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 overparameterized 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

Solving Large Scale Problems In Mechanics

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Solving Large Scale Problems In Mechanics:

Solving Large-scale Problems in Mechanics Manolis Papadrakakis,1993-06-01 Solving Large Scale Problems in Mechanics The Development and Application of Computational Solution Methods M Paradrakakis National Technical University of Athens Greece This book consists of a number of self contained chapters written by internationally acclaimed leading researchers It deals with the application of computational solution methods for handling large scale problems in mechanics The techniques explored here are applicable to any problem in the field where available computing power is liable to be stretched to its limit Emphasis is given to computational procedures suitable to computing systems with vector and parallel architectures Each chapter proceeds logically first with theory then with algorithmic computational analysis and finally applications to real problems This is a comprehensive state of the art treatment of theory and practice illustrated by extensive numerical examples which should serve as an essential reference book on the subject   **Wiley Series in Solving Large-scale Problems in Mechanics** ,19??   Solution of Superlarge Problems in Computational Mechanics James H. Kane,2012-12-06 There is a need to solve problems in solid and fluid mechanics that currently exceed the resources of current and foreseeable supercomputers The issue revolves around the number of degrees of freedom of simultaneous equations that one needs to accurately describe the problem and the computer storage and speed limitations which prohibit such solutions The goals of tHis symposium were to explore some of the latest work being done in both industry and academia to solve such extremely large problems and to provide a forum for the discussion and prognostication of necessary future direc tions of both man and machine As evidenced in this proceedings we believe these goals were met Contained in this volume are discussions of iterative solvers and their application to a variety of problems e g structures fluid dynamics and structural acoustics iterative dynamic substructuring and its use in structural acoustics the use of the boundary element method both alone and in conjunction with the finite element method the application of finite difference methods to problems of incompressible turbulent flow and algorithms amenable to concurrent computations and their applications Furthermore discussions of existing computational shortcomings from the big picture point of view are presented that include recommendations for future work   **Computational Mechanics '95** S.N. Atluri,G. Yagawa,Thomas A. Cruse,2013-11-11 AI in the earlier conferences Tokyo 1986 Atlanta 1988 Melbourne 1991 and Hong Kong 1992 the response to the call for presentations at ICES 95 in Hawaii has been overwhelming A very careful screening of the extended abstracts resulted in about 500 paper being accepted for presentation Out of these written versions of about 480 papers reached the conference secretariat in Atlanta in time for inclusion in these proceedings The topics covered at ICES 95 range over the broadest spectrum of computational engineering science The editors thank the international scientific committee for their advice and encouragement in making ICES 95 a successful scientific event Special thanks are expressed to the International Association for Boundary Elements Methods for hosting IABEM 95 in conjunction with ICES 95 The editors here express their deepest

gratitude to Ms Stacy Morgan for her careful handling of a myriad of details of ICES 95 often times under severe time constraints The editors hope that the readers of this proceedings will find a kaleidoscopic view of computational engineering in the year 1995 as practiced in various parts of the world Satya N Atluri Atlanta Georgia USA Genki Yagawa Tokyo Japan Thomas A Cruse Nashville TN USA Organizing Committee Professor Genki Yagawa University of Tokyo Japan Chair Professor Satya Atluri Georgia Institute of Technology U S A **High Performance Computing for Computational Science - VECPAR 2002** José M.L.M. Palma,2003-04-07 This book constitutes the thoroughly refereed post proceedings of the 5th International Conference on High Performance Computing for Computational Science VECPAR 2002 held in Porto Portugal in June 2002 The 45 revised full papers presented together with 4 invited papers were carefully selected during two rounds of reviewing and improvement The papers are organized in topical sections on fluids and structures data mining computing in chemistry and biology problem solving environments computational linear and non linear algebra cluster computing imaging and software tools and environments *Electromagnetic Properties of Multiphase Dielectrics* Tarek I. Zohdi,2012-04-09 Recently several applications primarily driven by microtechnology have emerged where the use of materials with tailored electromagnetic dielectric properties are necessary for a successful overall design The tailored aggregate properties are achieved by combining an easily moldable base matrix with particles having dielectric properties that are chosen to deliver desired effective properties In many cases the analysis of such materials requires the simulation of the macroscopic and microscopic electromagnetic response as well as its resulting coupled thermal response which can be important to determine possible failures in hot spots This necessitates a stress analysis Furthermore because oftentimes such processes initiate degratory chemical processes it can be necessary to also include models for these processes as well A central objective of this work is to provide basic models and numerical solution strategies to analyze the coupled response of such materials by direct simulation using standard laptop desktop equipment Accordingly this monograph covers 1 The foundations of Maxwell s equations 2 Basic homogenization theory 3 Coupled systems electromagnetic thermal mechanical and chemical 4 Numerical methods and 5 An introduction to select biological problems The text can be viewed as a research monograph suitable for use in an upper division undergraduate or first year graduate course geared towards students in the applied sciences mechanics and mathematics that have an interest in the analysis of particulate materials *Advances in Groundwater Pollution Control and Remediation* Mustafa Aral ARAL,2013-11-11 In the past decades environmental scientists economists and physicists have been juggling critical issues within environmental strategies and environmental management styles in order to find a feasible medium between limited resources long term demands and objectives and interest groups In the search for best management alternatives practice has undergone a pendulum swing between stages that can be characterised as frontier economics radical environmentalism resource management allocation selective environmentalism and sustainable environmental management The next stage of management must answer such questions as Can there be a

