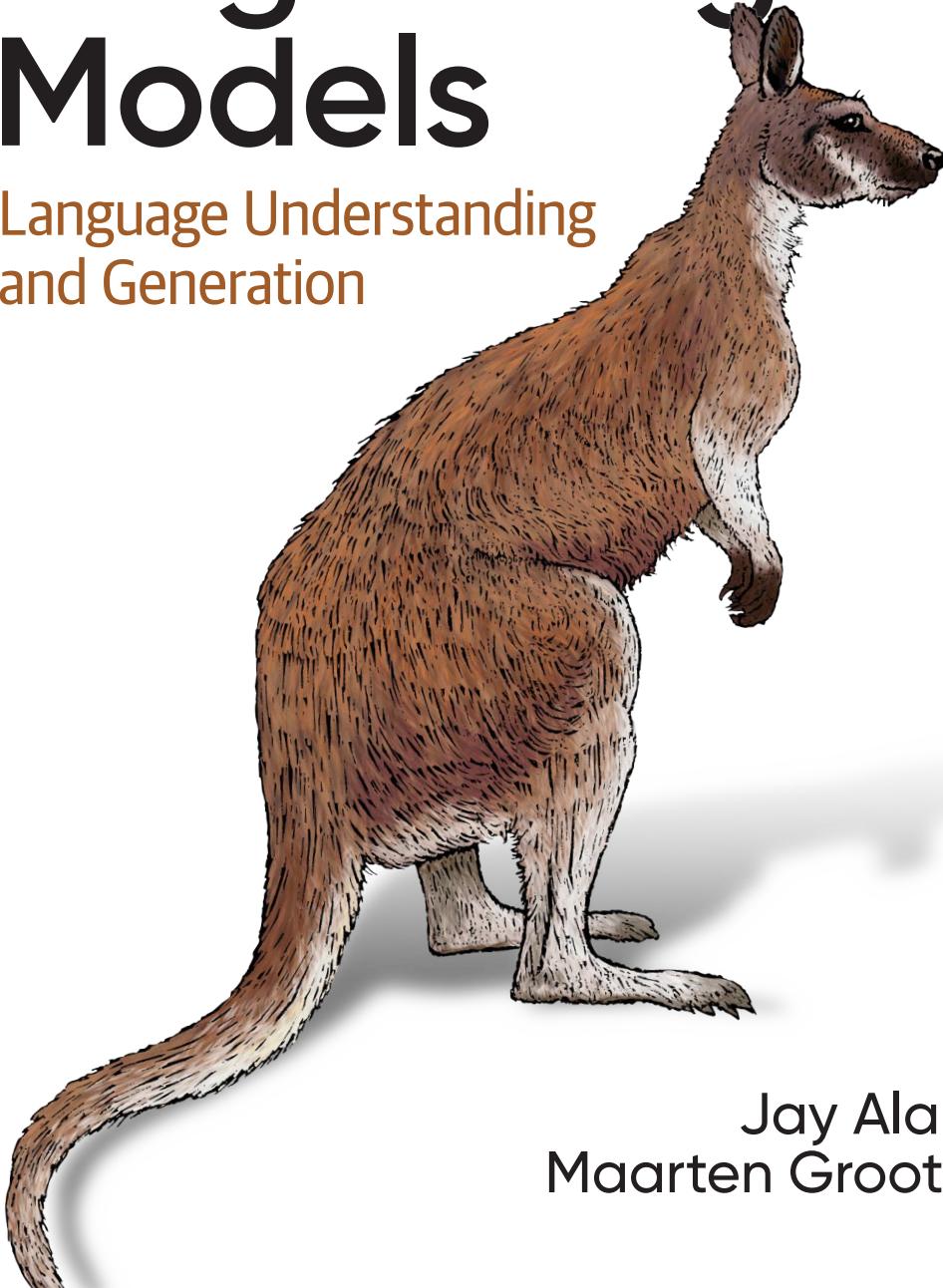


O'REILLY®

Hands-On Large Language Models

Language Understanding
and Generation



Jay Alammar &
Maarten Grootendorst

Hands-On Large Language Models

AI has acquired startling new language capabilities in just the past few years. Driven by rapid advances in deep learning, language AI systems are able to write and understand text better than ever before. This trend is enabling new features, products, and entire industries. Through this book's visually educational nature, readers will learn practical tools and concepts they need to use these capabilities today.

