HOW TRANSFERABLE ARE FEATURES IN CONVOLUTIONAL NEURAL NETWORK ACOUSTIC MODELS ACROSS LANGUAGES?

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ABSTRACT

Characterization of the representations learned in intermediate layers of deep networks can provide valuable insight into the nature of a task and can guide the development of well-tailored learning strategies. Here we study convolutional neural network (CNN)-based acoustic models in the context of automatic speech recognition. Adapting a method proposed by [1], we measure the transferability of each layer between English, Dutch and German to assess their language-specificity. We observed three distinct regions of transferability: (1) the first two layers were entirely transferable between languages, (2) layers 2–8 were also highly transferable but we found some evidence of language specificity, (3) the subsequent fully connected layers were more language specific but could be successfully finetuned to the target language. To further probe the effect of weight freezing, we performed follow-up experiments using freeze-training [2]. Our results are consistent with the observation that CNNs converge 'bottom up' during training and demonstrate the benefit of freeze training, especially for transfer learning.

Index Terms— CNNs, acoustic modeling, interpretability, transfer learning, language-specificity, freeze training

1. INTRODUCTION

The acoustic properties of speech vary across languages. This is evidenced by the fact that monolingual acoustic models (AMs) are the de facto standard in automatic speech recognition (ASR), while multi-lingual AMs are an active area of development [3, 4, 5, 6]. Requiring large amounts of training data to build separate AMs for every language is a barrier to successful ASR systems for low-resource languages. Ideally, AMs would be designed to strategically leverage off-task data as much as possible. AMs often take the form of a deep network which learns to map from acoustic features to context-dependent phones in a language-specific phone set. It is not clear how exactly this transformation is performed or what is represented in the intermediate layers of such networks. Better characterization of the intermediate representations of AMs may help to guide data-efficient training procedures.

Similar characterizations of networks trained on visual tasks have inspired new transfer learning procedures. For example, [1] characterized the task specificity at each layer of a network trained on ImageNet using transferability as a proxy for task-specificity. This characterization motivated Adaptive Transfer Networks [7] where parts of a network are trained on the source domain while other parts of the network are finetuned or adapted to the target domain, preserving the limited target data for learning highly task-specific parameters. Similar adaptive transfer learning procedures may also prove to be useful for building AMs for low-resource (data-poor) languages. A necessary first step is to characterize the shape of the transition from task-general to task-specific representations through the layers of deep network-based AMs.

Much of the previous work on characterizing intermediate layers of deep networks has focused on relatively solvable tasks in the visual domain (e.g. hand written digit recognition, visual object recognition) [8]. Few studies have characterized the intermediate representations of networks trained on acoustic tasks [9, 10, 11], which, in practice, are not always trained long enough to converge completely (test error still slowly decreasing at the end of training) due to the long training time required. It is not clear to what extent existing methods developed to probe networks trained on visual tasks will be applicable and useful to study networks that may be underfitting on difficult acoustic tasks.

Here we studied convolutional neural networks (CNNs) used for ASR systems. We characterized the language-specificity of each layer across languages using an approach inspired by [1]. Subsets of a network previously trained on one language were 'implanted' into another network which was subsequently trained on a second language. The effect of the implant on performance indicated the language-specificity of the features in the implant. Our main contribution is the

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Table 1: Speech Data

	English	German	Dutch
Hours	82h:44m	67h:42m	63h:46m
Utterances	87906	62294	95350
Phoneset size	49	49	48

characterization of the language-specificity of intermediate layers of CNN-based acoustic models. We also demonstrate the adaptation of an analysis method originally designed to probe visual networks to study networks in an underfitting regime on a phone classification task. Additionally, follow up experiments explore the role of weight freezing in transfer learning.

