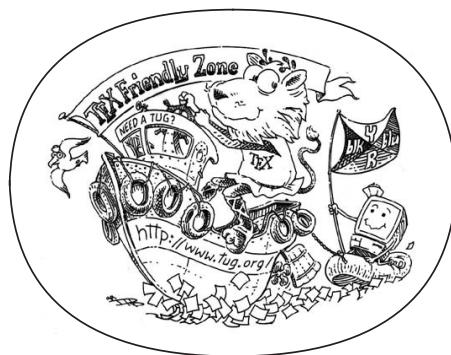


A CLASSIC THESIS STYLE

ANDRÉ MIEDE



An Homage to The Elements of Typographic Style

September 2015 – version 4.2

Ohana means family.
Family means nobody gets left behind, or forgotten.
— Lilo & Stitch

Dedicated to the loving memory of Rudolf Miede.

1939 – 2005

ABSTRACT

Short summary of the contents... a great guide by Kent Beck how to write good abstracts can be found here:

<https://plg.uwaterloo.ca/~migod/research/beck00PSLA.html>

PUBLICATIONS

Some ideas and figures have appeared previously in the following publications:

Put your publications from the thesis here. The packages `multibib` or `bibtopic` etc. can be used to handle multiple different bibliographies in your document.

*We have seen that computer programming is an art,
because it applies accumulated knowledge to the world,
because it requires skill and ingenuity, and especially
because it produces objects of beauty.*

— knuth:1974 [knuth:1974]

ACKNOWLEDGEMENTS

Put your acknowledgements here.

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Regarding LyX: The LyX port was initially done by Nicholas Mariette in March 2009 and continued by Ivo Pletikosić in 2011. Thank you very much for your work and the contributions to the original style.

¹ Members of GuIT (Gruppo Italiano Utilizzatori di T_EX e L^AT_EX)

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LISTINGS

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ACRONYMS

DRY Don't Repeat Yourself

API Application Programming Interface

UML Unified Modeling Language

Part I

TRANSFER LEARNING IN SUPERVISED LEARNING

TRANSFER LEARNING FROM THE NATURAL TO THE NON-NATURAL DOMAIN

CONTRIBUTIONS AND OUTLINE

This chapter contributes to the field of (Deep) Transfer Learning (TL) by investigating whether popular neural networks that come as pre-trained on datasets containing natural images can perform equally well once they are used on non-natural datasets. Specifically, we explore whether these models can be used for tackling three different art classification problems. Furthermore, assuming this is the case, we also explore whether it is possible to improve on such performance. The chapter is structured as follows: we start by providing the reader with some background information in Section 1.1. In Section 1.2 we present a brief theoretical reminder of the field of TL, a description of the datasets that we have used and the methodological details about the experiments that we have performed. In Section 2.4 we present and discuss our results. A summary of the main contributions of this work ends the chapter in Section 2.6.

This chapter is based on the publication Sabatelli et al. [43].

1.1 INTRODUCTION AND RELATED WORK

Over the past decade Deep Convolutional Neural Networks (DCNNs) have become one of the most used and successful algorithms in Computer Vision (CV) [10, 28, 52]. Due to their ability to automatically learn representative features by incrementally down sampling the input via a set of non linear transformations, these kind of neural networks have rapidly established themselves as the state of the art algorithm on a large set of CV problems. Within different CV testbeds large attention has been paid to the ImageNet challenge [9], a CV benchmark that aims to test the performance of different image classifiers on a dataset that contains one million natural images distributed over thousand different classes. The availability of such a large dataset, combined with the possibility of training deep neural networks in parallel over several GPUs [25], has lead to the development of a large set of different neural architectures that have continued to outperform each other over the years [7, 20, 21, 44, 49]. A promising research field in which the classification performances of such DCNNs can be exploited is that of *Digital Heritage* [37]. Due

to a growing and rapid process of digitization, museums have started to digitize large parts of their cultural heritage collections, leading to the creation of several digital open datasets [3, 32]. The images constituting these datasets are mostly matched with descriptive metadata which, as presented by Mensink and Van Gemert [32], can be used to define a set of challenging machine learning tasks. However, the number of samples in these datasets is far smaller than those in, for instance, the ImageNet challenge and this can become a serious constraint when trying to successfully train deep networks from scratch.

The lack of available training data is a well known issue in the deep learning community and is one of the main reasons that has led to the development of the research field of Transfer Learning (TL). The main idea of TL consists of training a machine learning algorithm on a new task (e.g. a classification problem) while exploiting knowledge that the algorithm has already learned on a previously related task (a different classification problem). This machine learning paradigm has proved to be extremely successful in deep learning, where it has been shown how popular models that were trained on many large datasets [22, 45], were able to achieve very promising results on classification problems from heterogeneous domains, ranging from medical imaging [50] or gender recognition [55] over plant classification [40] to galaxy detection [2].

In this work we explore whether the TL paradigm can be successfully applied to three different art classification problems. We use four neural architectures that have obtained strong results on the ImageNet challenge in recent years and we investigate their performance when it comes to attributing the *authorship* to different artworks, recognizing the *material* which has been used by the artists in their creations, and identifying the *artistic category* these artworks fall into. We do so by comparing two possible approaches that can be used to tackle the different classification tasks. The first one, known as off the shelf classification [39], simply retrieves the features that were learned by the networks on other datasets and uses them as input for a new classifier. In this scenario the weights of the model do not change during the training phase, and the final, top-layer classifier is the only component of the architecture which is actually trained. This changes in our second explored approach, known as fine tuning, where the weights of the original network are “unfrozen” and the neural architectures are trained together with the final classifier.

Kornblith, Shlens, and Le [24] have shown the benefits that this particular pre-training approach has. In particular, DCNNs which have been trained on the ImageNet challenge typically lead to superior results when compared to the same architectures trained from scratch. However, this is not necessarily beneficial and in some cases networks that are randomly initialized are able to achieve the same performance as ImageNet pre-trained models. However, none of the

results presented in [24] report experiments on datasets containing heritage objects, it is thus still an open question how such pre-trained DCNNs would perform in such a classification scenario. In the rest of this chapter we report results that extensively study the performance of such neural networks; at the same time we also assess whether better TL performance can be obtained when using neural networks that, in addition to the ImageNet dataset, have additionally been pre-trained on a large artistic collection.

1.2 METHODS

We now present the methods that underpin our research. We start by giving a brief formal reminder of TL. We then introduce the three classification tasks under scrutiny, together with a brief description of the datasets. Finally, we present the neural architectures that we have used for our experiments.

1.2.1 Transfer Learning

A supervised learning (SL) problem can be identified by three elements: an input space \mathcal{X}_t , an output space \mathcal{Y}_t , and a probability distribution $p_t(x, y)$ defined over $\mathcal{X}_t \times \mathcal{Y}_t$ (where t stands for ‘target’, as this is the main problem we would like to solve). The goal of SL is then to build a function $f : \mathcal{X}_t \rightarrow \mathcal{Y}_t$ that minimizes the expectation over $p_t(x, y)$ of a given loss function ℓ assessing the predictions made by f :

$$E_{(x,y) \sim p_t(x,y)} \{\ell(y, f(x))\}, \quad (1)$$

when the only information available to build this function is a learning sample of input-output pairs $LS_t = \{(x_i, y_i) | i = 1, \dots, N_t\}$ drawn independently from $p_t(x, y)$. In the general transfer learning setting, one assumes that an additional dataset LS_s , called the source data, is available that corresponds to a different, but related, SL problem. More formally, the source SL problem is assumed to be defined through a triplet $(\mathcal{X}_s, \mathcal{Y}_s, p_s(x, y))$, where at least either $\mathcal{X}_s \neq \mathcal{X}_t$, $\mathcal{Y}_s \neq \mathcal{Y}_t$, or $p_s \neq p_t$. The goal of TL is then to exploit the source data LS_s together with the target data LS_t to potentially find a better model f in terms of the expected loss (1) than when only LS_t is used for training this model. Transfer learning is especially useful when there is a lot of source data, whereas target data is more scarce.

Depending on the availability of labels in the target and source data and on how the source and target problems differ, one can distinguish different TL settings [36]. In what follows, we assume that labels are available in both the source and target data and that the input spaces \mathcal{X}_t and \mathcal{X}_s , that both correspond to color images, match. Output spaces and joint distributions will however differ between

the source and target problems, as they will typically correspond to different classification problems (ImageNet object recognition versus art classification tasks). Our problem is thus an instance of *inductive transfer learning* [36]. While several inductive transfer learning algorithms exist, hereafter we focus on model transfer techniques, where information between the source and target problems is exchanged in the form of a neural network that comes as pre-trained on the source data. Although potentially suboptimal, this approach has the advantage of being more computationally efficient, as it does not require to train a model using both the source and the target data.

1.2.2 Datasets and Classification Challenges

For our experiments we use two datasets which come from two different heritage collections. The first one contains the largest number of samples and comes from the Rijksmuseum in Amsterdam¹. On the other hand, our second ‘Antwerp’ dataset is much smaller. This dataset presents a random sample that is available as open data from a larger heritage repository: DAMS (Digital Asset Management System)². This repository can be searched manually via the web-interface or queried via a Linked Open Data API. It aggregates the digital collections of the foremost GLAM institutions (Galleries, Libraries, Archives, Museums) in the city of Antwerp in Belgium. Thus, this dataset presents a varied and representative sample of the sort of heritage data that is nowadays being collected at the level of individual cities across the globe. While it is much smaller, its coverage of cultural production is similar to that of the Rijksmuseum dataset and presents an ideal testing ground for the transfer learning task under scrutiny here.

