
Comparing Rewinding and Fine-tuning in Neural Network Pruning Reproducibility Challenge 2021

Anonymous Author(s)

Affiliation

email

Reproduction Summary

Scope of Reproducibility

We are reproducing *Comparing Rewinding and Fine-tuning in Neural Networks*, by Renda et al. [2020]. In this work the authors compare three different approaches to retraining neural networks after pruning: 1) fine-tuning, 2) rewinding weights as in Frankle and Carbin [2019] and 3) a new, original method involving learning rate rewinding, building upon Frankle and Carbin [2019]. We reproduce the results of all three approaches, but we focus on verifying their approach, learning rate rewinding, since it is newly proposed and is described as a universal alternative to other methods.

We used CIFAR10 for most reproductions along with additional experiments on the larger CIFAR100, which extends the results originally provided by the authors. We have also extended the list of tested network architectures to include Wide ResNets (Zagoruyko and Komodakis [2016]). The new experiments led us to discover the limitations of learning rate rewinding which can worsen pruning results on large architectures.

Methodology

We implemented the code ourselves in Python with TensorFlow 2, basing our implementation of the paper alone and without consulting the source code provided by the authors. We ran two sets of experiments. In the reproduction set, we have striven to exactly reproduce the experimental conditions of Renda et al. [2020]. We have also conducted additional experiments, which use other network architectures, effectively showing results previously unreported by the authors. We did not cover all originally reported experiments – we covered as many as needed to state the validity of claims. We used Google Cloud resources and a local machine with 2x RTX 3080 GPUs.

Results

We were able to reproduce the exact results reported by the authors in all originally reported scenarios. However, extended results on larger Wide Residual Networks have demonstrated the limitations of the newly proposed learning rate rewinding – we observed a previously unreported accuracy degradation for low sparsity ranges. Nevertheless, the general conclusion of the paper still holds and was indeed reproduced.

What was easy

Re-implementation of the pruning and retraining methods was technically easy, as it is based on a popular and simple pruning criterion – magnitude pruning. Original work was descriptive enough to reproduce the results with satisfying results without consulting the code.

What was difficult

Not every design choice was mentioned in the paper, thus reproducing the exact results was rather difficult and required a meticulous choice of hyper-parameters. Experiments on ImageNet and WMT16 datasets were time consuming and required extensive resources, thus we did not verify them.

Communication with original authors

We did not consult the original authors, as there was no need to

1 Introduction

Neural network pruning is an algorithm leading to decrease the size of a network, usually by removing its connections or setting their weights to 0. This procedure generally allows obtaining smaller and more efficient models. It often turns out that these smaller networks are as accurate as their bigger counterparts or the accuracy loss is negligible. A common way to obtain such high quality sparse network is to prune it after the training has finished (Liu et al. [2019], Frankle and Carbin [2019]). Networks that have already converged are easier to prune than randomly initialized networks (Liu et al. [2019], Lee et al. [2018]). After pruning, more training is usually required to restore the lost accuracy. Although there are a few ways to retrain the network, finetuning might be the easiest and most often chosen by researchers and practitioners. (Liu et al. [2019], Renda et al. [2020]).

Lottery Ticket Hypothesis from Frankle and Carbin [2019] formulates a hypothesis that for every dense neural network, there exists a smaller subnetwork that matches or exceeds results of the original. The algorithm originally used to obtain examples of such networks is iterative magnitude pruning with weight rewinding, and it is one of the methods of retraining after pruning compared in this work.

2 Scope of reproducibility

Renda et al. [2020] formulated the following claims:

Claim 1: Widely used method of training after pruning: finetuning yields worse results than rewinding based methods (supported by figures 1, 2, 3, 4 and table 5)

Claim 2: Newly introduced learning rate rewinding works as good or better as weight rewinding in all scenarios (supported by figures 1, 2, 3, 4 and table 5, but not supported by figure 5)

Claim 3: Iterative pruning with learning rate rewinding matches state-of-the-art pruning methods (supported by figures 1, 2, 3, 4 and table 5, but not supported by figure 5)

3 Methodology

We aimed to compare three retraining approaches: 1) finetuning, 2) weight rewinding and 3) learning rate rewinding. Our general strategy that repeated across all experiments was as follows:

1. train a dense network to convergence,
2. prune the network using magnitude criterion: remove weights with smallest L1 norm,
3. retrain the network using selected retraining approach.

