

HEX and Neurodynamic Programming

Debangshu Banerjee,

Abstract—Hex is a complex game with a high branching factor. For the first time Hex is being attempted to be solved without the use of game tree structures and associated methods of pruning. We also are abstaining from any heuristic information about Virtual Connections or Semi Virtual Connections which were previously used in all previous known computer versions of the game. The H-search algorithm which was the basis of finding such connections and had been used with success in previous Hex playing agents has been forgone. Instead what we use is reinforcement learning through self play and approximations through neural networks to by pass the problem of high branching factor and maintaining large tables for state-action evaluations. Our code is based primarily on Neuroflex. The inspiration is drawn from the recent success of AlphaGo Zero.

Keywords—Hex, Convolution Neural Networks, Recurrent Neural Networks, Reinforcement Learning, Projected Bellman Error

I. INTRODUCTION TO THE GAME OF HEX

HEX is a two-person board game invented by Danish mathematician Piet Hien in 1942 at Neils Bohr Institute and independently by Nobel-Laureate John Nash in 1948 at Princeton University [1]. Hex is a strategy game, that gives high significance to the players' decision-tree style thinking and situational awareness in determining the outcome [1]. The board consists of hexagonal grids called cells arranged to form a rhombus. Typically $n \times n$ boards are used with championships being held on 11×11 boards. Players alternate placing markers on unoccupied cells in an attempt to link the opposite sides of their board in a continuous chain.

A. Hex and Mathematics

The current area of research related to Hex can be found in areas of topology, graph and matroid theory, combinatorics, game theory, computer heuristics, artificial intelligence [1]. Hex is a connection game [1] in which players try to connect the opposite edges using their pieces by employing strategical decisions. It is a Maker-Breaker type positional game [1] which is described as : the Maker wins by capturing all positions that lead to a connection, while if the game ends with all positions claimed but the Maker not having won, it implies the Breaker has won. This brings to the first theorem about Hex that Hex cannot end in a draw [1], [2]. Though John Nash is credited for the proof [2] there is no supporting material. The proof is credited to David Gale, American Mathematician and Economist, University of California, Berkley [2].

Hex is a perfect information game [1], which means that each player while making a decision is perfectly informed

about all events that have previously happened. The condition of perfect information and no-draw makes Hex a determined game which means that for all instances of the game there is a winning strategy for one of the players [1].

This brings us to the most famous theorem about Hex, that the first player has the winning strategy [2]. This theorem was proved by John Nash using a strategy-stealing argument [2].

David Gale's proof that Hex cannot end in a draw uses a graph theory lemma [2]. A simple graph with nodes having degree at most 2 can be shown to be a union of disjoint sets of either isolated nodes, simple cycles or simple paths. By constructing a subgraph from the original Hex graph by including only special edges, the nodes of the subgraph is shown to have degree at most two. The lemma is then applied to show existence of simple paths between opposite edges [2]. That Hex cannot end in a draw has been shown equivalent to the existence of the two dimensional Brouwer fixed-point by David Gale [2]. The Brouwer fixed-point theorem was key to proving the existence of Nash Equilibrium [2].

B. HEX and Computers

With Nash's theorem about first person having the winning strategy, people were interested in solving the game of Hex by hand as well as by computers [3] .

The first hex playing machine was constructed in 1950 by Claude Shannon and E. F. Moore [4]. It was an analog machine. A two-dimensional potential field was set up corresponding to the playing board. With black trying to connect the top and bottom edges, black pieces and the top and bottom edges were given negative charge and white pieces were given positive charge along with the two sides. The move to be made was specified by a certain saddle point in the potential field. The machine performed reasonably well and won about 70 percent of the games with opening moves.

However, until recently, machines had never been able to challenge human capability [3]. To understand the complexity of Hex, note that the game-tree search techniques that are applicable in chess becomes less useful in Hex because of the large branching factor. A standard 11×11 board in Hex has on an average 100 legal moves compared to 38 for chess [5].

Another blow to the hopes of finding good algorithms to solve Hex came in 1976, when Shimon Even and Robert Tarjan showed the problem of determining which player has a winning strategy in Shannon's Switching Game is PSPACE complete [6] and finally in 1981 Stefan Reisch proved PSPACE completeness for $N \times N$ Hex [7]. These results indicate that there is little chance of having a polynomial time algorithm which could find a winning strategy.