You'll understand how to use pretrained large language models for use cases like copywriting and summarization; create semantic search systems that go beyond keyword matching; and use existing libraries and pretrained models for text classification, search, and clusterings.

This book also helps you:

- Understand the architecture of Transformer language models that excel at text generation and representation
- Build advanced LLM pipelines to cluster text documents and explore the topics they cover
- Build semantic search engines that go beyond keyword search, using methods like dense retrieval and rerankers
- Explore how generative models can be used, from prompt engineering all the way to retrieval-augmented generation
- Gain a deeper understanding of how to train LLMs and optimize them for specific applications using generative model fine-tuning, contrastive fine-tuning, and in-context learning

"Jay and Maarten have continued their tradition of providing beautifully illustrated and insightful descriptions of complex topics. Their book is a valuable resource for anyone looking to understand the main techniques behind how large language models are built."

—Andrew Ng
founder of DeepLearning.AI

"I can't think of another book that is more important to read right now. On every single page, I learned something that is critical to success in this era of language models."

—Josh Starmer, StatQuest

Jay Alammar is director and engineering fellow at Cohere.

Maarten Grootendorst is senior clinical data scientist at the Netherlands Comprehensive Cancer Organization (IKNL).

DATA

US \$79.99 CAN \$99.99

ISBN: 978-1-098-15096-9



linkedin.com/company/oreilly-media
youtube.com/oreillymedia

Praise for *Hands-On Large Language Models*

This is an exceptional guide to the world of language models and their practical applications in industry. Its highly-visual coverage of generative, representational, and retrieval applications of language models empowers readers to quickly understand, use, and refine LLMs. Highly recommended!

—Nils Reimers, Director of Machine Learning
at Cohere | creator of sentence-transformers

Jay and Maarten have continued their tradition of providing beautifully illustrated and insightful descriptions of complex topics in their new book. Bolstered with working code, timelines, and references to key papers, their book is a valuable resource for anyone looking to understand the main techniques behind how Large Language Models are built.

—Andrew Ng, founder of DeepLearning.AI

I can't think of another book that is more important to read right now. On every single page, I learned something that is critical to success in this era of language models.

—Josh Starmer, StatQuest

If you're looking to get up to speed in everything regarding LLMs, look no further! In this wonderful book, Jay and Maarten will take you from zero to expert in the history and latest advances in large language models. With very intuitive explanations, great real-life examples, clear illustrations, and comprehensive code labs, this book lifts the curtain on the complexities of transformer models, tokenizers, semantic search, RAG, and many other cutting-edge technologies. A must read for anyone interested in the latest AI technology!

—Luis Serrano, PhD, Founder and CEO of Serrano Academy

This book is a must-read for anyone interested in the rapidly-evolving field of generative AI. With a focus on both text and visual embeddings, it's a great blend of algorithmic evolution, theoretical rigor, and practical guidance. Whether you are a student, researcher, or industry professional, this book will equip you with the use cases and solutions needed to level-up your knowledge of generative AI. Well done!

—Chris Fregly, *Principal Solution Architect,
Generative AI at AWS*

In the heart of the GenAI revolution, this indispensable guide masterfully balances theory and practice, navigating the vast landscape of large language models to equip readers with the knowledge needed for immediate and transformative impact in the field of AI.

—Tarun Narayanan Venkatachalam, *AI Researcher,
University of Washington*

Timely reading to get hands-on experience with language models.

—Emir Muñoz, *Genesys*

Hands-On Large Language Models brings clarity and practical examples to cut through the hype of AI. It provides a wealth of great diagrams and visual aids to supplement the clear explanations. The worked examples and code make concrete what other books leave abstract. The book starts with simple introductory beginnings, and steadily builds in scope. By the final chapters, you will be fine-tuning and building your own large language models with confidence.

—Leland McInnes, *Researcher at the Tutte Institute for
Mathematics and Computing*

Finally, a book that not only avoids superficial coverage of large language models but also thoroughly explores the background in a way that is both accessible and engaging. The authors have masterfully created a definitive guide that will remain essential reading despite the fast-paced advancements in the field.