Both image datasets come with metadata encoded in the Dublin Core metadata standard [54]. We selected three well-understood classification challenges: (1) “material classification” which consists in identifying the material the different heritage objects are made of (e.g paper, gold, porcelain, ...); (2) “type classification” in which the neural networks have to classify in which artistic category the samples fall into (e.g. print, sculpture, drawing, ...), and finally (3) “artist classification”, where the main goal is to appropriately match each sample of the dataset with its creator (from now on we refer to these classification tasks as challenge 1, 2 and 3 respectively). As reported in Table 1 we can see that the Rijksmuseum collection is the dataset with the largest amount of samples per challenge (N_t) and the highest amount of labels to classify (Q_t). Furthermore it is also worth noting that there was no metadata available when it comes to the first classification challenge for the Antwerp dataset (as marked by the \times symbol),

¹ <https://staff.fnwi.uva.nl/t.e.j.mensink/uval2/rijks/>

² <https://dams.antwerpen.be/>



Figure 1: A visualization of the images that are used for our experiments. It is possible to see how the samples range from images representing plates made of porcelain to violins, and from Japanese artworks to a more simple picture of a key.

and that there are some common labels between the two heritage collections when it comes to challenge 2. A visualization reporting some of the images that are present in both datasets is shown in Figure 1.

Table 1: An overview of the two datasets that are used in our experiments. Each color of the table corresponds to a different classification challenge, starting from challenge 1 which is represented in yellow, challenge 2 in blue and finally challenge 3 in red. Furthermore we represent with N_t the amount of samples constituting the datasets and with Q_t the number of labels. Lastly, we also report if there are common labels between the two heritage collections.

Challenge	Dataset	N_t	Q_t	% of overlap
Material	Rijksmuseum	110,668	206	None
	Antwerp	×	×	
Type	Rijksmuseum	112,012	1,054	
	Antwerp	23,797	920	≈ 15%
Artist	Rijksmuseum	82,018	1,196	None
	Antwerp	18,656	903	

We use 80% of the datasets for training while the remaining $2 \times 10\%$ is used for validation and testing respectively. Furthermore, we ensure that only classes which occur at least once in all the splits are used for our experiments. Naturally, in order to keep all comparisons fair between neural architectures and different TL approaches, all experiments have been performed on the exact same data splits which, together with the code used for all our experiments, are publicly released to the CV community ³.

³ <https://github.com/paintception/Deep-Transfer-Learning-for-Art-Classification-Problems>

1.2.3 Neural Architectures and Classification Approaches

For our experiments we use four pre-trained DCNNs that have all obtained state of the art results on the ImageNet classification challenge. The neural architectures are VGG19 [44], Inception-V3 [49], Xception [7] and ResNet50 [57]. We use the implementations of the networks that are provided by the Keras Deep Learning library [8] together with their appropriate Tensorflow weights [1] that come from the Keras official repository as well. Since all architectures have been built in order to deal with the ImageNet dataset we replace the final classification layer of each network with a new one. This final layer simply consists of a new *softmax* output, with as many neurons as there are classes to classify, which follows a 2D global average pooling operation. We rely on this dimensionality reduction step because we do not add any fully connected layers between the last convolution layer and the *softmax* output. Hence, in this way we are able to obtain a feature vector, X , out of the rectified activation feature maps of the network that can be properly classified. Since all experiments are treated as a multi-class classification problem all networks minimize the *categorical crossentropy* function loss function.

We investigate two possible classification approaches that are based on the previously mentioned pre-trained architectures. The first one, denoted as off the shelf classification, only trains a final *softmax* classifier on X , which is retrieved from the different models after performing one forward pass of the image through the network⁴. This approach is intended to explore whether the features that are learned by the network on the ImageNet dataset are informative enough in order to properly train a machine learning classifier on the previously introduced art classification challenges. If this would be the case, such pre-trained models could be used as appropriate feature extractors without having to rely on expensive GPU computations for training. Naturally, they would only require the training of the final classifier without having to compute any backpropagation operations over the entire network. From now on we will refer to these networks with θ^- .

Our second approach is generally known as fine tuning and differs from the previous one by the fact that together with the final *softmax* output the entire network is trained as well. This means that unlike the off the shelf approach, the entirety of the neural architecture gets “unfrozen” and is optimized during training. The potential benefit of this approach lies in the fact that the models get independently trained on samples coming from the artistic datasets, and therefore their classification predictions will not be restricted to what the networks previously learned on the ImageNet dataset only. Evidently,

⁴ Please note that instead of a *softmax* layer any kind of machine learning classifier can be used instead. We experimented with both Support Vector Machines (SVMs) and Random Forests but since the results did not significantly differ between classifiers we decided to not include them here.

such an approach is computationally more demanding. We refer to these networks as θ^i , where i stands for the source task these models have been trained on, namely the ImageNet dataset.

In order to maximize the performance of all models we follow some of the recommendations presented by Masters and Luschi [30] and train the networks with a relatively small batch size of 32 samples. We do not perform any data augmentation operations besides a standard pixel normalization to the $[0, 1]$ range and a re-scaling operation which resizes the images to the input size that is required by the different models. Regarding the stochastic optimization procedures of the different classifiers, we use two different optimizers, that after preliminary experiments, turned out to be the best performing ones. For the off the shelf approach we use the RMSprop optimizer [51] which has been initialized with its default hyperparameters (learning rate = 0.001, a *momentum* value $\rho = 0.9$ and $\epsilon = 1e - 08$). On the other hand, when we fine tune the DCNNs we use the standard (and less greedy) Stochastic Gradient Descent (SGD) algorithm with the same learning rate, 0.001, and a *Nesterov Momentum* value set to 0.9. Training has been controlled by the *Early Stopping* method [6] which interrupted training as soon as the validation loss did not decrease for 7 epochs in a row. The model which is then used on the testing set is the one which obtained the smallest validation loss while training.

To the best of our knowledge, the results presented in this chapter are the first ones that systematically asses to which extent models pre-trained on the ImageNet dataset can be used as valuable architectures when tackling art classification problems. Furthermore, we also present the first results that investigate it is also not known whether the fine tuning approach can yield better results than the off the shelf one, and if using such pre-trained models would yield better performance than training the same architectures from scratch as observed by Kornblith, Shlens, and Le [24].

1.3 RESULTS

Our experimental results are divided in two different sections, depending on which kind of dataset has been used. We first report the results that we have obtained when using architectures that were pre-trained on the ImageNet dataset only, and aimed to tackle the three classification problems of the Rijksmuseum dataset that were presented in Section 1.2.2. We report these results in Section 1.3.1 where we explore the benefits of using the ImageNet dataset as the TL source data, and how well such pre-trained models generalize when it comes to the artistic domain. We then present the results from classifying the Antwerp dataset, using models that are both pre-trained on the ImageNet dataset and on the Rijksmuseum collection in Section 1.3.3. We investigate whether these neural architectures,

which have already been trained to tackle art classification problems before, perform better than the ones which have been trained on the ImageNet dataset only.

All results show comparisons between the off the shelf classification approach and the fine tuning scenario. In addition to that, in order to establish the potential benefits that TL from ImageNet has over training a model from scratch, we also report the results that have been obtained when training a network with weights that have been initially sampled from a “He-Uniform” distribution [19]. Since we take advantage of the work presented by Bidoia et al. [4] we use the Inception-V3 architecture. We refer to it in all figures as Scratch-V3 and always visualize it with a solid orange line. Figures 2 and 3 report the performance in terms of accuracy that the models have obtained on the validation sets. While the performances that the neural architectures have obtained on the final testing set are reported in Tables 2 and 3.

1.3.1 *From Natural to Art Images*

The first results that we report have been obtained on the “material” classification challenge. We believe that this can be considered as the easiest classification task within the ones that we have introduced in Section 1.2.2 for two main reasons. First, the number of possible classes the networks have to deal with is more than five times smaller when compared to the other two challenges. Furthermore, we also believe that this classification task is, within the limits, the most similar one when compared to the original ImageNet challenge. Hence, the features that might be useful in order to classify the different natural images on the latter classification testbed might be not too dissimilar from the ones that are needed to properly recognize the material that the different samples of the Rijksmuseum collection are made of. If this would be the case we would expect a very similar performance between the off the shelf classification approach and the fine tuning one. Comparing the learning curves of the two classification strategies in Figure 2, we actually observe that the fine tuning approach leads to significant improvements when compared to the off the shelf one, for three architectures out of the four tested ones. Note however that, in support of our hypothesis, the off the shelf approach can still reach high accuracy values on this problem and is also competitive with the DCNN trained from scratch. This suggests that features extracted from networks pretrained on ImageNet are relevant for material classification.

When comparing the learning curves of the two classification strategies reported in Figure 2, we can observe that the fine tuning approach leads to significant improvements when compared to the off the shelf one, for three architectures out of the four tested ones. Note

however that, in support of our hypothesis, the off the shelf approach can still reach high accuracy values on this problem and is also competitive with the network that is trained from scratch. This suggests that features extracted from pretrained ImageNet models are relevant for material classification.