Still there are many results about the solution of Hex which deserve a mention :

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Neurodynamic Programming

**Dimitri Bertsekas, Angelia
Nedic, Asuman Ozdaglar**



Neurodynamic Programming:

Neuro-Dynamic Programming Dimitri Bertsekas, John N. Tsitsiklis, 1996-11-01 This is historically the first book that fully explained the neuro dynamic programming reinforcement learning methodology a breakthrough in the practical application of neural networks and dynamic programming to complex problems of planning optimal decision making and intelligent control Neuro dynamic programming uses neural network approximations to overcome the curse of dimensionality and the curse of modeling that have been the bottlenecks to the practical application of dynamic programming and stochastic control to complex problems The methodology allows systems to learn about their behavior through simulation and to improve their performance through iterative reinforcement This book provides the first systematic presentation of the science and the art behind this exciting and far reaching methodology It develops a comprehensive analysis of reinforcement learning algorithms and guides the reader to their successful application through case studies from complex problem areas It contains material that is not available elsewhere in book form such as a comprehensive and rigorous analysis of temporal difference methods Q learning and error bounds associated with various methods

Adaptive Dynamic Programming with Applications in Optimal Control Derong Liu, Qinglai Wei, Ding Wang, Xiong Yang, Hongliang Li, 2017-01-04 This book covers the most recent developments in adaptive dynamic programming ADP The text begins with a thorough background review of ADP making sure that readers are sufficiently familiar with the fundamentals In the core of the book the authors address first discrete and then continuous time systems Coverage of discrete time systems starts with a more general form of value iteration to demonstrate its convergence optimality and stability with complete and thorough theoretical analysis A more realistic form of value iteration is studied where value function approximations are assumed to have finite errors Adaptive Dynamic Programming also details another avenue of the ADP approach policy iteration Both basic and generalized forms of policy iteration based ADP are studied with complete and thorough theoretical analysis in terms of convergence optimality stability and error bounds Among continuous time systems the control of affine and nonaffine nonlinear systems is studied using the ADP approach which is then extended to other branches of control theory including decentralized control robust and guaranteed cost control and game theory In the last part of the book the real world significance of ADP theory is presented focusing on three application examples developed from the authors work renewable energy scheduling for smart power grids coal gasification processes and water gas shift reactions Researchers studying intelligent control methods and practitioners looking to apply them in the chemical process and power supply industries will find much to interest them in this thorough treatment of an advanced approach to control

[Encyclopedia of Optimization](#) Christodoulos A. Floudas, Panos M. Pardalos, 2008-09-04 The goal of the Encyclopedia of Optimization is to introduce the reader to a complete set of topics that show the spectrum of research the richness of ideas and the breadth of applications that has come from this field The second edition builds on the success of the former edition with more than 150 completely new entries designed to ensure that the

reference addresses recent areas where optimization theories and techniques have advanced Particularly heavy attention resulted in health science and transportation with entries such as Algorithms for Genomics Optimization and Radiotherapy Treatment Design and Crew Scheduling Neural Information Processing Long Cheng,Andrew Chi Sing Leung,Seiichi Ozawa,2018-12-03 The seven volume set of LNCS 11301 11307 constitutes the proceedings of the 25th International Conference on Neural Information Processing ICONIP 2018 held in Siem Reap Cambodia in December 2018 The 401 full papers presented were carefully reviewed and selected from 575 submissions The papers address the emerging topics of theoretical research empirical studies and applications of neural information processing techniques across different domains The 7th and final volume LNCS 11307 is organized in topical sections on robotics and control biomedical applications and hardware **Soft Computing and Intelligent Systems** Madan M. Gupta,1999-10-28 The field of soft computing is emerging from the cutting edge research over the last ten years devoted to fuzzy engineering and genetic algorithms The subject is being called soft computing and computational intelligence With acceptance of the research fundamentals in these important areas the field is expanding into direct applications through engineering and systems science This book cover the fundamentals of this emerging filed as well as direct applications and case studies There is a need for practicing engineers computer scientists and system scientists to directly apply fuzzy engineering into a wide array of devices and systems