—Prof. DDr. Roman Egger, *CEO of Smartvisions.at
and Modul University Vienna*

Hands-On Large Language Models

Language Understanding and Generation

Jay Alammar and Maarten Grootendorst

Beijing • Boston • Farnham • Sebastopol • Tokyo

O'REILLY®

Hands-On Large Language Models

by Jay Alammar and Maarten Grootendorst

Copyright © 2024 Jay Alammar and Maarten Pieter Grootendorst. All rights reserved.

Printed in the United States of America.

Published by O'Reilly Media, Inc., 1005 Gravenstein Highway North, Sebastopol, CA 95472.

O'Reilly books may be purchased for educational, business, or sales promotional use. Online editions are also available for most titles (<http://oreilly.com>). For more information, contact our corporate/institutional sales department: 800-998-9938 or corporate@oreilly.com.

Acquisitions Editor: Nicole Butterfield

Development Editor: Michele Cronin

Production Editor: Ashley Stussy

Copyeditor: Charles Roumeliotis

Proofreader: Kim Cofer

Indexer: BIM Creatives, LLC

Interior Designer: David Futato

Cover Designer: Karen Montgomery

Illustrator: Kate Dullea

September 2024: First Edition

Revision History for the First Edition

2024-09-10: First Release

See <http://oreilly.com/catalog/errata.csp?isbn=9781098150969> for release details.

The O'Reilly logo is a registered trademark of O'Reilly Media, Inc. *Hands-On Large Language Models*, the cover image, and related trade dress are trademarks of O'Reilly Media, Inc.

The views expressed in this work are those of the authors and do not represent the publisher's views. While the publisher and the authors have used good faith efforts to ensure that the information and instructions contained in this work are accurate, the publisher and the authors disclaim all responsibility for errors or omissions, including without limitation responsibility for damages resulting from the use of or reliance on this work. Use of the information and instructions contained in this work is at your own risk. If any code samples or other technology this work contains or describes is subject to open source licenses or the intellectual property rights of others, it is your responsibility to ensure that your use thereof complies with such licenses and/or rights.

978-1-098-15096-9

[LSI]

Table of Contents

Preface.....	xi
--------------	----

Part I. Understanding Language Models

1. An Introduction to Large Language Models.....	3
What Is Language AI?	4
A Recent History of Language AI	5
Representing Language as a Bag-of-Words	6
Better Representations with Dense Vector Embeddings	8
Types of Embeddings	10
Encoding and Decoding Context with Attention	11
Attention Is All You Need	15
Representation Models: Encoder-Only Models	18
Generative Models: Decoder-Only Models	20
The Year of Generative AI	23
The Moving Definition of a “Large Language Model”	25
The Training Paradigm of Large Language Models	25
Large Language Model Applications: What Makes Them So Useful?	27
Responsible LLM Development and Usage	28
Limited Resources Are All You Need	28
Interfacing with Large Language Models	29
Proprietary, Private Models	29
Open Models	30
Open Source Frameworks	31
Generating Your First Text	32
Summary	34

2. Tokens and Embeddings.	37
LLM Tokenization	38
How Tokenizers Prepare the Inputs to the Language Model	38
Downloading and Running an LLM	39
How Does the Tokenizer Break Down Text?	43
Word Versus Subword Versus Character Versus Byte Tokens	44
Comparing Trained LLM Tokenizers	46
Tokenizer Properties	55
Token Embeddings	57
A Language Model Holds Embeddings for the Vocabulary of Its Tokenizer	57
Creating Contextualized Word Embeddings with Language Models	58
Text Embeddings (for Sentences and Whole Documents)	61
Word Embeddings Beyond LLMs	63
Using pretrained Word Embeddings	63
The Word2vec Algorithm and Contrastive Training	64
Embeddings for Recommendation Systems	67
Recommending Songs by Embeddings	67
Training a Song Embedding Model	69
Summary	71
3. Looking Inside Large Language Models.	73
An Overview of Transformer Models	74
The Inputs and Outputs of a Trained Transformer LLM	74
The Components of the Forward Pass	76
Choosing a Single Token from the Probability Distribution (Sampling/ Decoding)	79
Parallel Token Processing and Context Size	81
Speeding Up Generation by Caching Keys and Values	83
Inside the Transformer Block	85
Recent Improvements to the Transformer Architecture	95
More Efficient Attention	96
The Transformer Block	101
Positional Embeddings (RoPE)	102
Other Architectural Experiments and Improvements	105
Summary	106