In the case of structured pruning: in step 2, we removed structures (rows or convolutional channels) with the smallest average L1 norm (Crowley et al. [2018]), rather than removing separate connections.

In the case of iterative pruning: the network in step 1 was not randomly initialized, but instead: weights from a model from a previous iterative pruning step were loaded as the starting point.

We trained all our networks using Stochastic Gradient Descent with Nesterov Momentum. The learning rate was decreased in a piecewise manner during the training, but momentum coefficient was constant and equal to 0.9.

3.1 Model descriptions

In this report, we were focusing on an image recognition task using convolutional neural networks (LeCun [1988]). For most of our experiments, we chose to use identical architectures as Renda et al. [2020] to better validate their claims and double-check their results, rather than provide additional ones. Therefore, most of the used networks are residual networks, which were originally proposed in He et al. [2016a]. Additionally, to verify the general usefulness of pruning and retraining methods proposed in Renda et al. [2020] we extend the list of tested network architectures to much larger wide residual networks from Zagoruyko and Komodakis [2016].

3.1.1 Residual networks (ResNet)

Just as Renda et al. [2020], we chose to use the original version of ResNet as described in He et al. [2016a] rather than the more widely used, improved version (with preactivated blocks) from He et al. [2016b]. We created the models

77 ourselves, using TensorFlow (Abadi et al. [2015]) and Keras. We strove to replicate the exact architectures used by
 78 Renda et al. [2020] and He et al. [2016a] and train them from scratch.

Model	Trainable parameters	Kernel parameters	CIFAR-10	CIFAR-100
ResNet-20	272 282	270 896	92.46%	–
ResNet-56	855 578	851 504	93.71%	71.90%
ResNet-110	1 730 522	1 722 416	94.29%	72.21%

Table 1: ResNets architecture description, including baseline accuracy across datasets.

79 Hyper-parameters

Learning rate started with 0.1 and was multiplied by 0.1 twice, after 36 000 and 54 000 iterations. One training cycle was 72 000 iterations in total. For all batch normalization layers, we set the batch norm decay to 0.997, following Renda et al. [2020] which was also used in the original TensorFlow implementation¹. We initialize network’s weights with what is known as He uniform initialization from He et al. [2015]. We regularize ResNets, during both training and finetuning, using $L2$ penalty with 10^{-4} coefficient. In other words, the loss function (from which we calculate the gradients) looks as follows:

$$FinalLoss = CategoricalCrossentropy(GroundTruth, Prediction) + 10^{-4} \times \sum_{i \in W} w_i^2$$

80 3.1.2 Wide Residual Networks (Wide ResNet, WRN)

81 WRN networks were introduced in Zagoruyko and Komodakis [2016]. They are networks created by simply increasing
 82 the number of filters in preactivated ResNet networks (He et al. [2016b]).

Model	Trainable parameters	Kernel parameters	CIFAR-10
WRN-16-8	10 961 370	10 954 160	95.72%

Table 2: Wide ResNet architecture description.

83 Hyper-parameters

As Wide ResNets are newer and much larger than ResNets, hyper-parameters are slightly different. To choose them, we follow Zagoruyko and Komodakis [2016]. Learning rate starts with 0.1 and multiplied by 0.2 thrice: after 32 000, 48 000 and 64 000 iterations. Training lasts for 80 000 iterations. For all batch normalization layers, we use hyper-parameters from the newer TensorFlow implementation² with batch norm decay set to 0.9. Following Zagoruyko and Komodakis [2016], we use larger $L2$ penalty for this network: 2×10^{-4} . Finally, the loss function is as follows:

$$FinalLoss = CategoricalCrossentropy(GroundTruth, Prediction) + 2 \times 10^{-4} \times \sum_{i \in W} w_i^2$$

84 3.2 Datasets

85 CIFAR-10 and CIFAR-100 are image classification datasets introduced in Krizhevsky et al.. Following Renda et al.
 86 [2020], we use all (50 000) training examples to train the model.

¹https://github.com/tensorflow/models/blob/r1.13.0/official/resnet/resnet_model.py

²https://github.com/tensorflow/models/blob/r2.5.0/official/vision/image_classification/resnet/resnet_model.py

Dataset	Training examples	Validation examples	Classes	Resolution
CIFAR-10	50 000	10 000	10	32×32
CIFAR-100	50 000	10 000	100	32×32

Table 3: CIFAR datasets description.