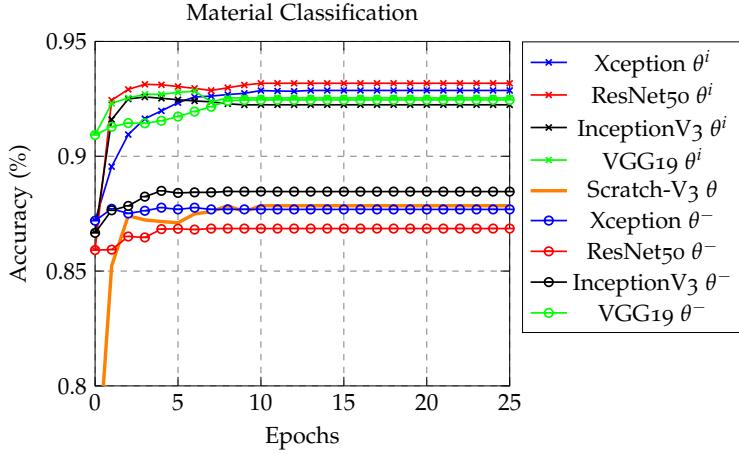


Figure 2: Comparison between the fine tuning approach (θ^i) versus the off the shelf one (θ^-) when classifying the material of the heritage objects of the Rijksmuseum dataset. We can observe that for three out of four neural architectures the first approach leads to significant improvements when compared to the latter one. Furthermore, we can also observe that training a randomly initialized model from scratch (solid orange line) leads to worse results than fine-tuning a network that comes as pre-trained on the ImageNet dataset.

We can also observe that the ResNet50 architecture is the architecture which, when fine tuned, performs overall best when compared to the other three models. This happens despite it being the network that initially performed worse as a simple feature extractor in the off the shelf experiments. As reported in Table 2 we can see that this kind of behavior reflects itself on the separated testing set as well, where it obtained the highest testing set accuracy when fine tuned (92.95%), and the lowest one when the off the shelf approach was used (86.81%). It is worth noting that the performance between the different neural architectures do not strongly differ between each other once they are fine tuned, with all models performing around $\approx 92\%$ on the final testing set. Furthermore, special attention needs to be given to the VGG19 architecture, which does not seem to benefit from the fine tuning approach as much as the other architectures do. In fact, its off the shelf performance on the testing set (92.12%) is very similar to its fine tuned one (92.23%). This suggests that this neural architecture is the only one which, in this task, and when pre-trained on ImageNet, can successfully be used as a simple feature extractor without having to rely on complete retraining.

When analyzing the performance of the different neural architectures on the “type” and “artist” classification challenges (respectively the left and right plots reported in Figure 3), we observe that on these problems fine tuning strategy leads to even more significant improvements when compared to what we observed in the previous experiment. The results obtained on the second challenge show again that the ResNet50 architecture is the architecture which leads to the worse results if the off the shelf approach is used (its testing set accuracy is as low as 71.23%) and similarly to what has been observed before, it then becomes the best performing model when fine tuned, with a final accuracy of 91.30%. Differently from what has been observed in the previous experiment, the VGG19 architecture, despite being the network performing best when used as off the shelf feature extractor, this time performs significantly worse than when it is fine tuned, which highlights the benefits of this latter training approach. Similarly to what has been observed before, our results are again not significantly in favor of any fine tuned neural architecture, with all final accuracies being around $\approx 91\%$.

If the classification challenges that we have analyzed so far have highlighted the significant benefits of the fine tuning approach over the off the shelf one, it is also important to note that the latter approach is still able to lead to satisfying results. In fact, a final accuracy of 92.12% has been obtained when using the VGG19 architecture on the first challenge and a classification rate of 77.33% was reached by the same architecture on the second challenge. Despite the latter accuracy being very far in terms of performance from the one obtained when fine tuning the network (90.27%), these results still show that models pre-trained on ImageNet do learn particular features that can also be used for classifying the “material” and the “type” of heritage objects. However, when analyzing the results from the “artist” challenge, we can see that this is partially not the case anymore.

When considering the third classification challenge we can observe that the Xception, ResNet50, and Inception-V3 architectures all perform extremely poorly if not fine tuned, with the latter two models not being able to even reach a 10% classification rate. Better results are obtained when using the VGG19 architecture, which reaches a final accuracy of 38.11%. Most importantly, the performance of each model are again significantly improved when the networks are fine tuned. As already observed in the previous experiments, ResNet50 outperforms the other architectures on the validation set. However, on the test set (see Table 2), the overall best performing network is Inception-V3 (with a final accuracy of 51.73%), which suggests that ResNet50 suffered from overfitting. It is important to state two major important points about this set of experiments. The first one relates to the final classification accuracy that is obtained by all models, and that at first sight might seem disappointing. While it is true that these

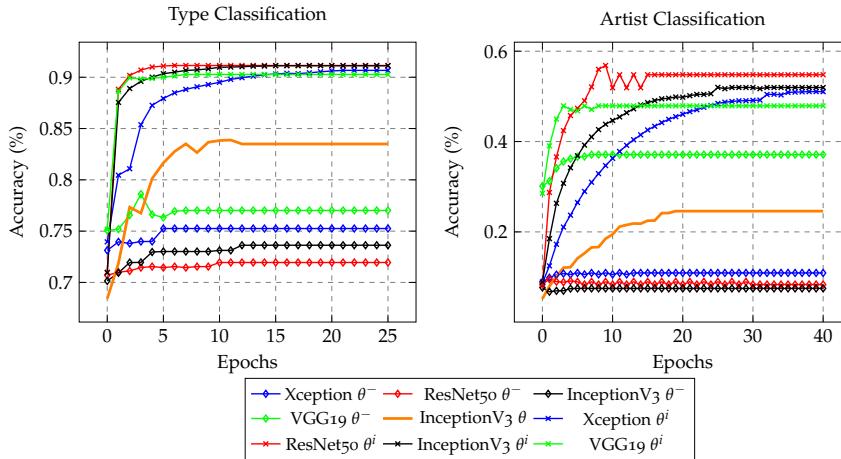


Figure 3: A similar analysis as the one which has been reported in Figure 2 but for the second and third classification challenges (left and right figures respectively). The results show again the significant benefits that fine tuning (reported by the dashed line plots) has when compared to the off the shelf approach (reported by the dash-dotted lines) and how this latter strategy miserably underperforms when it comes to artist classification. Furthermore we again see the benefits that using a pre-trained DCNN has over training the architecture from scratch (solid orange line).

classification rates are significantly lower when compared to the ones obtained in the previous two experiments, it is important to highlight how a large set of artists present in the dataset are associated to an extremely limited amount of samples. This reflects a lack of appropriate training data which does not allow the models to learn all the features that are necessary for successfully dealing with this particular classification challenge. In order to do so, we believe that more training data is required. Moreover, it is worth pointing out that despite performing very poorly when used as off the shelf feature extractors, ImageNet pre-trained models do still perform better once they are fine tuned than a model that is trained from scratch. This suggests that these networks do learn potentially representative features when it comes the classification of artists, but in order to properly classify them, the model need to be fine tuned.

1.3.2 Discussion

In the previous section, we have investigated whether four different architectures pre-trained on the ImageNet dataset can be successfully used to address three art classification problems. We have observed that this is particularly the case when it comes to classifying the material and the type, where in fact, the off the shelf approach already yielded satisfactory results. However, most importantly, we have also shown that the performance of all models can be significantly im-

Table 2: An overview of the results obtained by the different models on the testing set when classifying the heritage objects of the Rijksmuseum. The overall best performing architecture is reported in a green cell, while the second best performing one is reported in a yellow one. The additional columns “Params” and “X” report the amount of parameters the networks have to learn and the size of the feature vector that is used as input for the softmax classifier.

Challenge	DCNN	off the shelf	fine tuning	Params	X
1	Xception	87.69%	92.13%	21K	2048
1	InceptionV3	88.24%	92.10%	22K	2048
1	ResNet50	86.81%	92.95%	24K	2048
1	VGG19	92.12%	92.23%	20K	512
2	Xception	74.80%	90.67%	23K	2048
2	InceptionV3	72.96%	91.03%	24K	2048
2	ResNet50	71.23%	91.30%	25K	2048
2	VGG19	77.33%	90.27%	20K	512
3	Xception	10.92%	51.43%	23K	2048
3	InceptionV3	.07%	51.73%	24K	2048
3	ResNet50	.08%	46.13%	26K	2048
3	VGG19	38.11%	44.98%	20K	512

proved when the networks are fine tuned, and that an ImageNet initialization is beneficial when compared to training a randomly initialized network from scratch. Furthermore, we have discovered that the pre-trained DCNNs fail if used as simple feature extractors when having they are used for attributing the authorship to the different heritage objects. In the next section, we explore the performance of fine tuned models that are trained for tackling two of the already seen classification challenges on a different heritage collection. For this problem, we will again compare the off the shelf approach with the fine tuning one.