Advances in Neural Networks - ISSN 2024 Xinyi Le,Zhijun Zhang,2024-07-06 This volume constitutes the refereed proceedings of the 18th International Symposium on Neural Networks ISSN 2024 held in Weihai China during 11 14 July 2024 The 59 full papers were carefully reviewed and selected from 82 submission They are categorized in the following sections Optimization Algorithms Adversarial Learning Transfer Learning and Deep Learning Signal Image and Video Processing Modeling Analysis and Implementation of Neural Networks Control Systems Robotics and Autonomous Driving Fault Diagnosis and Intelligent Industry Bio signal Bioinformatics and Biomedical Engineering Adaptive Learning Methods for Nonlinear System Modeling Danilo Comminiello,Jose C. Principe,2018-06-11 Adaptive Learning Methods for Nonlinear System Modeling presents some of the recent advances on adaptive algorithms and machine learning methods designed for nonlinear system modeling and identification Real life problems always entail a certain degree of nonlinearity which makes linear models a non optimal choice This book mainly focuses on those methodologies for nonlinear modeling that involve any adaptive learning approaches to process data coming from an unknown nonlinear system By learning from available data such methods aim at estimating the nonlinearity introduced by the unknown system In particular the methods presented in this book are based on online learning approaches which process the data example by example and allow to model even complex nonlinearities e g showing time varying and dynamic behaviors Possible fields of applications of such algorithms includes distributed sensor networks wireless communications channel identification predictive maintenance wind prediction network security vehicular networks active noise control information forensics and security tracking control in

mobile robots power systems and nonlinear modeling in big data among many others This book serves as a crucial resource for researchers PhD and post graduate students working in the areas of machine learning signal processing adaptive filtering nonlinear control system identification cooperative systems computational intelligence This book may be also of interest to the industry market and practitioners working with a wide variety of nonlinear systems Presents the key trends and future perspectives in the field of nonlinear signal processing and adaptive learning Introduces novel solutions and improvements over the state of the art methods in the very exciting area of online and adaptive nonlinear identification Helps readers understand important methods that are effective in nonlinear system modelling suggesting the right methodology to address particular issues *Neural Information Processing* Derong Liu, Shengli Xie, Yuanqing Li, Dongbin Zhao, El-Sayed M.

El-Alfy, 2017-11-07 The six volume set LNCS 10634 LNCS 10635 LNCS 10636 LNCS 10637 LNCS 10638 and LNCS 10639 constitutes the proceedings of the 24rd International Conference on Neural Information Processing ICONIP 2017 held in Guangzhou China in November 2017 The 563 full papers presented were carefully reviewed and selected from 856 submissions The 6 volumes are organized in topical sections on Machine Learning Reinforcement Learning Big Data Analysis Deep Learning Brain Computer Interface Computational Finance Computer Vision Neurodynamics Sensory Perception and Decision Making Computational Intelligence Neural Data Analysis Biomedical Engineering Emotion and Bayesian Networks Data Mining Time Series Analysis Social Networks Bioinformatics Information Security and Social Cognition Robotics and Control Pattern Recognition Neuromorphic Hardware and Speech Processing Artificial Neural Networks in Finance and Manufacturing Kamruzzaman, Joarder, Begg, Rezaul, Sarker, Ruhul, 2006-03-31 This book presents a variety of practical applications of neural networks in two important domains of economic activity finance and manufacturing Provided by publisher *Adaptive Dynamic Programming for Control* Huaguang Zhang, Derong Liu, Yanhong Luo, Ding Wang, 2012-12-14