Part II. Using Pretrained Language Models

4. Text Classification.	111
The Sentiment of Movie Reviews	112
Text Classification with Representation Models	113

Model Selection	115
Using a Task-Specific Model	116
Classification Tasks That Leverage Embeddings	120
Supervised Classification	121
What If We Do Not Have Labeled Data?	123
Text Classification with Generative Models	127
Using the Text-to-Text Transfer Transformer	128
ChatGPT for Classification	132
Summary	135
5. Text Clustering and Topic Modeling.....	137
ArXiv’s Articles: Computation and Language	138
A Common Pipeline for Text Clustering	139
Embedding Documents	139
Reducing the Dimensionality of Embeddings	140
Cluster the Reduced Embeddings	142
Inspecting the Clusters	144
From Text Clustering to Topic Modeling	146
BERTopic: A Modular Topic Modeling Framework	148
Adding a Special Lego Block	156
The Text Generation Lego Block	160
Summary	164
6. Prompt Engineering.....	167
Using Text Generation Models	167
Choosing a Text Generation Model	167
Loading a Text Generation Model	168
Controlling Model Output	170
Intro to Prompt Engineering	173
The Basic Ingredients of a Prompt	173
Instruction-Based Prompting	175
Advanced Prompt Engineering	177
The Potential Complexity of a Prompt	177
In-Context Learning: Providing Examples	180
Chain Prompting: Breaking up the Problem	182
Reasoning with Generative Models	184
Chain-of-Thought: Think Before Answering	185
Self-Consistency: Sampling Outputs	188
Tree-of-Thought: Exploring Intermediate Steps	189
Output Verification	191
Providing Examples	192
Grammar: Constrained Sampling	194

Summary	198
7. Advanced Text Generation Techniques and Tools	199
Model I/O: Loading Quantized Models with LangChain	200
Chains: Extending the Capabilities of LLMs	202
A Single Link in the Chain: Prompt Template	203
A Chain with Multiple Prompts	206
Memory: Helping LLMs to Remember Conversations	209
Conversation Buffer	210
Windowed Conversation Buffer	212
Conversation Summary	214
Agents: Creating a System of LLMs	218
The Driving Power Behind Agents: Step-by-step Reasoning	219
ReAct in LangChain	221
Summary	224
8. Semantic Search and Retrieval-Augmented Generation	225
Overview of Semantic Search and RAG	226
Semantic Search with Language Models	228
Dense Retrieval	228
Reranking	240
Retrieval Evaluation Metrics	244
Retrieval-Augmented Generation (RAG)	249
From Search to RAG	250
Example: Grounded Generation with an LLM API	252
Example: RAG with Local Models	252
Advanced RAG Techniques	255
RAG Evaluation	257
Summary	258
9. Multimodal Large Language Models	259
Transformers for Vision	260
Multimodal Embedding Models	263
CLIP: Connecting Text and Images	265
How Can CLIP Generate Multimodal Embeddings?	265
OpenCLIP	268
Making Text Generation Models Multimodal	273
BLIP-2: Bridging the Modality Gap	273
Preprocessing Multimodal Inputs	278
Use Case 1: Image Captioning	280
Use Case 2: Multimodal Chat-Based Prompting	283
Summary	286