1.3.3 From One Art Collection to Another

Table 3 compares the results that we obtained on the Antwerp dataset when using ImageNet pre-trained models (θ^i) versus the same architectures that were fine tuned on the Rijksmuseum dataset (θ^r). While looking at the performance of the different neural architectures two interesting results can be highlighted. First, models which have been fine tuned on the Rijksmuseum dataset outperform the ones pre-trained on ImageNet in both classification challenges. This happens to be the case both when the networks are used as simple feature extractors and when they are fine tuned. On the “type” classification challenge, this result is not surprising since, as discussed in Section

[1.2.2](#), the types corresponding to the heritage objects of the two collections partially overlap. This is more surprising on the “artist” classification challenge however, since there is no overlap at all between the artists of the Rijksmuseum and the ones from the Antwerp dataset. A second interesting result, which is consistent with the results presented in the previous section, revolves around the observation that it is always beneficial to fine tune the networks over just using them as off the shelf feature extractors. Once the models get fine tuned on the Antwerp dataset, these DCNNs, which have also been fine tuned on the Rijksmuseum dataset, outperform the architectures that were pre-trained on ImageNet only. This happened to be the case for both classification challenges and for all considered architectures, as reported in Table 3. This demonstrates how beneficial it is for the models to have been trained on a similar source task and how this can lead to significant improvements both when the networks are used as feature extractors and when they are fine tuned.

Table 3: The results obtained on the classification experiments performed on the Antwerp dataset with models that have been initially pre-trained on ImageNet (θ^i) and the same architectures which have been fine tuned on the Rijksmuseum dataset (θ^r). Our results show that the latter pre-trained networks yield better results both if used as off the shelf feature extractors and if fine tuned.

Challenge	DCNN	$\theta^i + \text{off the shelf}$	$\theta^r + \text{off the shelf}$	$\theta^i + \text{fine tuning}$	$\theta^r + \text{fine tuning}$
2	Xception	42.01%	62.92%	69.74%	72.03%
	InceptionV3	43.90%	57.65%	70.58%	71.88%
	ResNet50	41.59%	64.95%	76.50%	78.15%
	VGG19	38.36%	60.10%	70.37%	71.21%
3	Xception	48.52%	54.81%	58.15%	58.47%
	InceptionV3	21.29%	53.41%	56.68%	57.84%
	ResNet50	22.39%	31.38%	62.57%	69.01%
	VGG19	49.90%	53.52%	54.90%	60.01%

1.3.4 Selective Attention

The benefits of the fine tuning approach over the off the shelf one are clear from our previous experiments. Nevertheless, we do not have any insights yet as to what exactly allows fine tuned models to outperform the architectures which are pre-trained on ImageNet only. In order to provide an answer to that, we investigate which pixels of each input image contribute the most to the final classification predictions of the networks. We do this by using the “VisualBackProp” algorithm presented by [5], which is able to identify which feature maps of the networks are the most informative ones with respect to their final prediction. Once these feature maps are identified, they get backpropagated to the original input image, and visualized as a saliency map according to their weights. The higher the activation of

the filters, the brighter the set of pixels covered by these filters are represented.

The results that we have obtained provide interesting insights about how fine tuned models develop novel selective attention mechanisms over the images, which are very different from the ones that characterize the networks that are pre-trained on ImageNet. We report the existence of these mechanisms in Figure 4 where we visualize the different saliency maps between a model pre-trained on ImageNet and the same neural architecture which has been fine tuned on the Rijksmuseum collection. In Figure 4 we visualize which sets of pixels allow the fine tuned model to successfully classify an artist of the Rijksmuseum collection that the same architecture was not able to initially recognize. It is possible to notice that the saliency maps of the latter architecture either correspond to what is more similar to a natural image, as represented by the central image of the first row of plots, or even to what appear to be non informative pixels at all, as shown by the second image in the second row. However, when considering the fine tuned model we clearly observe that these saliency maps change. In this case the network attends towards the set of pixels that represent people in the bottom, suggesting that this is what allows the model to appropriately recognize the artist of the considered artwork.

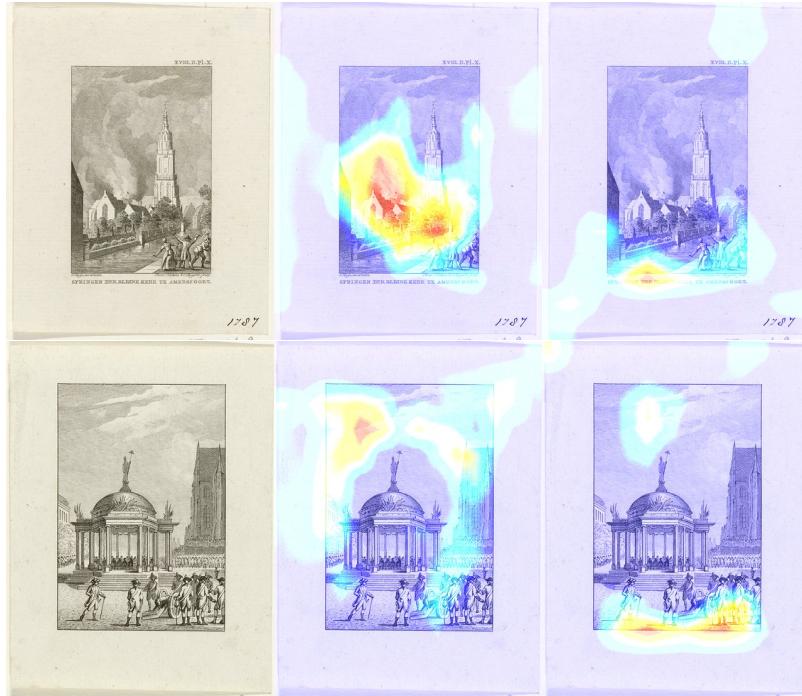


Figure 4: Add caption

These observations can be related to parallel insights in authorship attribution research [12], an established task from Natural Language Processing that is highly similar in nature to artist recognition. In this

field, preference is typically given to high-frequency function words (articles, prepositions, particles etc.) over content words (nouns, adjectives, verbs, etc.), because the former are generally considered to be less strongly related to the specific content or topic of a work. As such, function words or stop words lend themselves more easily to attribution across different topics and genres. In art history, strikingly similar views have been expressed by the well-known scholar Giovanni Morelli (1816-1891), who published seminal studies in the field of artist recognition [56]. In Morelli's view too, the attribution of a painting could not happen on the basis of the specific content or composition of a painting, because these items were too strongly influenced by the topic of a painting or the wishes of a patron. Instead, Morelli proposed to base attributions to so-called *Grundformen* or small, seemingly insignificant details that occur frequently in all paintings and typically show clear traces of an artist's individual style, such as ears, hands or feet, a painting's function words, so to speak. The saliency maps above reveal a similar shift in attention when the ImageNet weights are adapted on the Rijksmuseum data: instead of focusing on higher-level content features, the network shifts its attention to lower layers in the network, seemingly focusing on insignificant details, that nevertheless appear crucial to perform artist attribution.

1.4 CONCLUSION

This paper provides insights about the potential that the field of TL has for art classification. We have investigated the behavior of DCNNs which have been originally pre-trained on a very different classification task and shown how their performances can be improved when these networks are fine tuned. Moreover, we have observed how such neural architectures perform better than if they are trained from scratch and develop new saliency maps that can provide insights about what makes these DCNNs outperform the ones that are pre-trained on the ImageNet dataset. Such saliency maps reflect themselves in the development of new features, which can then be successfully used by the DCNNs when classifying heritage objects that come from different heritage collections. It turns out that the fine tuned models are a better alternative to the same kind of architectures which are pre-trained on ImageNet only, and can serve the CV community which will deal with similar machine learning problems.

As future work, we aim to investigate whether the results that we have obtained on the Antwerp dataset will also apply to a larger set of smaller heritage collections. Furthermore, we want to explore the performances of densely connected layers [21] and understand which layers of the currently analyzed networks contribute the most to their final classification performances. This might allow us to combine the

best parts of each neural architecture into one single novel DCNN which will be able to tackle all three classification tasks at the same time.

2

TRANSFER LEARNING WITH NATURAL LOTTERY WINNERS

CONTRIBUTIONS AND OUTLINE

In Chapters 1 and we have always performed Transfer Learning (TL) with extremely large and deep convolutional neural networks. In this chapter however, we take a different approach. We use TL as a tool for, not only exploiting the performance of pruned neural networks, but also for characterizing a relatively new deep learning phenomenon that comes with the name of the “Lottery Ticket Hypothesis” (LTH). Specifically we investigate whether lottery winners that are found on datasets of natural images contain inductive biases that are generic enough to allow them to generalize to non-natural image distributions. To do so, we present to the first results that study the transferability of winning initializations in this particular training setting. Furthermore we also show that the LTH offers a novel way for doing TL when the training data is scarce. The rest of this chapter is structured as follows: Sec. 2.1 introduces the LTH and presents the reasons that have motivated studying this phenomenon from a TL perspective. Sec. 2.2 and Sec. 2.3 present the experimental setup that was used throughout this chapter, while Sec. 2.4 and Sec. 2.4.3 present the main findings of our research. The chapter ends by contextualizing its content with respect to the existing literature in Sec. 2.5 and by identifying some potential avenues for future work in Sec. 2.6.

This chapter is based on the publication Sabatelli, Kestemont, and Geurts [42].