There are many methods of stable controller design for nonlinear systems In seeking to go beyond the minimum requirement of stability Adaptive Dynamic Programming in Discrete Time approaches the challenging topic of optimal control for nonlinear systems using the tools of adaptive dynamic programming ADP The range of systems treated is extensive affine switched singularly perturbed and time delay nonlinear systems are discussed as are the uses of neural networks and techniques of value and policy iteration The text features three main aspects of ADP in which the methods proposed for stabilization and for tracking and games benefit from the incorporation of optimal control methods infinite horizon control for which the difficulty of solving partial differential Hamilton Jacobi Bellman equations directly is overcome and proof provided that the iterative value function updating sequence converges to the infimum of all the value functions obtained by admissible control law sequences finite horizon control implemented in discrete time nonlinear systems showing the reader how to obtain suboptimal control solutions within a fixed number of control steps and with results more easily applied in real systems than those usually gained from infinite horizon control nonlinear games for which a pair of mixed optimal policies

are derived for solving games both when the saddle point does not exist and when it does avoiding the existence conditions of the saddle point Non zero sum games are studied in the context of a single network scheme in which policies are obtained guaranteeing system stability and minimizing the individual performance function yielding a Nash equilibrium In order to make the coverage suitable for the student as well as for the expert reader Adaptive Dynamic Programming in Discrete Time establishes the fundamental theory involved clearly with each chapter devoted to a clearly identifiable control paradigm demonstrates convergence proofs of the ADP algorithms to deepen understanding of the derivation of stability and convergence with the iterative computational methods used and shows how ADP methods can be put to use both in simulation and in real applications This text will be of considerable interest to researchers interested in optimal control and its applications in operations research applied mathematics computational intelligence and engineering Graduate students working in control and operations research will also find the ideas presented here to be a source of powerful methods for furthering their study

Neural Information Processing Tingwen Huang,Zhigang Zeng,Chuangdong Li,Chi Sing Leung,2012-11-05 The five volume set LNCS 7663 LNCS 7664 LNCS 7665 LNCS 7666 and LNCS 7667 constitutes the proceedings of the 19th International Conference on Neural Information Processing ICONIP 2012 held in Doha Qatar in November 2012 The 423 regular session papers presented were carefully reviewed and selected from numerous submissions These papers cover all major topics of theoretical research empirical study and applications of neural information processing research The 5 volumes represent 5 topical sections containing articles on theoretical analysis neural modeling algorithms applications as well as simulation and synthesis

Numerical Analysis and Optimization Mehiddin Al-Baali,Lucio Grandinetti,Anton Purnama,2018-05-31 This volume contains 13 selected keynote papers presented at the Fourth International Conference on Numerical Analysis and Optimization Held every three years at Sultan Qaboos University in Muscat Oman this conference highlights novel and advanced applications of recent research in numerical analysis and optimization Each peer reviewed chapter featured in this book reports on developments in key fields such as numerical analysis numerical optimization numerical linear algebra numerical differential equations optimal control approximation theory applied mathematics derivative free optimization methods programming models and challenging applications that frequently arise in statistics econometrics finance physics medicine biology engineering and industry Any graduate student or researcher wishing to know the latest research in the field will be interested in this volume This book is dedicated to the late Professors Mike JD Powell and Roger Fletcher who were the pioneers and leading figures in the mathematics of nonlinear optimization

Advances in Neural Networks- ISSN 2013 Chengan Guo,Zeng-Guang Hou,Zhigang Zeng,2013-07-04 The two volume set LNCS 7951 and 7952 constitutes the refereed proceedings of the 10th International Symposium on Neural Networks ISSN 2013 held in Dalian China in July 2013 The 157 revised full papers presented were carefully reviewed and selected from numerous submissions The papers are organized in following topics computational

neuroscience cognitive science neural network models learning algorithms stability and convergence analysis kernel methods large margin methods and SVM optimization algorithms variational methods control robotics bioinformatics and biomedical engineering brain like systems and brain computer interfaces data mining and knowledge discovery and other applications of neural networks

Holonic and Multi-Agent Systems for Manufacturing Vladimir Marik, Duncan McFarlane, Paul Valckenaers, 2004-01-24 The increasing complexity of manufacturing systems as well as the overall demands for flexible and fault tolerant control of production processes stimulates among many others two key emerging technologies that are already making an important breakthrough in the field of intelligent manufacturing control and diagnostics These two paradigms are the holonic approach based on the event driven control strategy usually aimed at modular control systems that are directly physically linked with the manufacturing hardware equipment and the multi agent approach developed in the area of distributed information processing The research communities working in both these fields are approaching the problem of intelligent manufacturing from different viewpoints and until recently to a certain extent in an independent way We can however observe quite a clear convergence of these fields in the last few years the communities have started to cooperate joining efforts to solve the painful problems involved in achieving effective industrial practice We can see convergence in the terminology standards and methods being applied