Part III. Training and Fine-Tuning Language Models

10. Creating Text Embedding Models.....	289
Embedding Models	289
What Is Contrastive Learning?	291
SBERT	293
Creating an Embedding Model	296
Generating Contrastive Examples	296
Train Model	297
In-Depth Evaluation	300
Loss Functions	301
Fine-Tuning an Embedding Model	309
Supervised	309
Augmented SBERT	311
Unsupervised Learning	316
Transformer-Based Sequential Denoising Auto-Encoder	316
Using TSDAE for Domain Adaptation	320
Summary	321
11. Fine-Tuning Representation Models for Classification.....	323
Supervised Classification	323
Fine-Tuning a Pretrained BERT Model	325
Freezing Layers	328
Few-Shot Classification	333
SetFit: Efficient Fine-Tuning with Few Training Examples	333
Fine-Tuning for Few-Shot Classification	337
Continued Pretraining with Masked Language Modeling	340
Named-Entity Recognition	345
Preparing Data for Named-Entity Recognition	347
Fine-Tuning for Named-Entity Recognition	352
Summary	353
12. Fine-Tuning Generation Models.....	355
The Three LLM Training Steps: Pretraining, Supervised Fine-Tuning, and Preference Tuning	355
Supervised Fine-Tuning (SFT)	357
Full Fine-Tuning	357
Parameter-Efficient Fine-Tuning (PEFT)	359
Instruction Tuning with QLoRA	367
Templating Instruction Data	367
Model Quantization	369
LoRA Configuration	370

Training Configuration	371
Training	372
Merge Weights	373
Evaluating Generative Models	373
Word-Level Metrics	374
Benchmarks	374
Leaderboards	376
Automated Evaluation	376
Human Evaluation	376
Preference-Tuning / Alignment / RLHF	378
Automating Preference Evaluation Using Reward Models	379
The Inputs and Outputs of a Reward Model	380
Training a Reward Model	380
Training No Reward Model	384
Preference Tuning with DPO	385
Templating Alignment Data	386
Model Quantization	386
Training Configuration	387
Training	388
Summary	389
Afterword.....	391
Index.....	393

Preface

Large language models (LLMs) have had a profound and far-reaching impact on the world. By enabling machines to better understand and generate human-like language, LLMs have opened new possibilities in the field of AI and impacted entire industries.

This book provides a comprehensive and highly visual introduction to the world of LLMs, covering both the conceptual foundations and practical applications. From word representations that preceded deep learning to the cutting-edge (at the time of this writing) Transformer architecture, we will explore the history and evolution of LLMs. We delve into the inner workings of LLMs, exploring their architectures, training methods, and fine-tuning techniques. We also examine various applications of LLMs in text classification, clustering, topic modeling, chatbots, search engines, and more.

With its unique blend of intuition-building, applications, and illustrative style, we hope that this book provides the ideal foundation for those looking to explore the exciting world of LLMs. Whether you are a beginner or an expert, we invite you to join us on this journey to start building with LLMs.

An Intuition-First Philosophy

The main goal of this book is to provide an *intuition* into the field of LLMs. The pace of development in the Language AI field is incredibly fast and frustration can build trying to keep up with the latest technologies. Instead, we focus on the fundamentals of LLMs and intend to provide a fun and easy learning process.

To achieve this *intuition-first philosophy* we liberally make use of visual language. Illustrations will help give a visual identity to major concepts and processes involved

in the learning process of LLMs.¹ With our illustrative method of storytelling, we want to take you on a journey to this exciting and potentially world-changing field.

Throughout the book, we make a clear distinction between representation and generative language models. Representation models are LLMs that do not generate text but are commonly used for task-specific use cases, like classification, whereas generation models are LLMs that generate text, like GPT models. Although generative models are typically the first thing that comes to mind when thinking about LLMs, there is still much use for representation models. We are also loosely using the word “large” in *large language models* and often elect to simply call them language models as size descriptions are often rather arbitrary and not always indicative of capability.

Prerequisites

This book assumes that you have some experience programming in Python and are familiar with the fundamentals of machine learning. The focus will be on building a strong intuition rather than deriving mathematical equations. As such, illustrations combined with hands-on examples will drive the examples and learning through this book. This book assumes no prior knowledge of popular deep learning frameworks such as PyTorch or TensorFlow nor any prior knowledge of generative modeling.

If you are not familiar with Python, a great place to start is [Learn Python](#), where you will find many tutorials on the basics of the language. To further ease the learning process, we made all the code available on [Google Colab](#), a platform where you can run all of the code without the need to install anything locally.

Book Structure

The book is broadly divided into three parts. They are illustrated in [Figure P-1](#) to give you a full view of the book. Note that each chapter can be read independently, so feel free to skim chapters you are already familiar with.