3.2.1 Postprocessing

We used a standard postprocessing for both CIFAR-10 and CIFAR-100 datasets (Renda et al. [2020], Frankle and Carbin [2019], Zagoruyko and Komodakis [2016]). During training and just before passing data to the model, we:

1. standardized the input by subtracting the mean and dividing by the std of RGB channels (calculated on training dataset),
2. randomly flipped in horizontal axis,
3. added a four pixel reflection padding,
4. randomly cropped the image to its original size.

During the validation, we did only the first step of the above.

3.3 Experimental setup and code

Our ready-to-use code, which includes experiment definitions, can be found at <https://github.com/gahaalt/reproducing-comparing-rewinding-and-finetuning>. It's written using TensorFlow (Abadi et al. [2015]) version 2.4.2 in Python. More details are included in the repository.

3.4 Computational requirements

Recreating the experiments required a modern GPU, training all models on CPU was virtually impossible. Training time varies depending on a lot of factors: network version and size, exact version of the deep learning library, and even the operating system. In our case, using TensorFlow 2.4.2 on Ubuntu and a single RTX 3080 GPU, the smallest of the used models, ResNet-20, takes about 20 minutes to train on CIFAR-10 dataset. To replicate our experiments, training at least a single baseline network and then, separately, a single pruned network, is required. To reduce computational requirements, we reused one dense baseline for multiple compression ratios. Approximated training time requirements can be seen in the table below.

Model	Dataset	Number of iterations	Iterations per second	Time for training cycle
ResNet-20	CIFAR-10	72 000	59.0	22 min
ResNet-56	CIFAR-10	72 000	28.6	43 min
ResNet-110	CIFAR-10	72 000	15.9	77 min
WRN-16-8	CIFAR-10	80 000	17.4	78 min

Table 4: Time requirements for replicating or running experiments from this report. Reported times are obtained using a single RTX 3080 GPU in Linux environment, using TensorFlow in version 2.4.2.

For all our experiments in total, we used around 536 GPU hours.

4 Method description

We compare three methods of training after pruning. For all of them, the starting point for this is a network that was already trained to convergence, then pruned to a desired sparsity.

4.1 Fine-tuning

Fine-tuning is retraining with a small, constant learning rate – in our case, whenever fine-tuning was used, it always was 0.001, as in Renda et al. [2020]. We fine-tune the network for all original training time – 72 000 iterations in the case of the original ResNet architecture.

4.2 Weight rewinding

Weight rewinding restores the network’s weights from a previous point (possibly beginning) in the training history and then continues from this point, using the original training schedule – in our case a piecewise constant decaying learning rate schedule.

4.3 Learning rate rewinding

Learning rate rewinding continues training with weights that have already converged, but restores the learning rate schedule to the first step and then trains to the convergence. This reminds the cyclical learning rates from Smith [2017].

5 Results

In most of our experiment, just as Renda et al. [2020], we investigate how does the trade-off between prediction accuracy and compression ratio look like. In one of the experiments (table 5), we check what is the accuracy of the pruned network with only one compression level. We report a median result out of 2 up to 12 trials for each compression ratio. To better utilize our compute capabilities, we decided to spend more training cycles in situations where there is no clear winner between methods. On each plot, we include error bars showing 80% confidence intervals.

5.1 Results reproducing original paper

In this section, we include experiments that were successfully reproduced and match the original ones within 1% error margin.

Across all scenarios where finetuning was tested, it was by far the worst of the three methods, which is a direct support for claim 1 (section 2). Weight rewinding and learning rate rewinding most often are equally matched, but in some cases learning rate rewinding works a little better.

