Lifelong Machine Learning

Second Edition

Synthesis Lectures on Artificial Intelligence and Machine Learning

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ISBN: 978-3-031-00453-7 paperback
ISBN: 978-3-031-01581-6 ebook
ISBN: 978-3-031-02709-3 epub
ISBN: 978-3-031-00026-3 hardcover

DOI 10.1007/978-3-031-01581-6

A Publication in the Springer series
SYNTHESIS LECTURES ON ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

Lecture #38
Series Editors: Ronald J. Brachman, *Jacobs Technion-Cornell Institute at Cornell Tech*
Peter Stone, *University of Texas at Austin*
Series ISSN
Print 1939-4608 Electronic 1939-4616

Lifelong Machine Learning

Second Edition

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SYNTHESIS LECTURES ON ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING #38

ABSTRACT

Lifelong Machine Learning, Second Edition is an introduction to an advanced machine learning paradigm that continuously learns by accumulating past knowledge that it then uses in future learning and problem solving. In contrast, the current dominant machine learning paradigm learns in isolation: given a training dataset, it runs a machine learning algorithm on the dataset to produce a model that is then used in its intended application. It makes no attempt to retain the learned knowledge and use it in subsequent learning. Unlike this isolated system, humans learn effectively with only a few examples precisely because our learning is very knowledge-driven: the knowledge learned in the past helps us learn new things with little data or effort. Lifelong learning aims to emulate this capability, because without it, an AI system cannot be considered truly intelligent.

Research in lifelong learning has developed significantly in the relatively short time since the first edition of this book was published. The purpose of this second edition is to expand the definition of lifelong learning, update the content of several chapters, and add a new chapter about continual learning in deep neural networks—which has been actively researched over the past two or three years. A few chapters have also been reorganized to make each of them more coherent for the reader. Moreover, the authors want to propose a unified framework for the research area. Currently, there are several research topics in machine learning that are closely related to lifelong learning—most notably, multi-task learning, transfer learning, and meta-learning—because they also employ the idea of knowledge sharing and transfer. This book brings all these topics under one roof and discusses their similarities and differences. Its goal is to introduce this emerging machine learning paradigm and present a comprehensive survey and review of the important research results and latest ideas in the area. This book is thus suitable for students, researchers, and practitioners who are interested in machine learning, data mining, natural language processing, or pattern recognition. Lecturers can readily use the book for courses in any of these related fields.

KEYWORDS

lifelong machine learning; lifelong learning; continuous learning; continual learning; meta-learning, never-ending learning; multi-task learning; transfer learning

Zhiyuan dedicates this book to his wife, Vena Li, and his parents.

Bing dedicates this book to his wife, Yue He; his children, Shelley and Kate; and his parents.

Contents

Preface

The purpose of writing this second edition is to extend the definition of lifelong learning, to update the content of several chapters, and to add a new chapter about *continual learning in deep neural networks*, which has been actively researched for the past two to three years. A few chapters are also reorganized to make each of them more coherent.

The project of writing this book started with a tutorial on *lifelong machine learning* that we gave at the 24th International Joint Conference on Artificial Intelligence (IJCAI) in 2015. At that time, we had worked on the topic for a while and published several papers in ICML, KDD, and ACL. When Morgan & Claypool Publishers contacted us about the possibility of developing a book on the topic, we were excited. We strongly believe that lifelong machine learning (or simply lifelong learning) is very important for the future of machine learning and artificial intelligence (AI). Note that lifelong learning is sometimes also called *continual learning* or *continuous learning* in the literature. Our original research interest in the topic stemmed from extensive application experiences in sentiment analysis (SA) in a start-up company several years ago. A typical SA project starts with a client who is interested in consumer opinions expressed in social media about their products or services and those of their competitors. There are two main analysis tasks that an SA system needs to do: (1) discover the entities (e.g., *iPhone*) and entity attributes/features (e.g., *battery life*) that people talked about in opinion documents such as online reviews and (2) determine whether the opinion about each entity or entity attribute is positive, negative, or neutral [Liu, 2012, 2015]. For example, from the sentence "*iPhone is really cool, but its battery life sucks,*" an SA system should discover that the author is (1) positive about *iPhone* and (2) negative about iPhone's *battery life*.