2.1 INTRODUCTION

The “Lottery-Ticket-Hypothesis” (LTH) [14] states that within large randomly initialized neural networks there exist smaller sub-networks which, if trained from their initial weights, can perform just as well as the fully trained unpruned network from which they are extracted. This happens to be possible because the weights of these sub-networks seem to be particularly well initialized before training starts, therefore making these smaller architectures suitable for learning (see Fig 5 for an illustration). These sub-networks, i.e., the pruned structure together with their initial weights, are called winning tickets, as they

appear to have won the initialization lottery. Since winning tickets only contain a very limited amount of parameters, they yield faster training, inference, and sometimes even better final performance than their larger over-parametrized counterparts [14, 16]. So far, winning tickets are typically identified by an iterative procedure that cycles through several steps of network training and weight pruning, starting from a randomly initialized unpruned network. While simple and intuitive, the resulting algorithm, has unfortunately a high computational cost. Despite the fact that the resulting sparse networks can be trained efficiently and in isolation from their initial weights, the LTH idea has not yet led to more efficient solutions for training a sparse network, than existing pruning algorithms that all also require to first fully train an unpruned network [11, 18, 26, 33, 59].

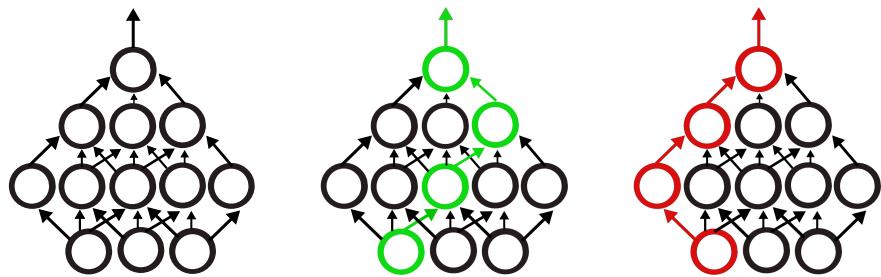


Figure 5: A visual representation of the LTH as introduced by Frankle and Carbin [14]. Let us consider a simplified version of a two hidden layer feedforward neural network as is depicted in the first image on the left. The LTH states that within this neural network there exist multiple smaller networks (represented in green), which can perform just as well as their larger counterpart. Training these sparse models from scratch successfully is only possible as long as their weights are initialized with the same values that were also used when the larger (black) model was initialized. Furthermore, the structure of these sparse models appears to be crucial as well, since it is not possible to randomly extract any subset of weights from an unpruned model and successfully train the resulting sparse network (represented in red in the last figure) from scratch. We visually represent the performance od models that are the winners of the LTH in the two plots reported in Figure 6.

Since the introduction of the idea of the LTH, several research works have focused on understanding what makes some weights so special to be the winners of the initialization lottery. Among the different tested approaches, which will be reviewed in Sec. 2.5, one research direction in particular has looked into how well winning ticket initializations can be transferred among different training settings (datasets and optimizers), an approach which aims at characterizing the winners of the LTH by studying to what extent their inductive biases are generic [34]. The most interesting findings of this study

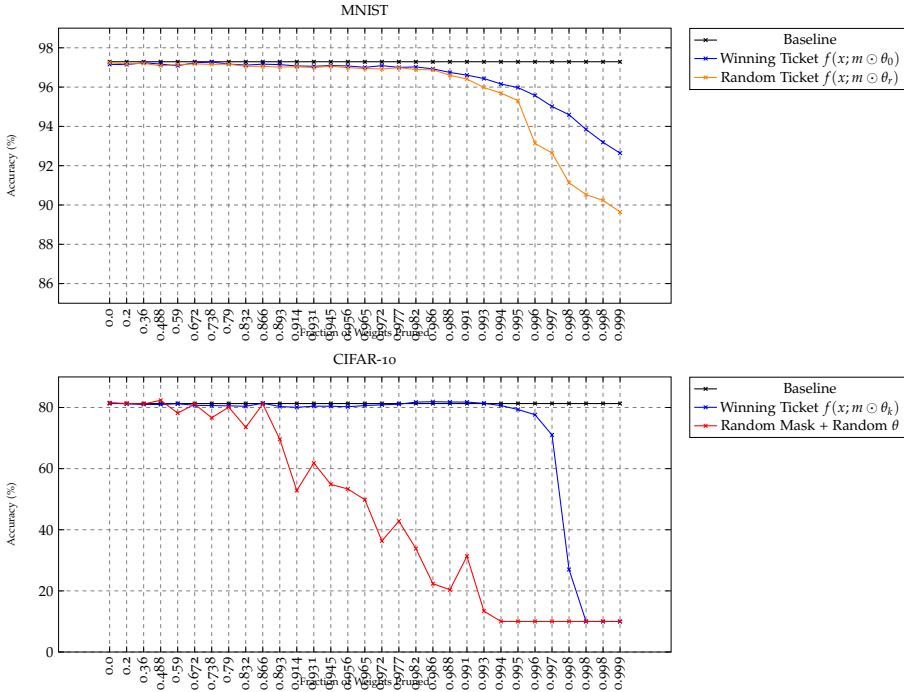


Figure 6: A visual representation of the performance of lottery winners that replicate the findings first presented by Frankle and Carbin [14]. In the first plot we consider a multilayer perceptron that gets trained on the MNIST dataset. After the network gets trained from scratch it obtains a final accuracy of $\approx 97\%$ as reported by the black line. We can observe that winning tickets $f(x; m \odot \theta_0)$ only start performing worse than the network they have been extracted from once a large fraction of their weights gets pruned. We can also observe how crucial it is to re-initialize the weights of the pruned models with the same weights that were used when initializing the unpruned model from scratch (θ_0). If random weights are used instead (θ_r), the pruned masks appear to be less robust to pruning (orange curve). In the second plot we show how important it is for a pruned model to come in the form of $f(x; \odot \theta_k)$ after training a ResNet-50 architecture on the CIFAR-10 dataset, since we show that it is not possible to simply extract any random subset of weights from a deep convolutional network and obtain a performance that is robust to pruning after randomly initializing the parameters of the model (red curve).

are that winning tickets generalize across datasets, within the natural image domain at least, and that tickets obtained from larger datasets typically generalize better. This opens the door to the transfer of winning tickets between datasets, which makes the high computational cost required to identify them much more acceptable practically, as this cost has to be paid only once and can be shared across datasets.

In this paper, we build on top of this latter work. While Morcos et al. [34] focused on the natural image domain, we investigate the possibility of transferring winning tickets obtained from the natural

image domain to datasets in non natural image domains. This question has an important practical interest as datasets in non natural image domains are typically scarcer than datasets in natural image domains. They would therefore potentially benefit more from a successful transfer of sparse networks, since the latter can be expected to require less data for training than large over-parametrized networks. Furthermore, besides studying their generalization capabilities, we also focus on another interesting property that characterizes models that win the LTH, and which so far has received less research attention. As originally presented in [14], pruned models which are the winners of the LTH can yield a final performance which is better than the one obtained by larger over-parametrized networks. In this work we explore whether it is worth seeking for such pruned models when training data is scarce, a scenario that is well known to constraint the training of deep neural networks. To answer these two questions, we carried out experiments on several datasets from two very different non natural image domains: digital pathology and digital heritage.

2.2 DATASETS

We consider seven datasets that come from two different, unrelated sources: histopathology and digital heritage. Each dataset comes with its training, validation and testing splits. Furthermore the datasets change in terms of size, resolution, and amount of labels that need to be classified. We report an overview about the size of these datasets in Table 4 while a visual representation of the samples constituting these datasets in Fig. 7. The Digital-PATHology (DP) data comes from the Cytomine [29] web application, an open-source platform that allows interdisciplinary researchers to work with large-scale images. While Cytomine has collected a large number of datasets over the years, in this work we have limited our analysis to a subset of four datasets that all represent tissues and cells from either human or animal organs: Human-LBA, Lung-Tissues, and Mouse-LBA were originally proposed in [35], while Bone-Marrow comes from [23]. All four datasets have been used in [35], that researched whether neural networks pre-trained on natural images could successfully be re-used in the DP domain. In this paper, we explore whether an alternative to the transfer-learning approaches presented in [35] could be based on training pruned networks that are the winners of the LTH. This will allow us to investigate the two research questions introduced in Sec. 2.1: we will explore whether winning initializations that are found on datasets of natural images do generalize to non-natural domains, and whether sparse models winners of the LTH can perform better than larger unpruned models that get trained from scratch. Regarding the field of Digital-Humanities (DH) we have created three novel datasets that all revolve around the classification of artworks. We consider two dif-

ferent classification tasks that have already been thoroughly studied by researchers bridging between the fields of Computer Vision (CV) and DH [32, 43, 46]. The first task consists in identifying the artist of the different artworks, while the second one aims at classifying which kind of artwork is depicted in the different images, a challenge which is usually referred to in the literature as type-classification [32, 43]. When it comes to the artist-classification task we have created two different datasets, which purpose will be better explained in Sec. 2.4.3. All images are publicly available as part of the WikiArt gallery [38] and can also be found within the large popular OmniArt dataset [47]. Albeit as we have seen in Chapter 1 in DH it is actually easier to find large datasets than in histopathology, it is worth mentioning that we have kept the size of these datasets intentionally small in order to fit the research questions introduced in Sec. 2.1. Furthermore, it is also worth noting that there are several additional challenges that need to be overcome when training deep neural networks on artistic collections, which therefore motivate the use of this kind of datasets in this work. The size, texture, and resolution of the images coming from the DH are usually representative of different time periods, artistic movements and might have gone through different digitization processes, which are all reasons that make these datasets largely varied and challenging.

Table 4: A brief overview of the seven different datasets which have been used in this work. As usual throughout this thesis N_t corresponds to the total amount of samples that are present in the dataset, while Q_t represents the number of classes.