ResNets on CIFAR-10 dataset

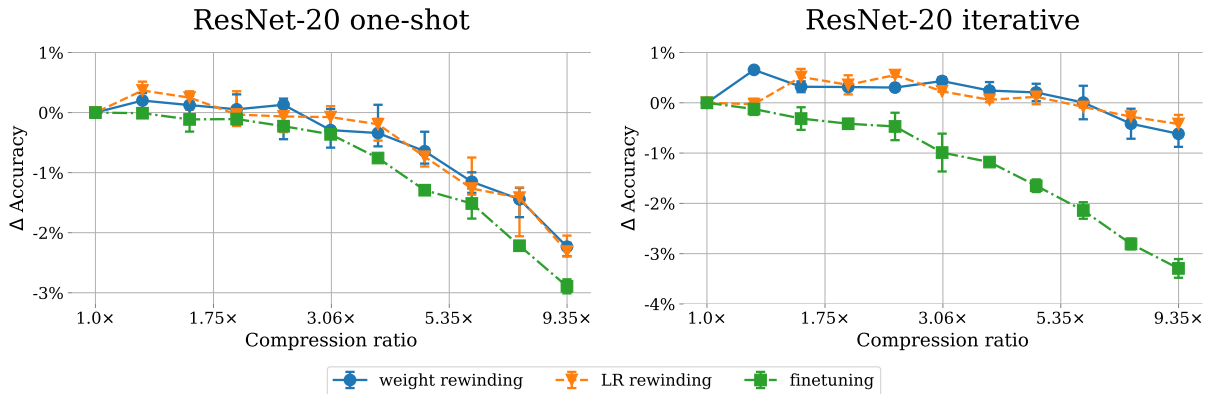


Figure 1: Results of ResNet-20 (table 1) on CIFAR-10 (table 3) with unstructured, magnitude pruning in versions: one-shot and iterative. Results show varying compression ratios. Maximal compression ratio (9.35 \times) means that there are only 29 000 non-zero kernel parameters left. This experiment supports claims 1, 2, 3 (section 2).

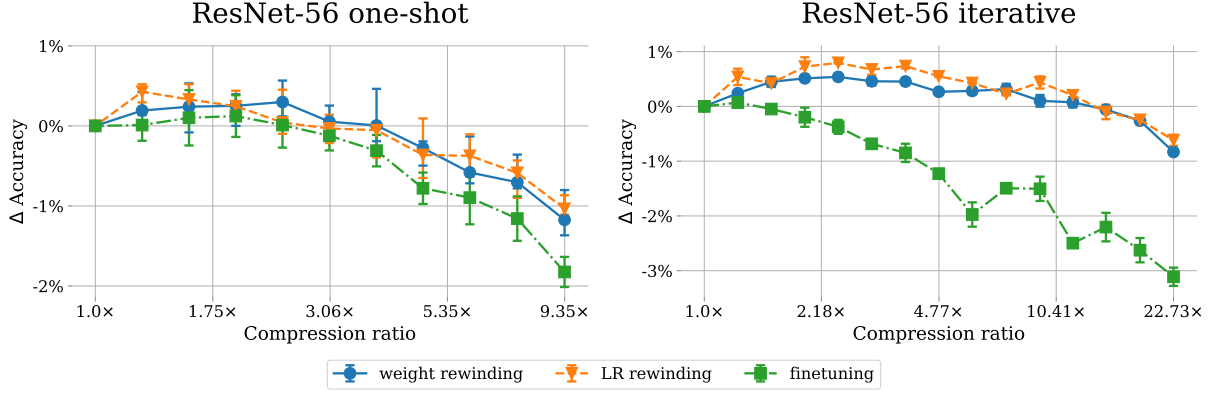


Figure 2: Results of ResNet-56 (table 1) on CIFAR-10 (table 3) with unstructured, magnitude pruning in versions: one-shot and iterative. Results with varying compression ratios. Maximal compression ratio means ($22.73\times$) that there are only 37 600 non-zero kernel parameters left. This experiment supports claims 1, 2, 3 (section 2).

Network	Dataset	Retraining	Sparsity	Test Accuracy
ResNet-110	CIFAR-10	None	0%	94.29%
ResNet-110	CIFAR-10	LR rewinding	89.3%	93.74%
ResNet-110	CIFAR-10	weight rewinding	89.3%	93.73%
ResNet-110	CIFAR-10	finetuning	89.3%	93.32%

Table 5: Results of ResNet-110 (table 1) trained on CIFAR-10 (table 3) with unstructured, one-shot magnitude pruning. Sparsity 89.3% corresponds to $9.35\times$ compression ratio. This experiment supports claims 1, 2, 3 (section 2).

