

Solving Large-scale Spatial Problems with Convolutional Neural Networks

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Abstract—Over the past decade, deep learning research has been accelerated by increasingly powerful hardware, which facilitated rapid growth in the model complexity and the amount of data ingested. This is becoming unsustainable and therefore refocusing on efficiency is necessary. In this paper, we employ transfer learning to improve training efficiency for large-scale spatial problems. We propose that a convolutional neural network (CNN) can be trained on small windows of signals, but evaluated on arbitrarily large signals with little to no performance degradation, and provide a theoretical bound on the resulting generalization error. Our proof leverages shift-equivariance of CNNs, a property that is underexploited in transfer learning. The theoretical results are experimentally supported in the context of mobile infrastructure on demand (MID). The proposed approach is able to tackle MID at large scales with hundreds of agents, which was computationally intractable prior to this work.

Index Terms—convolutional neural networks, transfer learning, deep learning, stationary process

I. INTRODUCTION

Over the past decade, there has been a rapid advancement in machine learning (ML), particularly in deep learning, which has produced state-of-the-art results in a wide range of applications [1]–[3]. This progress has been fueled by increasingly powerful hardware [1], [2] that has enabled the processing of larger datasets [4] and the training of deep learning models with more parameters. Theoretical evidence [5], [6] and empirical evidence [7], [8] suggest that using overparametrized models and larger datasets benefits neural network training. Large language models, such as GPT-3, with 175 billion parameters trained on a dataset of approximately 374 billion words, represent a new extreme in this trend [9]–[12]. However, the trend of increasing model complexity and dataset size is not sustainable in the long term due to diminishing returns on costs of computation and data acquisition [13], [14]. Moreover, some applications lack data availability, making this strategy impossible. Therefore, it is necessary to refocus on efficiency and explore more sustainable ML approaches.

Transfer learning [15]–[18] is a powerful tool for efficient and sustainable ML. It refers to a set of methodologies to apply knowledge learned from a source domain to a different target domain. For example, in [19] the authors demonstrate that it is consistently beneficial to pre-train a convolutional neural

network (CNN) on ImageNet before fine-tuning on medical images. In this case, transfer learning is especially beneficial because of the unavailability of large medical image datasets.

CNNs are one of the most popular deep learning architectures [2], especially for image classification [20]. Although initially used for image processing, they have proven useful for a wide variety of other signals such as text, audio, weather, ECG data, traffic data and many others [2], [21], [22]. Shift-equivariance is an interesting property of CNNs. When there are no dilations, any translation of the input to the CNN will also translate the output by the same amount. Previous works focus on leveraging this property to achieve translation invariant image classification [23], [24]. However, it is difficult to exploit shift-equivariance for small images with deep architectures [25], [26]. Nevertheless, our work shows that shift-equivariance is fundamental for efficient large-scale image-to-image regression tasks, as we explain below.

In this paper, we use CNNs and transfer learning to tackle large-scale spatial problems. In particular, we leverage the shift-equivariance property of CNNs to efficiently train when the input-output signals are jointly stationary. Our analysis uses stochastic process theory to provide a bound on the generalization error of CNNs. The derived bound implies that a CNN can be trained on small signal windows, yet evaluated on arbitrarily large windows with minimal performance loss. Following, our theoretical result, we propose to recast spatial problems as image-to-image prediction tasks and use CNNs to solve them on a large scale. The proposed framework is applied to mobile infrastructure on demand (MID) tasks [27]. Our experimental results showcase that transfer learning with CNNs can tackle MID at scales that were previously considered intractable. Our main contributions are summarized as follows.

- (C1) Provide a bound on CNN generalization error after training on a small window and executing on arbitrarily large signals.
- (C2) Propose how to reinterpret large-scale spatial problems as image-to-image tasks.
- (C3) Demonstrate the proposed method by solving the MID problem at scale.

Notation: We denote a stochastic process as $\{X(t)\}$, where

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Lingjun Ying



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