Dataset	Training-Set	Validation-Set	Testing-Set	N_t	Q_t
Human-LBA	4051	346	1023	5420	9
Lung-Tissues	4881	562	888	6331	10
Mouse-LBA	1722	716	1846	4284	8
Bone-Marrow	522	130	639	1291	8
Artist-Classification-1	3103	389	389	3881	20
Type-Classification	2868	360	360	3588	20
Artist-Classification-2	2827	353	353	3533	19

2.3 EXPERIMENTAL SETUP

We follow an experimental set-up similar to the one that was introduced in [34] (and that has been validated by [17]). Let us define a neural network $f(x; \theta)$ that gets randomly initialized with parameters $\theta_0 \sim \mathcal{D}_\theta$ and then trained for j iterations over an input space \mathcal{X} , and an output space \mathcal{Y} . At the end of training a percentage of the parameters in θ_j gets pruned, a procedure which results in a mask m . The parameters in θ_j which did not get pruned are then reset to the values

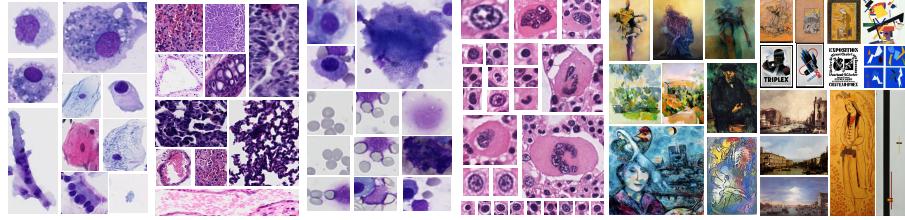


Figure 7: Some image samples that constitute the non-natural image datasets which have been used in this work. From left to right we have the Human-LBA, Lung-Tissues, Mouse-LBA and Bone-Marrow datasets, while finally we report some examples that represent artworks which come from the field of digital heritage and that are therefore similar to the images we have used for the experiments reported in Chapter 1.

they had at θ_k , where k represents an early training iteration. A winning ticket corresponds to the combination between the previously obtained mask, and the parameters θ_k , and is defined as $f(x; m \odot \theta_k)$ ¹. Constructing a winning ticket with parameters θ_k , instead of θ_0 , is a procedure which is known as late-resetting [16], and is a simple but effective trick that makes it possible to stably find winning initializations in deep convolutional neural networks [16, 34]. In this study $f(x; \theta)$ comes in the form of a ResNet-50 architecture [18] which gets trained on the three popular CV natural image datasets (visually represented in Fig. 8): CIFAR-10/100 and Fashion-MNIST. Following [18, 34], 31 winning tickets $f(x; m \odot \theta_k)$ of increasing sparsity are obtained from each of these three datasets by repeating 31 iterations of network training and magnitude pruning with a pruning rate of 20%. More precisely, at each pruning iteration, the network is trained for several epochs (using early stopping on the validation set as described in the appendix) and then the 20% of weights with the lowest magnitudes are pruned. The parameters θ_k that define each of the 31 tickets are then taken as the weights of the corresponding pruned networks at the k th epoch of the first pruning iteration. Once these pruned networks are found we aim at investigating whether their parameters θ_k contain inductive biases that allow them to generalize to the non-natural image domain. To do so we replace the final fully connected layer of each winning ticket with a randomly initialized layer that has as many output nodes as there are classes to classify. We then fine-tune each of these networks on the non-natural image datasets considered in this study. At the end of training, we study the performance of each winning ticket in two different ways. First, we compare the performance of each network to the performance of

¹ Note that this formulation generalizes the original version of the LTH [14] that we have represented in Fig. 5, where a winning ticket is obtained after resetting the unpruned parameters of the network to the values they had right after initialization, therefore defining a winning ticket as $f(x; m \odot \theta_0)$.



Figure 8: The three natural datasets used in our experiments to find winning tickets. From left to right samples from the CIFAR-10/100 and Fashion-MNIST datasets.

a fully unpruned network that gets randomly initialized and trained from scratch. Second, we also compare the performance of winning tickets that have been found on a natural image dataset to 31 new sparse models that are the winners of the LTH on the considered target dataset. Since it is not known to which extent pruned networks that contain weights that are the winners of the LTH on a natural image dataset can generalize to target distributions that do not contain natural images, we report the first results that investigate the potential of a novel transfer-learning scheme which has so far only been studied on datasets from the natural image domain. Moreover, testing the performance of sparse networks that contain winning tickets that are specific to a non-natural image target distribution also allows us to investigate whether it is worth pruning large networks with the hope of finding smaller models that might perform better than a large over-parametrized one. As mentioned in Sec. 2.1, pruned networks that are initialized with the winning weights can sometimes perform better than a fully unpruned network. Identifying such sparse networks leads to a very significant reduction of model size, which can be a very effective way of regularization when training data is scarce.

2.4 RESULTS

The results of all our experiments are visually reported in the plots of Fig. 9. Each line plot represents the final performance that is obtained by a pruned model that contains a winning ticket initialization on the final testing-set of our target datasets. This performance is reported on the y-axis of the plots, while on the x-axis we represent the fraction of weights that is pruned from the original ResNet-50 architecture. As explained in the previous section the performance of each winning ticket is compared to the performance that is obtained by an unpruned, over-parametrized architecture that is reported by the black dashed lines. The models that are the winners of the LTH on a natural image dataset are reported by the green, red and purple

lines, while the winners of the LTH on a non-natural target dataset are reported by the blue lines. Furthermore, when it comes to the latter lottery tickets, we also report the performance that is obtained by winning tickets that get randomly reinitialized ($f(x; m \odot \theta'_0)$ with $\theta'_0 \sim \mathcal{D}_\theta$). These results are reported by the orange lines. Shaded areas around all line plots correspond to ± 1 std. that has been obtained after repeating and averaging the results of our experiments over four different random seeds.

2.4.1 *On the Importance of Finding Winning Initializations*

We can start by observing that pruned models which happen to be the winners of the LTH either on a natural dataset, or on a non-natural one, can maintain a good final performance until large pruning rates are reached. This is particularly evident on the first three datasets, where models that keep only $\approx 1\%$ of their original weights barely suffer from any drop in performance. This gets a little bit less evident on the last three datasets, where the performance of winning ticket initializations that are directly found on the considered target dataset starts getting harmed once a fraction of $\approx 97\%$ of original weights are pruned. These results show that an extremely large part of the parameters of a ResNet-50 architecture can be considered as superfluous, therefore confirming the LTH when datasets contain non-natural images. More importantly, we also observe that pruned models winners of the LTH, significantly outperform larger over-parametrized models that get trained from scratch. This can be very clearly seen in all plots where the performance of pruned models is always consistently better than what is reported by the black dashed line. To get a better sense of how much these pruned networks perform better than their larger unpruned counterparts, we report in Table 5 the performance that is obtained by the best performing pruned model, found over all 31 possible pruned models, and compare it to the performance of an unpruned architecture. The exact fraction of weights which is pruned from an original ResNet-50 architecture is reported in Table 6 for each configuration. We can observe that no matter which dataset has been used as a source for finding a winning ticket initialization, all pruned networks reach a final accuracy that is significantly higher than the one that is obtained after training an unpruned model from scratch. While in most cases the difference in terms of performance is of $\approx 10\%$ (see e.g. the Human-LBA, Lung-Tissues and the Type-Classification datasets), it is worth highlighting that there are other cases in which this difference is even larger. This is the case for the Mouse-LBA and Artist-Classification-1 datasets where a winning ticket coming from the CIFAR-10 dataset performs more than 20% better than a model trained from scratch. These results show that in order to maximize the performance of deep networks it is always

worth finding and training pruned models which are the winners of the LTH.

Table 5: The results comparing the performance that is obtained on the testing-set by the best pruned model winner of the LTH, and an unpruned architecture trained from scratch. The overall best performing model is reported in a green cell, while the second best one in a yellow cell. We can observe that pruned models winners of the LTH perform significantly better than a larger over-parametrized architecture that gets trained from scratch. As can be seen by the results obtained on the Mouse-LBA and Artist-Classification-1 datasets the difference in terms of performance can be particularly large ($\approx 20\%$).

Target-Dataset	Scratch-Training	CIFAR-10	CIFAR-100	Fashion-MNIST	Target-Ticket
Human-LBA	71.85 \pm 1.12	79.17 \pm 1.85	76.97 \pm 0.73	77.32 \pm 1.85	81.72 \pm 0.39
Lung-Tissues	84.75 \pm 0.81	88.90 \pm 1.97	87.61 \pm 0.90	87.61 \pm 0.11	90.48 \pm 0.16
Mouse-LBA	48.17 \pm 1.18	74.20 \pm 2.04	57.42 \pm 0.48	52.27 \pm 1.73	68.20 \pm 3.79
Bone-Marrow	64.66 \pm 1.36	71.75 \pm 3.36	69.87 \pm 0.39	68.77 \pm 0.39	72.55 \pm 0.46
Artist-Classification-1	45.88 \pm 0.42	66.58 \pm 1.54	65.55 \pm 1.79	63.88 \pm 0.12	58.74 \pm 1.92
Type-Classification	41.36 \pm 2.31	58.63 \pm 2.97	60.56 \pm 0.44	58.92 \pm 0.59	50.44 \pm 2.23

Table 6: Some additional information about the lottery winners which performance is reported in Table 5. For each winning ticket we report the fraction of weights that is pruned from an original ResNet-50 architecture and that therefore characterizes the level of sparsity of the overall best performing lottery ticket. The results in the Scratch-Training column are not reported since these are unpruned models that are trained from scratch.