Part I: Understanding Language Models

In Part I of the book, we explore the inner workings of language models both small and large. We start with an overview of the field and common techniques (see [Chapter 1](#)) before moving over to two central components of these models, tokenization and embeddings (see [Chapter 2](#)). We finish this part of the book with an updated and expanded version of Jay’s well-known [Illustrated Transformer](#), which dives into

¹ J. Alammar. “Machine learning research communication via illustrated and interactive web articles.” *Beyond Static Papers: Rethinking How We Share Scientific Understanding in ML*. ICLR 2021 Workshop (2021).

the architecture of these models (see [Chapter 3](#)). Many terms and definitions will be introduced that are used throughout the book.

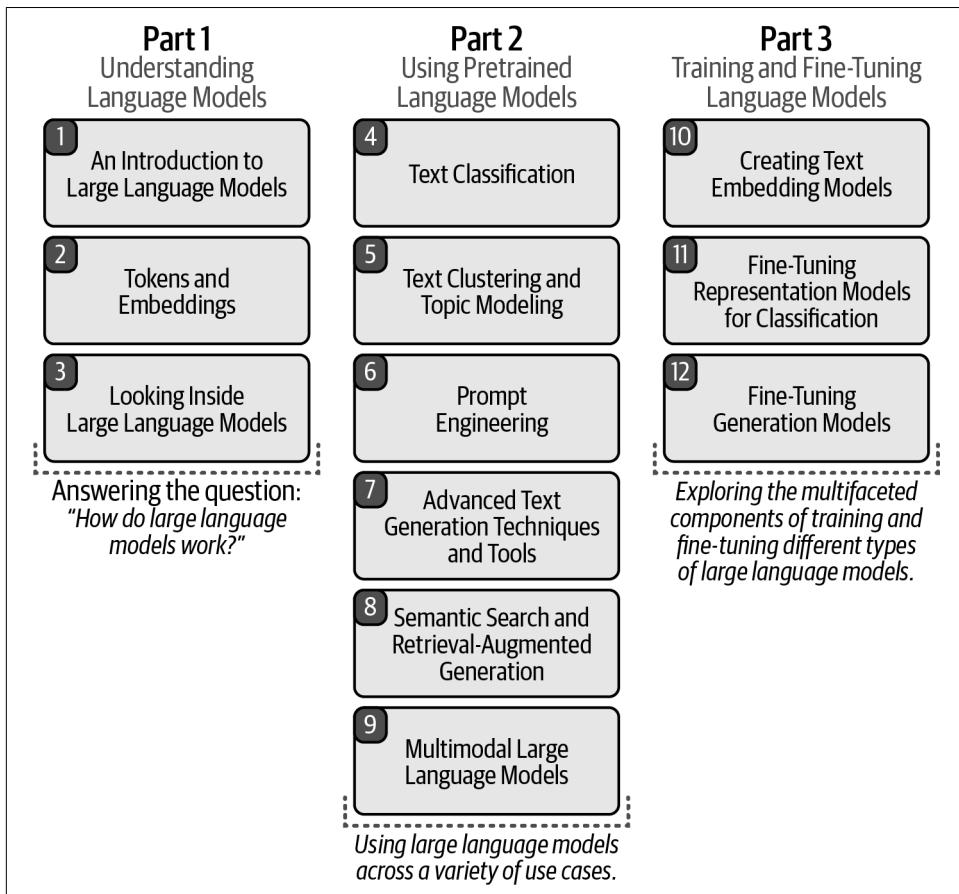


Figure P-1. All parts and chapters of the book.

Part II: Using Pretrained Language Models

In Part II of the book, we explore how LLMs can be used through common use cases. We use pretrained models and demonstrate their capabilities without the need to fine-tune them.

You learn how to use language models for supervised classification (see [Chapter 4](#)), text clustering and topic modeling (see [Chapter 5](#)), leveraging embedding models for semantic search (see [Chapter 6](#)), generating text (see [Chapters 7 and 8](#)), and extending the capabilities of text generation to the visual domain (see [Chapter 9](#)).

Learning these individual language model capabilities will equip you with the skill set to problem-solve with LLMs and build more and more advanced systems and pipelines.