global uniform environmental strategy or Based on their characteristics can different issues different regions and different applications have unique environmental strategies Based on this premise the next stage of management may be identified as risk based sustainable environmental management The goal of this style will be the risk based long term harmonious management of economic resources and environmental preservation for health safety and prosperity of sustainable populations When evaluation of risk or risk based ranking of management alternatives enter the picture as part of the overall puzzle then social policy ethics and health issues assume a very important role in the management strategy Economic incentives and environmental constraints have to be considered harmoniously the main emphasis being placed on protection and preservation of human health and the long term sustaining of populations **Surface Effects and Contact Mechanics X** J. T. M. De Hosson,C. A. Brebbia,2011 Contact mechanics and surface effects as well as their interaction are important in modern engineering The life and performance of structural components is affected by surface conditions such as wear corrosion and high cycle fatigue Surface treatments that address contact conditions can reduce costs by extending the life of components These are the subjects of a biennial conference first held in 1993 the papers from the latest of which are collected in this volume The book discusses Computer simulation Surface modification Surface treatments Surface problems in contact mechanics Contact mechanics Applications and case studies Indentation and hardness Thick and thin coatings Corrosion problems Nano characterisation Test methodology Multiscale experiments and modelling and Fracture fatigue and mechanics **Advanced Methods for Groundwater Pollution Control** Guiseppe Gambolati,Giorgio Verri,2014-05-04 In recent years the analysis control preservation remediation and correct management of underground resources have received a growing attention in a variety of sectors including industrial professional and academic environments The volume describes new developments in both applied research and design technology to maintain sustainability of a vital resource groundwater which is continuously threatened by contamination resulting from solid waste disposal operations site reutilization intensive extraction accidental leakage of spill in working installations and non point source pollution in agriculture It is directed to managers professionals and researchers working in any of the areas concerned with the control prediction and remediation of soil and groundwater contamination An Introduction to Computational Micromechanics Tarek I. Zohdi,Peter Wriggers,2008-03-15 In this its second corrected printing Zohdi and Wriggers illuminating text presents a comprehensive introduction to the subject The authors include in their scope basic homogenization theory microstructural optimization and multifield analysis of heterogeneous materials This volume is ideal for researchers and engineers and can be used in a first year course for graduate students with an interest in the computational micromechanical analysis of new materials **Applied Mechanics Reviews** ,1968 *Simulation of Manufacturing Sequences of Functionally Graded Structures* Gleim, Tobias,2017-02-10 The current paper establishes an axisymmetric model for an inductive heating process Therein the fully coupled MAXWELL equations assuming a temperature dependent permeability are combined with the non linear heat