Target-Dataset	Scratch-Training	CIFAR-10	CIFAR-100	Fashion-MNIST	Target-Ticket
Human-LBA	-	0.945	0.79	0.886	0.832
Lung-Tissues	-	0.977	0.977	0.672	0.965
Mouse-LBA	-	0.972	0.893	0.738	0.931
Bone-Marrow	-	0.866	0.988	0.931	0.914
Artist-Classification-1	-	0.972	0.993	0.991	0.931
Type-Classification	-	0.991	0.931	0.995	0.963

2.4.2 On the Generalization Properties of Lottery Winners

We then investigate whether natural image tickets can generalize to the non-natural setting. Findings differ across datasets. When considering the datasets that come from the field of DP, we can see that, in three out of four cases, winning tickets that are found on a natural image dataset get outperformed by sparse winning networks that come after training a model on the biomedical dataset. This is particularly evident in the results obtained on the Human-LBA and Lung-Tissues datasets where the highest testing-set accuracy is consistently reached by the blue line plots. When it comes to the Bone-Marrow dataset the difference in terms of performance between the best natural image ticket, in this case coming from the CIFAR-10 dataset, and the one

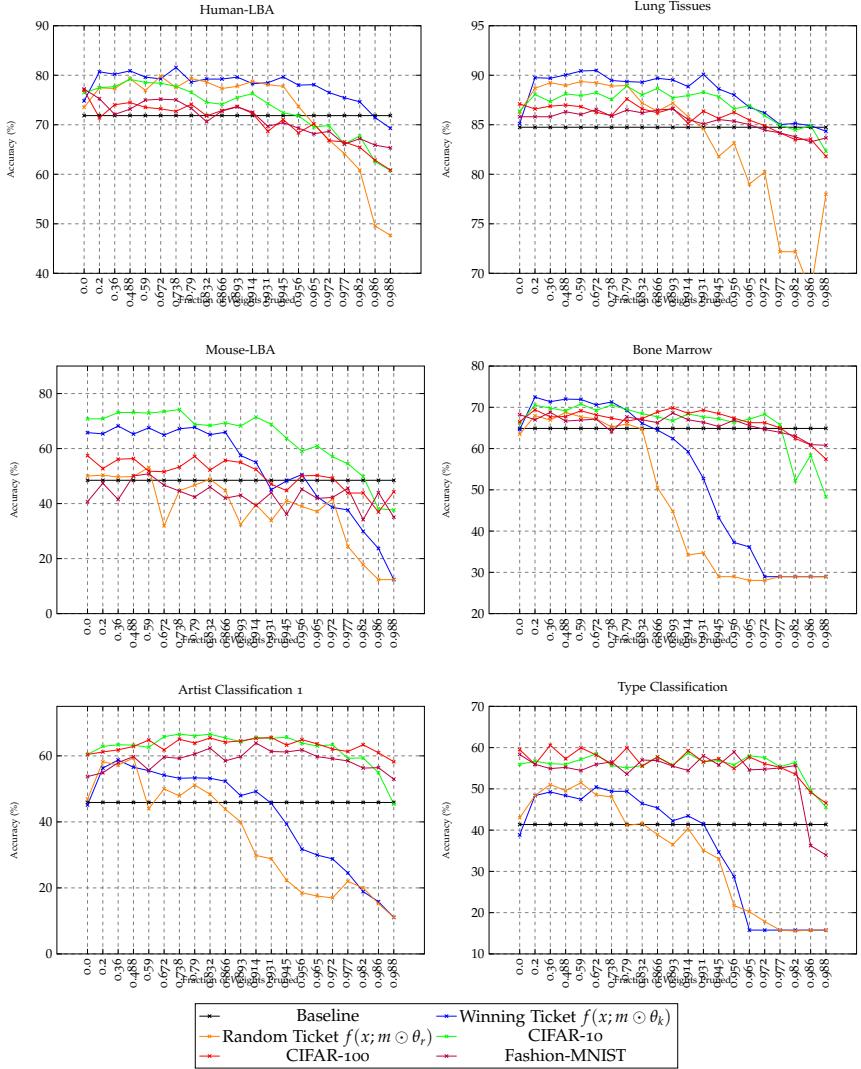


Figure 9: An overview of the results showing that sparse models that are the winners of the LTH (represented by the coloured lines) significantly outperform unpruned networks which get randomly initialized and trained from scratch (dashed black line). This happens to be the case on all tested datasets, no matter whether a winning initialization comes from a natural image source or not. It is however worth mentioning that, especially on the biomedical datasets, natural image tickets get outperformed by sparse networks that are the winners of the LTH on a biomedical dataset. On the other hand this is not the case when it comes to the classification of arts where natural image tickets outperform the ones which are found within artistic collections.

coming from the biomedical dataset, is less evident (see Table 5 for the exact accuracies). Furthermore, it is worth highlighting that on the Bone-Marrow dataset, albeit natural image models seem to get outperformed by the ones found on the biomedical dataset, the performance of the latter ones appears to be less stable once extremely large prun-

ing rates are reached. When it comes to the Mouse-LBA dataset these results slightly differ. In fact, this dataset corresponds to the only case where a natural image source ticket outperforms a non-natural one. As can be seen, by the green line plot, pruned models coming from the CIFAR-10 dataset outperform the ones found on the Mouse-LBA dataset. When focusing our analysis on the classification of arts, we see that the results change greatly from the ones obtained on the biomedical datasets. In this case, all of the natural image lottery winners, no matter the dataset they were originally found on, outperform the same kind of models that were found after training a full network on the artistic collection. We can see from Table 5 that the final testing performance is similar among all of the best natural image tickets. Similarly to what has been noticed on the Bone-Marrow dataset we can again observe that tickets coming from a non-natural data distribution seem to suffer more from large pruning rates.

These results show both the potential and the limitations that natural image winners of the LTH can offer when they are fine-tuned on datasets of non-natural images. The results obtained on the artistic datasets suggest that winning initializations contain inductive biases that are strong enough to get at least successfully transferred to the artistic domain, therefore confirming some of the claims that were made by Morcos et al. [34]. However, it also appears that there are stronger limitations to the transferability of winning initializations which were not observed by Morcos et al. [34]. In fact, our results show that on DP data the best strategy is to find a winning ticket directly on the biomedical dataset, and that winning initializations found on natural image datasets, albeit outperforming a randomly initialized unpruned network, perform worse than pruned models that are the winners of the LTH on a biomedical dataset.

2.4.3 Additional Studies

To characterize the transferability of winning initializations even more, while at the same time gaining a deeper understanding of the LTH, we have performed a set of three additional experiments which help us characterize this phenomenon even better.

2.4.3.1 Lottery Tickets VS fine-tuned pruned models

So far we have focused our transfer-learning study on lottery tickets that come in the form of $f(x; m \odot \theta_k)$, where, as mentioned in Sec. 2.3, θ_k corresponds to the weights that parametrize a neural network at a very early training iteration. This formalization is however different from more common transfer-learning scenarios like the ones we have explored in Chapter 1 where neural networks get transferred with the weights that are obtained at the end of the training process [35, 43]. We have therefore studied whether there is a difference

in terms of performance between transferring and fine-tuning a lottery ticket with parameters θ_k , and the same kind of pruned network which is initialized with the weights that are obtained once the network is fully trained on a source task. We define these kind of models as $f(x; m \odot \theta_i)$ where i stays for the last training iteration. We report some examples of this behaviour in the plots presented in Fig. 10, where we consider $f(x; m \odot \theta_i)$ models which were trained on the CIFAR-10 and CIFAR-100 datasets, and then transferred and fine-tuned on the Human-LBA dataset. We found that these models overall perform worse than lottery tickets, while also being less robust to pruning. This also shows that on this dataset, the slightly inferior performance of the natural image tickets with respect to the target tickets is not due to the weight re-initialization.

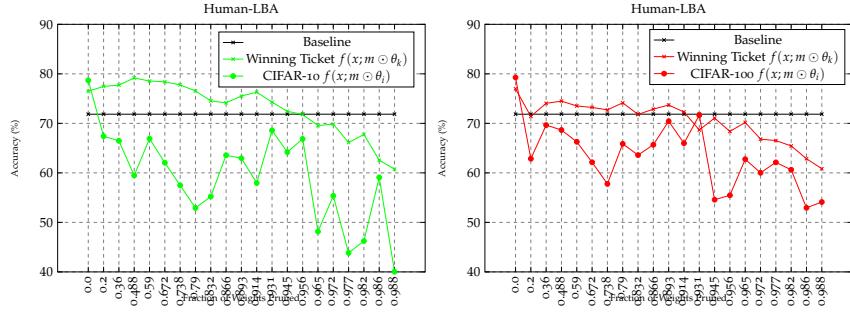


Figure 10: Our results showing the advantages of transferring lottery winners over pruned models that are fully fine-tuned on natural datasets (CIFAR-10/100). We can observe that their performance is overall inferior to the one of lottery tickets and that these models are significantly less robust to pruning. We believe that the reason behind their poor performance revolves around the fact that, once completely trained on a specific source task, and after having gone through the pruning stage, these models lose the necessary flexibility that is required for them to adapt to a new task.