Neural Information Processing Sabri Arik, Tingwen Huang, Weng Kin Lai, Qingshan Liu, 2015-12-08 The four volume set LNCS 9489 LNCS 9490 LNCS 9491 and LNCS 9492 constitutes the proceedings of the 22nd International Conference on Neural Information Processing ICONIP 2015 held in Istanbul Turkey in November 2015 The 231 full papers presented were carefully reviewed and selected from 375 submissions The 4 volumes represent topical sections containing articles on Learning Algorithms and Classification Systems Artificial Intelligence and Neural Networks Theory Design and Applications Image and Signal Processing and Intelligent Social Networks

Neural Information Processing Mohammad Tanveer, Sonali Agarwal, Seiichi Ozawa, Asif Ekbal, Adam Jatowt, 2023-04-12 The three volume set LNCS 13623 13624 and 13625 constitutes the refereed proceedings of the 29th International Conference on Neural Information Processing ICONIP 2022 held as a virtual event November 22-26 2022 The 146 papers presented in the proceedings set were carefully reviewed and selected from 810 submissions They were organized in topical sections as follows Theory and Algorithms Cognitive Neurosciences Human Centered Computing and Applications The ICONIP conference aims to provide a leading international forum for researchers scientists and industry professionals who are working in neuroscience neural networks deep learning and related fields to share their new ideas progress and achievements

Control of Complex Systems Kyriakos Vamvoudakis, Sarangapani Jagannathan, 2016-07-27 In the era of cyber physical systems the area of control of complex systems has grown to be one of the hardest in terms of algorithmic design techniques and analytical tools The 23 chapters written by international specialists in the field cover a variety of interests within the broader field of learning adaptation optimization and networked control The editors have grouped these

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Convex Analysis and Optimization

Dimitri Bertsekas, Angelia Nedic, Asuman Ozdaglar, 2003-03-01 A uniquely pedagogical insightful and rigorous treatment of the analytical geometrical foundations of optimization The book provides a comprehensive development of convexity theory and its rich applications in optimization including duality minimax saddle point theory Lagrange multipliers and Lagrangian relaxation nondifferentiable optimization It is an excellent supplement to several of our books Convex Optimization Theory Athena Scientific 2009 Convex Optimization Algorithms Athena Scientific 2015 Nonlinear Programming Athena Scientific 2016 Network Optimization Athena Scientific 1998 and Introduction to Linear Optimization Athena Scientific 1997 Aside from a thorough account of convex analysis and optimization the book aims to restructure the theory of the subject by introducing several novel unifying lines of analysis including

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Neural Information Processing Akira Hirose, Seiichi Ozawa, Kenji Doya, Kazushi Ikeda, Minh Lee, Derong Liu, 2016-09-30 The four volume set LNCS 9947 LNCS 9948 LNCS 9949 and LNCS 9950 constitutes the proceedings of the 23rd International Conference on Neural Information Processing ICONIP 2016 held in Kyoto Japan in October 2016 The 296 full papers presented were carefully reviewed and selected from 431 submissions The 4 volumes are organized in topical sections on deep and reinforcement learning big data analysis neural data analysis robotics and control bio inspired energy efficient information processing whole brain architecture neurodynamics bioinformatics biomedical engineering data mining and cybersecurity workshop machine learning neuromorphic hardware sensory perception pattern recognition social networks brain machine interface computer vision time series analysis data driven approach for extracting latent features topological and graph based clustering methods computational intelligence data mining deep neural networks computational and cognitive neurosciences theory and algorithms

Decision Making: Neural and Behavioural Approaches, 2013-01-10 This well established international series examines major areas of basic and clinical research within neuroscience as well as emerging and promising subfields This volume explores interdisciplinary research on decision making taking a neural and behavioural approach Leading authors review the state of the art in their field of investigation and provide their views and perspectives for future research Chapters are extensively referenced to provide readers with a comprehensive list of resources on the topics covered All chapters include comprehensive background information and are written in a clear form that is also accessible to the non specialist

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