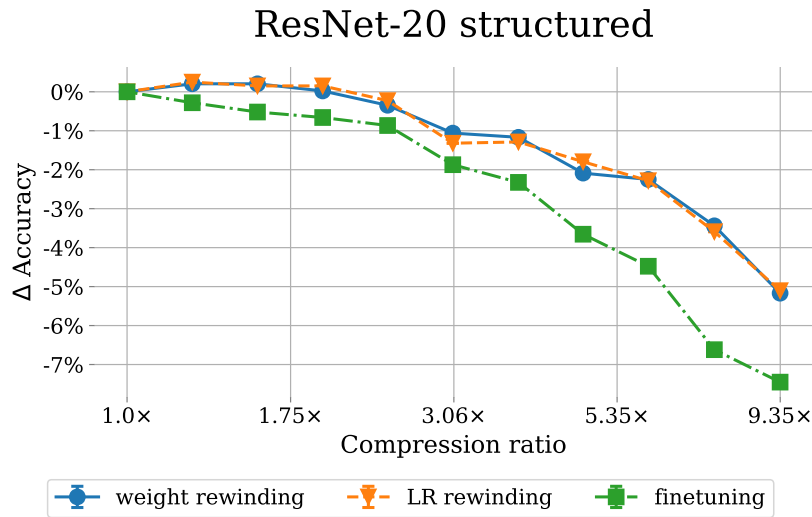


Figure 3: Results of ResNet-20 (table 1) on CIFAR-10 (table 3) with structured, magnitude, one-shot pruning. Results show varying compression ratios. Maximal compression ratio ($9.35\times$) means that there are only 29 000 non-zero kernel parameters left in ResNet-20.

5.2 Results beyond original paper

ResNets on CIFAR-100 dataset

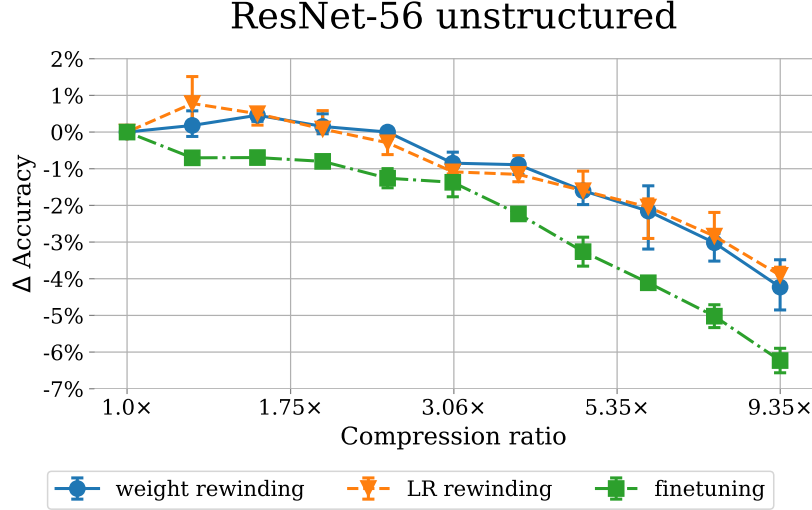


Figure 4: Results of ResNet-56 (table 1) on CIFAR-100 (table 3) with magnitude, unstructured, one-shot pruning. Results with varying compression ratios. Maximal compression ratio ($9.35\times$) means that there are only 91 500 non-zero kernel parameters left. This experiment supports claims 1, 2, 3 (section 2) even though this scenario wasn't originally tested in Renda et al. [2020].

WRN-16-8 on CIFAR-10 dataset

WRN-16-8 shows consistent behaviour – accuracy in the low sparsity regime is reduced in comparison to the baseline. In the case of iterative pruning, where each step is another pruning in the low sparsity regime, after a few steps it leads to a catastrophic difference between the two retraining methods.