2.4.3.2 Transferring tickets from similar non-natural domains

We investigated whether it is beneficial to fine-tune lottery winners that, instead of coming from a natural image distribution, come from a related non-natural dataset. Specifically we tested whether winning tickets generated on the Human-LBA dataset generalize to the Mouse-LBA one (since both datasets are representative of the field of Live-Blood-Analysis), and whether lottery winners coming from the Artist-Classification-1 dataset generalized to the Artist-Classification-2 one. We visually represent these results in Fig. 11. As one might expect, we found that it is beneficial to transfer winning tickets that come from a related source. Specifically, Human-LBA tickets can perform just as well as winning tickets that are generated on the Mouse-LBA dataset, while at the same time also being more robust to large prun-

ing rates. When it comes to lottery winners found on the Artist-Classification-1 dataset we have observed that these tickets can even outperform the ones generated on the Artist-Classification-2 one. Overall these results confirm the claims that we made in Chapter 1 where we already highlighted the benefits that could come from transferring models that were trained on a similar source as the target task. This conclusion now also holds for models that are the winners of the LTH.

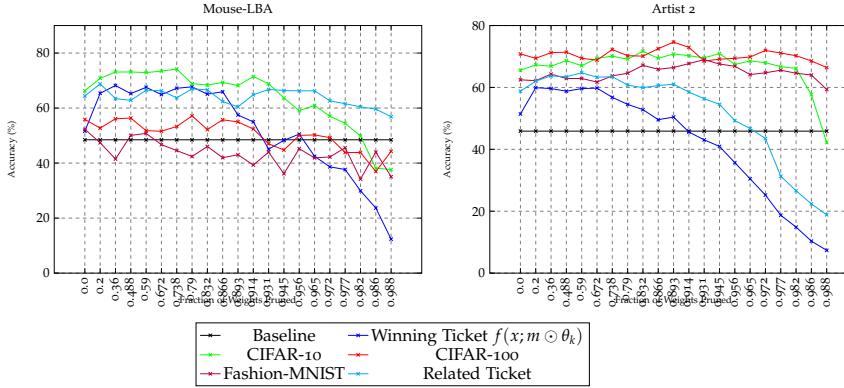


Figure 11: Our results showing the benefits of transferring lottery winners that have been identified on a related source task. We can observe that on the Mouse-LBA dataset, winning tickets that were obtained on the Human-LBA dataset are the ones that are the most robust ones to pruning, while on the Artist-Classification-2 dataset we can observe that lottery winners that have been obtained on the Artist-Classification-1 dataset are both more robust to pruning, while they also yield overall better performance.

2.4.3.3 On the size of the training set

We have observed from the blue line plots of Fig. 9 that there are cases in which lottery winners are very robust to extremely large pruning rates (see as an example the first and second plots), while there are other cases in which their performance deteriorates faster with respect to the fraction of weights that get pruned. The most robust performance is obtained by winning tickets that are generated on the Human-LBA and Lung-Tissues datasets, which are the two target datasets that contain the largest amount of training samples. We have therefore studied whether there is a relationship between the size of the training data that is used for finding lottery winners, and the robustness in terms of performance of the resulting pruned models. We generated lottery winners after incrementally reducing the size of the training data by 75%, 50% and 25%, and then investigated whether we could observe a similar drop in performance as the one we have observed in the last three blue line-plots of Fig. 9 once a large fraction of weights got pruned. Perhaps surprisingly, we have observed that this was not the case, and as can be seen by the plots represented

in Fig. 12, the performance of lottery winners that are found when using only 25% of the training set is just as stable as the one of winning tickets which are generated on the entire dataset. It is however worth mentioning that, albeit the performance of such sparse models is robust, their final performance on the testing set is lower than the one that is obtained by winning tickets that have been trained on the full training data distribution.

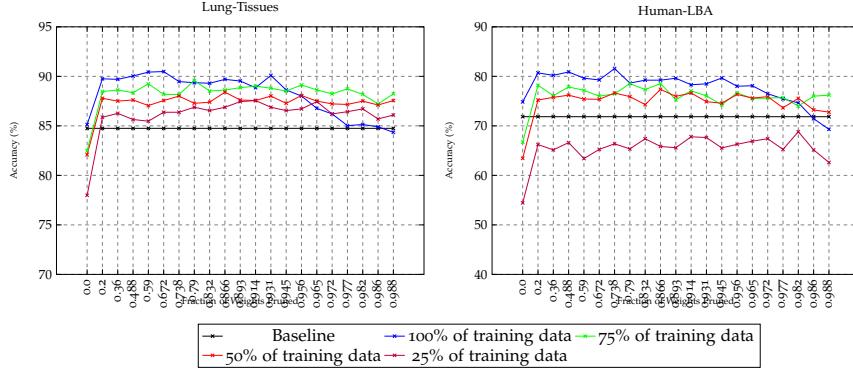


Figure 12: Our study showing that the robustness to large pruning rates of lottery winners does not depend from the size of the training dataset. We can observe that even when lottery tickets after are trained on only 25% of the dataset their performance remains stable with respect to the fraction of pruned weights. These results suggest that the less stable performance of Bone-Marrow lottery tickets observed in Fig. 9 does not depend from the small training set.

2.5 RELATED WORK

The research presented in this paper contributes to a better understanding of the LTH by exploring the generalization and transfer-learning properties of lottery tickets. The closest approach to what has been presented in this work is certainly [34], which shows that winning models can generalize across datasets of natural images and across different optimizers. As mentioned in Sec. 2.3, a large part of our experimental setup is based on this work. Besides the work presented in [34], there have been other attempts that aimed to better understand the LTH after studying it from a transfer-learning perspective. However, just as the study presented by Morcos et al. [34], all this research limited its analysis to natural images. Van Soelen and Sheppard [53] transfer winning tickets among different partitions of the CIFAR-10 dataset, while Mehta [31] shows that sparse models can successfully get transferred from the CIFAR-10 dataset to other object recognition tasks. While these results seem to suggest that lottery tickets contain inductive biases which are strong enough to generalize to different domains, it is worth highlighting that their transfer-

learning properties were only studied after considering the CIFAR-10 dataset as a possible source for winning ticket initializations, a limitation which we overcome in this work. It is also worth mentioning that the research presented in this paper is strongly connected to the work presented by Frankle et al. [16]. While the first paper that introduced the LTH limited its analysis to relatively simple neural architectures, such as multilayer perceptrons and convolutional networks which were tested on small CV datasets, the presence of winning initializations in larger, more popular convolutional models such as the ones that we used in Chapter 1 trained on large datasets [41] was only first presented by [16]. Since in this work we have used a ResNet-50 architecture [20], we have followed all the recommendations that were introduced in [16], for successfully identifying the winners of the LTH in larger models. More specifically we mention the late-resetting procedure which resets the weights of a pruned model to the weights that are obtained after k training iterations instead of to the values which were used at the beginning of training (as explained in Sec. 2.3), a procedure which has shown to be related to *linear mode connectivity* [15]. While the work presented in this paper has limited its analysis to networks that minimize an objective function that is relevant for classification problems, it is worth noting that more recent approaches have identified lottery winners in different training settings. Yu et al. [58] have shown that winning initializations can be found when neural networks are trained on tasks ranging from natural language processing to reinforcement learning, while Sun et al. [48] successfully identify sparse winning models in a multi-task learning scenario. As future work, we want to study whether lottery tickets can be found on different neural architectures, and also when neural networks are trained on CV tasks other than classification. More specifically we aim at studying whether winners of the LTH, which are found on popular natural image datasets such as [27] and [13] when tackling image localization and segmentation tasks, can generalize to non-natural settings which might include the segmentation of biomedical data, or the localization of objects within artworks.

2.6 CONCLUSION

We have investigated the transfer learning potential of pruned neural networks that are the winners of the LTH from datasets of natural images to datasets containing non-natural images. We have explored this in training conditions where the size of the training data is relatively small. All of the results presented in this work confirm that it is always beneficial to train a sparse model, winner of the LTH, instead of a larger over-parametrized one. Regarding our study on the transferability of winning tickets we have reported the first results which study this phenomenon under non-natural data distributions

by using datasets coming from the fields of digital pathology and heritage. While for the case of artistic data it seems that winning tickets from the natural image domain contain inductive biases which are strong enough to generalize to this specific domain, we have also shown that this approach can present stronger limitations when it comes to biomedical data. This probably stems from the fact that DP images are further away from natural images than artistic ones. We have also shown that lottery tickets perform significantly better than fully trained pruned models, that it is beneficial to transfer lottery winners from different, but related, non-natural sources, and that the performance of lottery tickets is not dependant on the size of the training data. To conclude, we provide a better characterization of the LTH while simultaneously showing that when training data is limited, the performance of deep neural networks can get significantly improved by using lottery winners over larger over-parametrized ones.

Part II

TRANSFER LEARNING IN REINFORCEMENT LEARNING

Part III
APPENDIX

A

APPENDIX TEST

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A.1 APPENDIX SECTION TEST

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A.2 ANOTHER APPENDIX SECTION TEST

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There is also a useless Pascal listing below: [Listing 1](#).

Listing 1: A floating example (listings manual)

```

1 for i:=maxint downto 0 do
begin
{ do nothing }
end;
```

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DECLARATION

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Saarbrücken, September 2015

André Miede

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