2. EXPERIMENTS

The datasets for this experiment consisted of German, Dutch and American English speech, recorded in similar environments, with corresponding text transcriptions. We chose these languages because we expected a large degree of transferability based on their phonetic similarity. Logarithmic Mel filter bank features were calculated, creating a 45-dimensional feature vector for every 10ms of audio (spectrograms). Each observation was associated with one of 9000 context-dependent phone classes (language-specific). A summary of the speech data can be found in Table 1.

2.1. Baseline models

For each language, a CNN consisting of nine convolutional layers followed by three fully connected layers was trained to recognize context-dependent phones. The architecture was as follows, where triplets specify the filter size and number of feature maps in each convolutional layer and the singletons specify how many units in each fully connected layer: (7, 7, 1024), (3, 3, 256), (3, 3, 256), (3, 3, 128), (3, 3, 128), (3, 3, 128), (3, 3, 64), (3, 3, 64), (3, 3, 64), (600), (190), (9000). This resulted in a total of approximately 7.2 million parameters. All networks were trained using the ADAM optimizer [12] as implemented in Tensorflow [13] with a minibatch size of 256, a starting learning rate of $10e^{-5}$ and rectified linear units. Approximately 98% of the data was used for training and the remaining 2% for testing. All model parameters were replicated on four GPUs. Different minibatches were given to each GPU and their gradients were averaged to calculate updates. As a balance between training time and accuracy, each network was trained for a fixed period of 100 epochs (which took approximately two weeks).

2.2. Experimental setup

The subsequent experimental setup was similar to that described in [1]. Several ‘network surgeries‘ were performed. The first n layers of a network trained on Language A were implanted into a new network of identical architecture where the layers after layer n were randomly initialized. This ‘chimera’ network was further trained in four different ways. It was either trained on Language A (self-transfer or ‘selfer‘ network) or Language B (transfer network) and the implanted parameters were either fixed or allowed to be finetuned during training. This process was repeated $\forall\ 1 \leq n \leq 11$ and for all pairs of languages resulting in a total of 198 networks (see Figure 1 in [1] for a graphical depiction of a similar experimental setup). The selfer networks served as a control to capture any changes in performance associated with the surgery but unrelated to the transfer. As in [1], we also measured the effect of leaving the first n layers untrained, i.e. fixed at their random initialization, while training subsequent layers normally. All networks were trained for 100 epochs. Training parameters were identical to those of the baseline models.

3. RESULTS

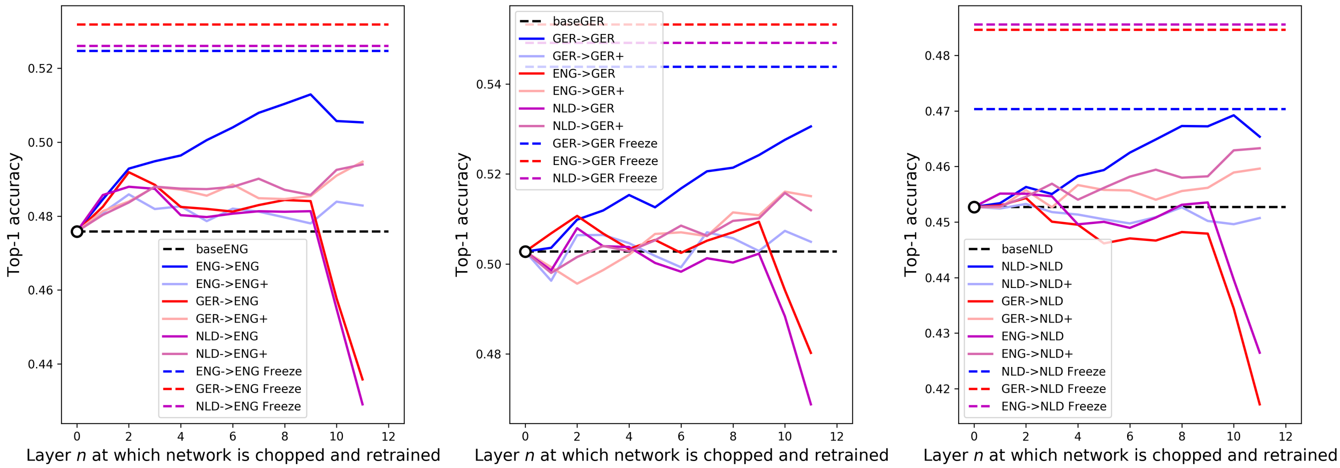
We found representations throughout the networks to be highly transferable between all three languages. Top-1 test phone classification accuracy for each network is plotted as a function of the layer at which the surgery was performed in Figure 1. Phone classification accuracy is measured with respect to per frame phone-labels established in a forced alignment.