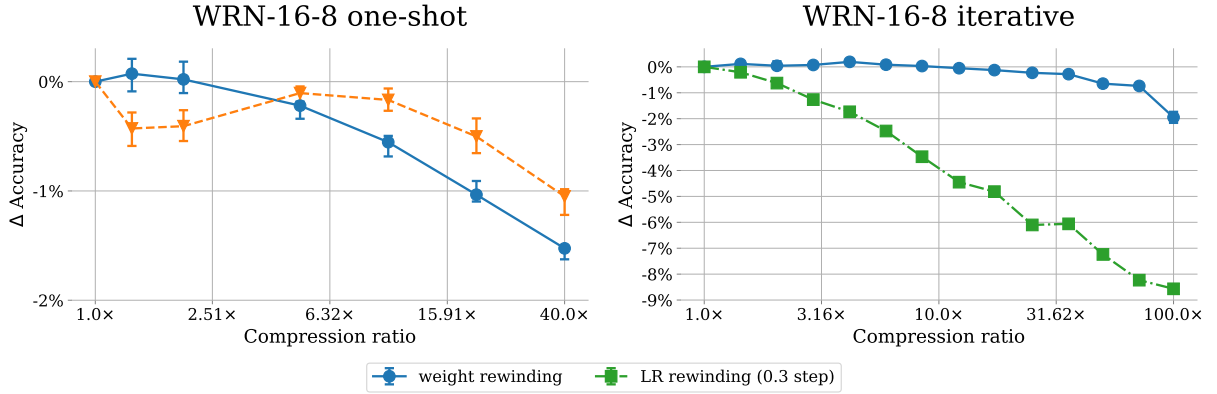


Figure 5: Results of WRN-16-8 (table 2) on CIFAR-10 (table 3) with magnitude, unstructured pruning in versions: one-shot and iterative. Results with varying compression ratios. Maximal compression ratio ($100\times$) leaves 109 500 non-zero kernel parameters while achieving around 94% accuracy or around 95% when leaving 153 400 non-zero parameters. One can see catastrophic effects of low-sparsity pruning when using learning rate rewinding procedure.

For iterative pruning (figures 1, 2) we used a nonstandard step size of 30% per iterative pruning iteration. We provide a comparison of our step size (30%) to more commonly used 20%. We show that there is no difference in both cases, there is a catastrophic degradation when pruning in the low sparsity regime.

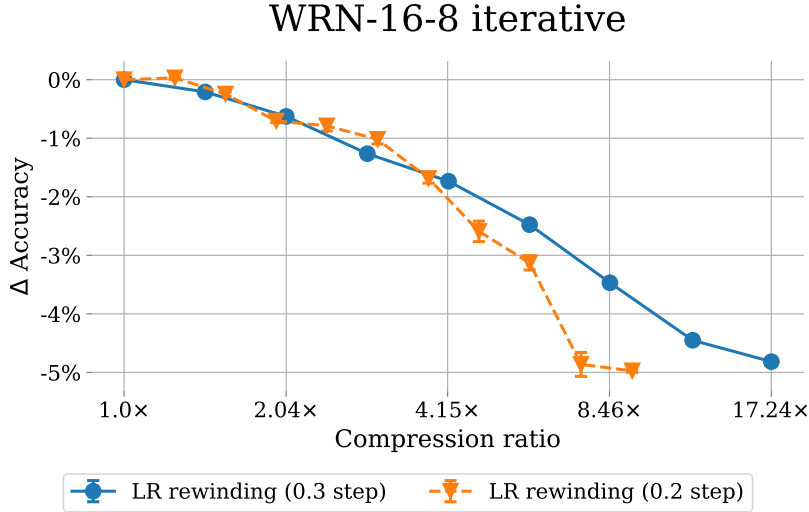


Figure 6: Results of WRN-16-8 (table 2) on CIFAR-10 (table 3) with magnitude, unstructured, iterative pruning with two different step sizes. Results with varying compression ratios and accuracy.

6 Discussion

We were able to confirm the general conclusion of Renda et al. [2020]. Fine-tuning can mostly be replaced by other retraining techniques, e.g., by weight rewinding as done by Frankle and Carbin [2019]. However, we have also shown in figure 5 that the newly proposed learning rate rewinding was a poor choice when we were pruning larger networks – in our case that was WRN-16-8. We believe this should be further examined as there might exist a simple workaround to this problem – a retraining procedure in between weight rewinding and learning rate rewinding which would work in all cases. Furthermore, it would be interesting to see where exactly learning rate rewinding starts losing accuracy in comparison to weight rewinding and why this catastrophic accuracy degradation occurs. Perhaps, the reason for it not occurring with the original ResNet architecture is the degree to which the larger networks overtrain – larger networks tend to overtrain more. Such an overtrained network might not be a good starting point for the retraining.

Acknowledgements

The authors thank Polish National Science Center for funding under the OPUS-18 2019/35/B/ST6/04379 grant and the PiGrid consortium for computational resources.