conduction equation to yield a monolithic solution strategy The latter is based on a consistent linearization together with a higher order finite element discretization using GALERKIN S method in space For the temporal discretization the generalized Newmark methods higher order RUNGE KUTTA methods and discontinuous and continuous GALERKIN methods are used Furthermore the residual error is introduced to open an alternative way to obtain a numerically efficient estimation of the time integration accuracy Simulation results of the electric magnetic and thermal fields are provided together with parameter studies concerning spatial discretization frequency dependence and penetration depth of the heating zone Another topic analyzed is the residual error and its estimation quality regarding polynomial degree and time step size A further aspect of this work is the investigation of the thermal fluid structure interaction with respect to functionally graded materials Different coupling strategies for the acceleration of the fixed point iteration in each time step is in the foreground Relaxation methods as well as extrapolation methods make it possible to significantly reduce the number of fixed point iterations At the same time an adaptive strategy with higher order RUNGE KUTTA methods can provide a further advantage in combination with acceleration methods   **Computer Methods in Biomechanics and Biomedical Engineering 2** J. Middleton,Gyan Pande,M. L. Jones,2020-09-11 Contains papers presented at the Third International Symposium on Computer Methods in Biomechanics and Biomedical Engineering 1997 which provide evidence that computer based models and in particular numerical methods are becoming essential tools for the solution of many problems encountered in the field of biomedical engineering The range of subject areas presented include the modeling of hip and knee joint replacements assessment of fatigue damage in cemented hip prostheses nonlinear analysis of hard and soft tissue methods for the simulation of bone adaptation bone reconstruction using implants and computational techniques to model human impact Computer Methods in Biomechanics and Biomedical Engineering also details the application of numerical techniques applied to orthodontic treatment together with introducing new methods for modeling and assessing the behavior of dental implants adhesives and restorations For more information visit the http www uwcm ac uk biorome international symposium on Computer Methods in Biomechanics and Biomedical Engineering home page or http www gbhap com Computer_Methods_Biomechanic s_Biome dical_Engineering the home page for the journal   Introduction to Numerical Continuation Methods Eugene L. Allgower,Kurt Georg,2003-01-01 Numerical continuation methods have provided important contributions toward the numerical solution of nonlinear systems of equations for many years The methods may be used not only to compute solutions which might otherwise be hard to obtain but also to gain insight into qualitative properties of the solutions Introduction to Numerical Continuation Methods originally published in 1979 was the first book to provide easy access to the numerical aspects of predictor corrector continuation and piecewise linear continuation methods Not only do these seemingly distinct methods share many common features and general principles they can be numerically implemented in similar ways Introduction to Numerical Continuation Methods also features the piecewise linear approximation of

implicitly defined surfaces the algorithms of which are frequently used in computer graphics mesh generation and the evaluation of surface integrals **Nonlinear Finite Element Methods** Peter Wriggers,2008-11-04 Finite element methods have become ever more important to engineers as tools for design and optimization now even for solving non linear technological problems However several aspects must be considered for finite element simulations which are specific for non linear problems These problems require the knowledge and the understanding of theoretical foundations and their finite element discretization as well as algorithms for solving the non linear equations This book provides the reader with the required knowledge covering the complete field of finite element analyses in solid mechanics It is written for advanced students in engineering fields but serves also as an introduction into non linear simulation for the practising engineer

Computational Contact Mechanics Peter Wriggers,Tod A. Laursen,2008-04-01 Topics of this book span the range from spatial and temporal discretization techniques for contact and impact problems with small and finite deformations over investigations on the reliability of micromechanical contact models over emerging techniques for rolling contact mechanics to homogenization methods and multi scale approaches in contact problems Furthermore solution algorithms for single and multi processor computing environments enabling methods that span from multi contact to multi scale approaches are discussed together with numerical experiments related to soil mechanics using discontinuous deformation analysis

Mechanical Behaviors of Carbon Nanotubes K.M. Liew,Yan Jianwei,Lu-Wen Zhang,2016-12-25 Mechanical Behaviors of Carbon Nanotubes Theoretical and Numerical Approaches presents various theoretical and numerical studies on mechanical behaviors of carbon nanotubes The main theoretical aspects included in the book contain classical molecular dynamics simulation atomistic continuum theory atomic finite element method continuum plate nonlocal continuum plate and shell models Detailed coverage is also given to structural and elastic properties trace of large deformation buckling and post buckling behaviors fracture vibration characteristics wave propagation and the most promising engineering applications This book not only illustrates the theoretical and numerical methods for analyzing the mechanical behavior of carbon nanotubes but also contains computational results from experiments that have already taken place Covers various theoretical and numerical studies giving readers a greater understanding of the mechanical behavior of carbon nanotubes Includes multiscale methods that provide the advantages of atomistic and continuum approaches helping readers solve complex large system engineering problems Allows engineers to create more efficient carbon nanotube structures and devices

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