Part III: Training and Fine-Tuning Language Models

In Part III of the book, we explore advanced concepts through training and fine-tuning all kinds of language models. We will explore how to create and fine-tune an embedding model (see [Chapter 10](#)), review how to fine-tune BERT for classification (see [Chapter 11](#)), and end the book with several methods for fine-tuning generation models (see [Chapter 12](#)).

Hardware and Software Requirements

Running generative models is generally a compute-intensive task that requires a computer with a strong GPU. Since those are not available to every reader, all examples in this book are made to run using an online platform, namely [Google Colaboratory](#), often shortened to “Google Colab.” At the time of writing, this platform allows you to use an NVIDIA GPU (T4) for free to run your code. This GPU has 16 GB of VRAM (which is the memory of your GPU), which is the minimum amount of VRAM we expect for the examples throughout the book.



Not all chapters require a minimum of 16 GB VRAM as some examples, like training and fine-tuning, are more compute-intensive than others, such as prompt engineering. In the repository, you will find the minimum GPU requirements for each chapter.

All code, requirements, and additional tutorials are available in [this book’s repository](#). If you want to run the examples locally, we recommend access to an NVIDIA GPU with a minimum of 16 GB of VRAM. For a local installation, for example with conda, you can follow this setup to create your environment:

```
conda create -n thellmbook python=3.10
conda activate thellmbook
```

You can install all the necessary dependencies by forking or cloning the repository and then running the following in your newly created Python 3.10 environment:

```
pip install -r requirements.txt
```

API Keys

We use both open source and proprietary models throughout the examples to demonstrate the advantages and disadvantages of both. For the proprietary models, using OpenAI and Cohere’s offering, you will need to create a free account:

OpenAI

Click “sign up” on the site to create a free account. This account allows you to create an API key, which can be used to access GPT-3.5. Then, go to “API keys” to create a secret key.

Cohere

Register a free account on the website. Then, go to “API keys” to create a secret key.

Note that with both accounts, rate limits apply and that these free API keys only allow for a limited number of calls per minute. Throughout all examples, we have taken that into account and provided local alternatives if necessary.

For the open source models, you do not need to create an account with the exception of the Llama 2 model in [Chapter 2](#). To use that model, you will need a Hugging Face account:

Hugging Face

Click “sign up” on the Hugging Face website to create a free account. Then, in “Settings” go to “Access Tokens” to create a token that you can use to download certain LLMs.

Conventions Used in This Book

The following typographical conventions are used in this book:

Italic

Indicates new terms, URLs, email addresses, filenames, and file extensions.

Constant width

Used for program listings, as well as within paragraphs to refer to program elements such as variable or function names, databases, data types, environment variables, statements, and keywords.

Constant width bold

Shows commands or other text that should be typed literally by the user.

Constant width italic

Shows text that should be replaced with user-supplied values or by values determined by context.



This element signifies a tip or suggestion.



This element signifies a general note.

Using Code Examples

Supplemental material (code examples, exercises, etc.) is available for download at <https://github.com/HandsOnLLM/Hands-On-Large-Language-Models>.

If you have a technical question or a problem using the code examples, please send email to support@oreilly.com.

This book is here to help you get your job done. In general, if example code is offered with this book, you may use it in your programs and documentation. You do not need to contact us for permission unless you're reproducing a significant portion of the code. For example, writing a program that uses several chunks of code from this book does not require permission. Selling or distributing examples from O'Reilly books does require permission. Answering a question by citing this book and quoting example code does not require permission. Incorporating a significant amount of example code from this book into your product's documentation does require permission.

We appreciate, but generally do not require, attribution. An attribution usually includes the title, author, publisher, and ISBN. For example: “*Hands-On Large Language Models* by Jay Alammar and Maarten Grootendorst (O'Reilly). Copyright 2024 Jay Alammar and Maarten Pieter Grootendorst, 978-1-098-15096-9.”

If you feel your use of code examples falls outside fair use or the permission given above, feel free to contact us at permissions@oreilly.com.

O'Reilly Online Learning

O'REILLY[®]

For more than 40 years, *O'Reilly Media* has provided technology and business training, knowledge, and insight to help companies succeed.