3.1. Transfer networks

The only models that performed considerably worse than the monolingual baseline models were the transfer networks without finetuning whose surgery occurred at one of the fully connected layers (the penultimate two layers). Transfer networks cut at any of the convolutional layers performed as well as the monolingual baseline model, regardless of whether the implanted layers were finetuned or not. We observed a slight improvement over the monolingual baseline (1.3 percentage points (pp)) for transfer networks with finetuning chopped at one of the fully connected layers.

3.2. Selfer networks

All selfer networks with finetuning performed at the same level as the mono-lingual baseline. Somewhat unexpectedly, the selfer networks without finetuning performed best overall among the chimera networks. Selfer networks chopped at late layers whose implants were not finetuned showed an improvement of 2.7 pp.



(a) Test on English

(b) Test on German

(c) Test on Dutch

Fig. 1: Test accuracy as a function of depth after 100 epochs. The plus sign indicates that the implanted pretrained layers were finetuned. Th dashed black line indicates the performance of the monolingual baseline models. Up to the ninth layer, layers trained on one language could be copied directly (without finetuning) in a network whose subsequent layers were trained on another language with little to no loss in performance compared to baseline. Selfer networks without finetuning show an improvement compared to baseline. Freeze trained transfer networks yielded the best overall performance. The pattern is similar for all three languages.

3.3. Random features

Previous work has shown that random, untrained weights can often perform remarkably well in certain scenarios [14, 15]. Figure 2 shows accuracy as a function of the layer at which training began, meaning that layers below layer n were randomly initialized and never updated. We observed a gradual drop in performance as a function of the depth at which training began. Random weights in early layers did not have a large impact on performance. Using random weights for all but the last layer resulted in near-chance performance. This verifies the non-triviality of the success of our transfer networks without finetuning.

3.4. Freeze Training

The training of our selfer networks without finetuning somewhat resembles the *freeze training* procedure proposed by [2]. According to this procedure, layers are successively frozen over the course of training, gradually reducing the number of parameters to be updated until, by the end of training, only the last layer is being updated. We hypothesized that weight freezing partly explained the success of our selfer networks without finetuning, so we created freeze trained versions of both our selfer and transfer networks. Starting with a pretrained network, layers 1–11 (excluding layer 0) were trained for 5 epochs. Then, for the next 5 epochs, only layers 2–11 were trained. From then on, another layer was removed from the trainable parameters every 10 epochs for a total of 100 training epochs. The freeze trained models are represented by the coloured dashed lines in Figure 1. All freeze trained networks outperformed all other networks. The freeze trained transfer networks performed best overall, achieving 4.5 pp above baseline on average.

4. DISCUSSION

Our results suggest that, despite a large degree of transferability of intermediate acoustic features between languages, naive approaches to transfer (e.g. initializing with parameters from another language) are not the most effective nor the most efficient. In particular, early layers need not be finetuned on the target language at all. Subsequent layers benefit greatly from freeze training on the target language. These freeze trained transfer networks outperform all networks trained solely on the target language, which demonstrates the improved generalization that can be achieved when incorporating data from multiple sources.

There are many differences between the current experiments and those presented in [1] (task, domain, architecture). While comparison between these studies is not straightforward, it may still aid interpretation of our results. To what extent do these characterizations apply to all convolutional architectures and tasks, in which case we expect alignment of our results, and to what extent can the deviations that we observe be explained by the particulars of our task or setup?