After working on many projects in many domains (which are types of products or services) for clients, we realized that there is a great deal of sharing of information across domains and projects. As we see more and more, new things get fewer and fewer. It is easy to see that sentiment words and expressions (such as *good*, *bad*, *poor*, *terrible*, and *cost an arm and a leg*) are shared across domains. There is also a great deal of sharing of entities and attributes. For example, every product has the attribute of *price*, most electronic products have *battery*, and many of them also have *screen*. It is silly not to exploit such sharing to significantly improve SA to make it much more accurate than without using such sharing but only working on each project and its data in isolation. The classic machine learning paradigm learns exactly in isolation. Given a dataset, a learning algorithm runs on the data to produce a model. The algorithm has no memory and thus is unable to use the previously learned knowledge. In order to exploit knowledge sharing, an SA system has to retain and accumulate the knowledge learned in the past and use it to help future learning and problem solving, which is exactly what *lifelong learning* aims to do.

It is not hard to imagine that this sharing of information or knowledge across domains and tasks is generally true in every field. It is particularly obvious in natural language processing because the meanings of words and phrases are basically the same across domains and tasks and so is the sentence syntax. No matter what subject matter we talk about, we use the same language, although each subject may use only a small subset of the words and phrases in a language. If that is not the case, it is doubtful that a natural language would have ever been developed by humans. Thus, lifelong learning is generally applicable, not just restricted to sentiment analysis.

The goal of this book is to introduce this emerging machine learning paradigm and to present a comprehensive survey and review of the important research results and latest ideas in the area. We also want to propose a unified framework for the research area. Currently, there are several research topics in machine learning that are closely related to lifelong learning, most notably, multi-task learning and transfer learning, because they also employ the idea of knowledge sharing and transfer. This book brings all these topics under one roof and discusses their similarities and differences. We see lifelong learning as an extension to these related paradigms. Through this book, we would also like to motivate and encourage researchers to work on lifelong learning. We believe it represents a major research direction for both machine learning and artificial intelligence for years to come. Without the capability of retaining and accumulating knowledge learned in the past, making inferences about it, and using the knowledge to help future learning and problem solving, achieving artificial general intelligence (AGI) is unlikely.

Two main principles have guided the writing of this book. First, it should contain strong motivations for conducting research in lifelong learning in order to encourage graduate students and researchers to work on lifelong learning problems. Second, the writing should be accessible to practitioners and upper-level undergraduate students who have basic knowledge of machine learning and data mining. Yet there should be sufficient in-depth materials for graduate students who plan to pursue Ph.D. degrees in the machine learning and/or data mining fields.

This book is thus suitable for students, researchers, and practitioners who are interested in machine learning, data mining, natural language processing, or pattern recognition. Lecturers can readily use the book in class for courses in any of these related fields.

Zhiyuan Chen and Bing Liu
August 2018

Acknowledgments

We would like to thank the current and former graduate students in our group and our collaborators: Geli Fei, Zhiqiang Gao, Estevam R. Hruschka Jr., Wenpeng Hu, Minlie Huang, Yongbing Huang, Doo Soon Kim, Huayi Li, Jian Li, Lifeng Liu, Qian Liu, Guangyi Lv, Sahisnu Mazumder, Arjun Mukherjee, Nianzu Ma, Lei Shu, Tao Huang, William Underwood, Hao Wang, Shuai Wang, Hu Xu, Yueshen Xu, Tim Yin, Tim Yuan, and Yuanlin Zhang, for their contributions of numerous research ideas and helpful discussions over the years. We are especially grateful to the two expert reviewers of the first edition, Eric Eaton and Matthew E. Taylor. Despite their busy schedules, they read the first draft of the book very carefully and gave us so many excellent comments and suggestions, which were not only insightful and comprehensive, but also detailed and very constructive. German I. Parisi reviewed Chapter 4 of this second edition and gave us many valuable comments. Their suggestions have helped us improve the book tremendously.

On the publication side, we thank the editors of Synthesis Lectures on Artificial Intelligence and Machine Learning, Ronald Brachman, William W. Cohen, and Peter Stone, for initiating this project. The President and CEO of Morgan & Claypool Publishers, Michael Morgan, and his staff, Christine Kiilerich, and C.L. Tondo have given us all kinds of help promptly whenever requested, for which we are very grateful.

Our greatest gratitude go to our own families. Zhiyuan Chen would like to thank his wife Vena Li and his parents. Bing Liu would like to thank his wife Yue, his children Shelley and Kate, and his parents. They have helped in so many ways.

The writing of this book was partially supported by two National Science Foundation (NSF) grants IIS-1407927 and IIS-1650900, an NCI grant R01CA192240, a research gift from Huawei Technologies, and a research gift from Robert Bosch GmbH. The content of the book is solely the responsibility of the authors and does not necessarily represent the official views of the NSF, NCI, Huawei, or Bosch. The Department of Computer Science at the University of Illinois at Chicago provided computing resources and a very supportive environment for this project. Working at Google has also given Zhiyuan Chen a broader perspective on machine learning.

Zhiyuan Chen and Bing Liu
August 2018