Our unique network of experts and innovators share their knowledge and expertise through books, articles, and our online learning platform. O’Reilly’s online learning platform gives you on-demand access to live training courses, in-depth learning paths, interactive coding environments, and a vast collection of text and video from O’Reilly and 200+ other publishers. For more information, visit <https://oreilly.com>.

How to Contact Us

Please address comments and questions concerning this book to the publisher:

O’Reilly Media, Inc.
1005 Gravenstein Highway North
Sebastopol, CA 95472
800-889-8969 (in the United States or Canada)
707-827-7019 (international or local)
707-829-0104 (fax)
support@oreilly.com
<https://www.oreilly.com/about/contact.html>

We have a web page for this book, where we list errata, examples, and any additional information. You can access this page at https://oreil.ly/hands_on_LLMs_1e.

For news and information about our books and courses, visit <https://oreilly.com>.

Find us on LinkedIn: <https://linkedin.com/company/oreilly-media>.

Watch us on YouTube: <https://youtube.com/oreillymedia>.

Acknowledgments

Writing this book has been an incredible experience, collaboration, and journey for us.

The field of (large) language models is one of the most dynamic areas in technology today, and within the span of writing this book, we have witnessed extraordinary advancements. Yet, despite the rapid pace of change, the fundamental principles remain strikingly consistent which made the writing process particularly intriguing. We are grateful to have had the opportunity to explore this field in-depth at such a pivotal moment.

Working with our O’Reilly team was incredible! Special thanks to Michele Cronin for her amazing feedback, support, and enthusiasm for this book from day one. We could not have asked for a better editor—you are amazing! Thank you, Nicole Butterfield, for kicking off this book and helping us maintain a structured approach throughout the writing. Thank you to Karen Montgomery for creating our wonderful cover, we

love the kangaroo! Big thanks to Kate Dullea for being so patient with us having to go through hundreds of illustrations many times over. The timely early releases by Clare Laylock helped us see our work grow which was a big motivator, thank you. Thanks to Ashley Stussy and Charles Roumeliotis for the development in the final stages of the book and everyone else at O'Reilly who contributed.

Thanks to our amazing crew of technical reviewers. Invaluable feedback was given by Harm Buisman, Emir Muñoz, Luba Elliott, Guarav Chawla, Rafael V. Pierre, Luba Elliott, Tarun Narayanan, Nikhil Buduma, and Patrick Harrison.

Jay

I'd love to extend my deepest gratitude to my family for their unwavering support and inspiration. I would like to specifically acknowledge my parents, Abdullah and Mishael, and my aunts, Hussah and Aljoharah.

I'm grateful to the friends, colleagues, and collaborators who helped me understand and explain the tricky concepts covered in this book as well as to the Cohere folks who cultivate a supporting learning and sharing environment. Thank you to Adrien Morisot, Aidan Gomez, Andy Toulis, Anfal Alatawi, Arash Ahmadian, Bharat Venkitesh, Edward Grefenstette, Ivan Zhang, Joao Araújo, Luis Serrano, Matthias Gallé, Meor Amer, Nick Frosst, Patrick Lewis, Phil Blunsom, Sara Hooker, and Suhas Pai.

I couldn't conceive of this project getting accomplished to the level it has without the extraordinary talent and tireless effort of Maarten, my coauthor. Your ability to repeatedly nail the technical details (from the pinned version of the `nth` import dependency to the latest in LLM quantization) while weaving some of the world's best visual narratives is absolutely breathtaking.

Lastly, a tip of the hat to the incredible coffee shop scene of Riyadh, Saudi Arabia for supplying me with caffeine and a good place to focus from dawn until midnight. It's where I read most of these papers and worked out my understanding (looking at you, Elixir Bunn).

Maarten

I want to begin by expressing my heartfelt appreciation to my coauthor, Jay. Your insights have made this not only possible but incredibly fulfilling. This journey has been nothing short of amazing and collaborating with you has been an absolute joy.

I want to sincerely thank my wonderful colleagues at IKNL for their continued support throughout this journey. A special mention goes to Harm—our Monday morning coffee breaks discussing this book were a constant source of encouragement.

Thank you to my family and friends for their unwavering support, and to my parents in particular. Pap, despite the challenges you faced, you always found a way to be