The performance of the networks with finetuning is

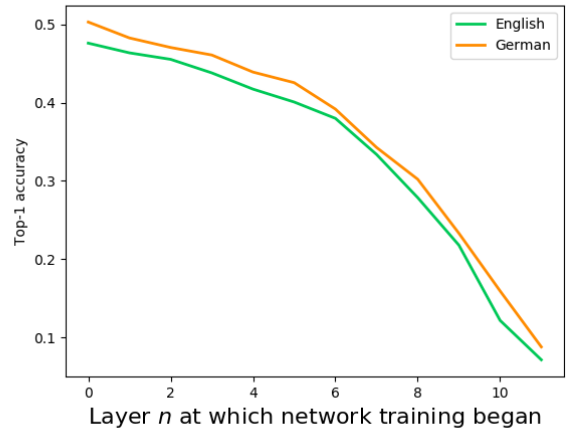


Fig. 2: Using random weights up to layer n. The leftmost points represent the baseline models. Performance decays gradually as more layers are left untrained, only reaching near-chance performance when nearly all layers are random.

largely consistent with [1]. However, the performance of networks without finetuning deviates considerably. The transfer networks without finetuning in [1] show a gradual drop in performance, starting at the 4th convolutional layer and eventually dropping nearly 8 pp by the penultimate layer (see Figure 2 from [1]). Our transfer networks without finetuning, on the other hand, show a sharp drop in performance that starts only at the first fully connected layer (layer 9). For the selfer networks without finetuning, we did not observe a performance drop when networks were chopped at middle layers, as was reported in [1]. Instead, our selfer networks without finetuning outperformed all other 'chimera' networks, with accuracy increasing nearly monotonically with the depth at which the surgery was performed. Finally, [1]'s experiments with random weights quickly drop to near-chance performance by layer 3, whereas our networks with random weights decline gradually with depth, only approaching near-chance performance when all but the last layer are random.

The success of our selfer networks without finetuning is at least partly explained by the fact that we are in an underfitting regime. Unlike in [1], our baseline model has not converged completely and we would expect continued training to improve performance. However, if that were the only factor at play, we would also expect our selfer networks with finetuning to show improvement over baseline, but they do not. This difference between selfer networks with and without finetuning may be explained by weight freezing and the fact that smaller networks train faster [16]. However, we don't see a benefit of weight freezing in the transfer networks without finetuning. Something about freezing all but the last layer(s) facilitates a 2.7 pp improvement over baseline in the selfer but not the transfer networks. This suggests that there is some important language-specific information in the layers that show a difference between the selfer and transfer networks without finetuning (layer 3 and above). Layers 10 and 11 show worse than baseline performance for the transfer network without finetuning, indicating a larger degree of language-specificity in these representations.

Our freeze training results corroborate the interpretation that weight freezing is responsible for the success of our selfer networks without finetuning. Furthermore, our freeze-trained transfer networks performed best overall, demonstrating that freeze training can actually recover the language-specific information lacking in our transfer networks without finetuning, yielding improved generalization. This likely reflects the observation from [2] that CNNs converge 'bottom-up' during training, with early layers stabilizing earlier in training. Relatedly, [17] state the proposition that no intermediate layer of a multi-layer neural network will contain more target-related information than the raw input, which requires a 'bottom-up' flow of information; intermediate layers cannot pass on target-related information that they do not receive. Thus, we conclude that freezing the weights of a given layer can only improve performance if that layer already passes on the target-related information in a representation that can be disentangled by subsequent layers. This was not generally the case in our transfer chimera networks because important language-specific information was not being conveyed. The progressive freeze training regime, proposed by [2], allowed this important language-specific information to be learned, whereas generic fine-tuning did not. In this way, making fewer parameter updates actually led to significant performance gains.

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