References

- Alex Renda, Jonathan Frankle, and Michael Carbin. Comparing Rewinding and Fine-tuning in Neural Network Pruning. 2020. URL <http://arxiv.org/abs/2003.02389>. arXiv: 2003.02389.
- Jonathan Frankle and Michael Carbin. The lottery ticket hypothesis: Finding sparse, trainable neural networks. *7th International Conference on Learning Representations, ICLR 2019*, page 1–42, 2019. arXiv: 1803.03635 Citation Key: Frankle2019.
- Sergey Zagoruyko and Nikos Komodakis. Wide residual networks. In Edwin R. Hancock Richard C. Wilson and William A. P. Smith, editors, *Proceedings of the British Machine Vision Conference (BMVC)*, pages 87.1–87.12. BMVA Press, September 2016. ISBN 1-901725-59-6. doi: 10.5244/C.30.87. URL <https://dx.doi.org/10.5244/C.30.87>.
- Zhuang Liu, Mingjie Sun, Tinghui Zhou, Gao Huang, and Trevor Darrell. Rethinking the value of network pruning. *7th International Conference on Learning Representations, ICLR 2019*, page 1–21, 2019. arXiv: 1810.05270 Citation Key: Liu2019a.
- Namhoon Lee, Thalaiyasingam Ajanthan, and Philip H. S. Torr. SNIP: single-shot network pruning based on connection sensitivity. *CoRR*, abs/1810.02340, 2018. URL <http://arxiv.org/abs/1810.02340>.

- 172 Elliot J. Crowley, Jack Turner, Amos Storkey, and Michael O’Boyle. A closer look at structured pruning for neural
 173 network compression. 10:1–12, 2018. URL <http://arxiv.org/abs/1810.04622>. arXiv: 1810.04622 Citation
 174 Key: Crowley2018.
- 175 Yann LeCun. Handwritten Digit Recognition with a Back-Propagation Network. In *Neural Information Processing*
 176 *Systems*. American Institute of Physics, 1988. URL [https://proceedings.neurips.cc/paper/1987/file/](https://proceedings.neurips.cc/paper/1987/file/a684ecccc76fc522773286a895bc8436-Paper.pdf)
 177 [a684ecccc76fc522773286a895bc8436-Paper.pdf](https://proceedings.neurips.cc/paper/1987/file/a684ecccc76fc522773286a895bc8436-Paper.pdf).
- 178 Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. Deep residual learning for image recognition. *Proceedings*
 179 *of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, 2016-Decem:770–778,
 180 2016a. doi: 10.1109/CVPR.2016.90. arXiv: 1512.03385 Citation Key: He2016 ISBN: 9781467388504.
- 181 Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. Identity mappings in deep residual networks. *Lecture Notes*
 182 *in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*,
 183 9908 LNCS:630–645, 2016b. ISSN 16113349. doi: 10.1007/978-3-319-46493-0_38. arXiv: 1603.05027 ISBN:
 184 9783319464923.
- 185 Martín Abadi, Ashish Agarwal, Paul Barham, Eugene Brevdo, Zhifeng Chen, Craig Citro, Greg S. Corrado, Andy
 186 Davis, Jeffrey Dean, Matthieu Devin, Sanjay Ghemawat, Ian Goodfellow, Andrew Harp, Geoffrey Irving, Michael
 187 Isard, Yangqing Jia, Rafal Jozefowicz, Lukasz Kaiser, Manjunath Kudlur, Josh Levenberg, Dandelion Mané, Rajat
 188 Monga, Sherry Moore, Derek Murray, Chris Olah, Mike Schuster, Jonathon Shlens, Benoit Steiner, Ilya Sutskever,
 189 Kunal Talwar, Paul Tucker, Vincent Vanhoucke, Vijay Vasudevan, Fernanda Viégas, Oriol Vinyals, Pete Warden,
 190 Martin Wattenberg, Martin Wicke, Yuan Yu, and Xiaoqiang Zheng. TensorFlow: Large-scale machine learning on
 191 heterogeneous systems, 2015. URL <https://www.tensorflow.org/>. Software available from tensorflow.org.
- 192 Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. Delving deep into rectifiers: Surpassing human-level
 193 performance on imagenet classification. In *Proceedings of the IEEE International Conference on Computer Vision*
 194 *(ICCV)*, December 2015.
- 195 Alex Krizhevsky, Vinod Nair, and Geoffrey Hinton. Cifar-10 (canadian institute for advanced research). URL
 196 <http://www.cs.toronto.edu/~kriz/cifar.html>.
- 197 Leslie N. Smith. Cyclical learning rates for training neural networks, 2017.