD: Communication-Efficient Decentralized Training on Heterogeneous Unreliable Devices.” In: *CoRR* abs/2103.03239 (2021). arXiv: 2103.03239.
- [Sha+17] N. Shazeer, A. Mirhoseini, K. Maziarz, A. Davis, Q. V. Le, G. E. Hinton, and J. Dean. “Outrageously Large Neural Networks: The Sparsely-Gated Mixture-of-Experts Layer.” In: *CoRR* abs/1701.06538 (2017). arXiv: 1701.06538.
- [Sho+19] M. Shoenybi, M. Patwary, R. Puri, P. LeGresley, J. Casper, and B. Catanzaro. “Megatron-LM: Training Multi-Billion Parameter Language Models Using Model Parallelism.” In: *CoRR* abs/1909.08053 (2019). arXiv: 1909.08053.

- [Smi+22] S. Smith, M. Patwary, B. Norick, P. LeGresley, S. Rajbhandari, J. Casper, Z. Liu, S. Prabhumoye, G. Zerveas, V. Korthikanti, E. Zheng, R. Child, R. Y. Aminabadi, J. Bernauer, X. Song, M. Shoeybi, Y. He, M. Houston, S. Tiwary, and B. Catanzaro. “Using DeepSpeed and Megatron to Train Megatron-Turing NLG 530B, A Large-Scale Generative Language Model.” In: *CoRR* abs/2201.11990 (2022). arXiv: 2201.11990.
- [tea20] L. team. *Hivemind: a Library for Decentralized Deep Learning*. <https://github.com/learning-at-home/hivemind>. 2020.
- [Xin+21] D. Xin, H. Miao, A. G. Parameswaran, and N. Polyzotis. “Production Machine Learning Pipelines: Empirical Analysis and Optimization Opportunities.” In: *CoRR* abs/2103.16007 (2021). arXiv: 2103.16007.