# Deep Learning Systems: Algorithms and Implementation

# Introduction and Logistics

J. Zico Kolter (this time) and Tianqi Chen
Carnegie Mellon University

# Outline

Why study deep learning systems?

Course info and logistics

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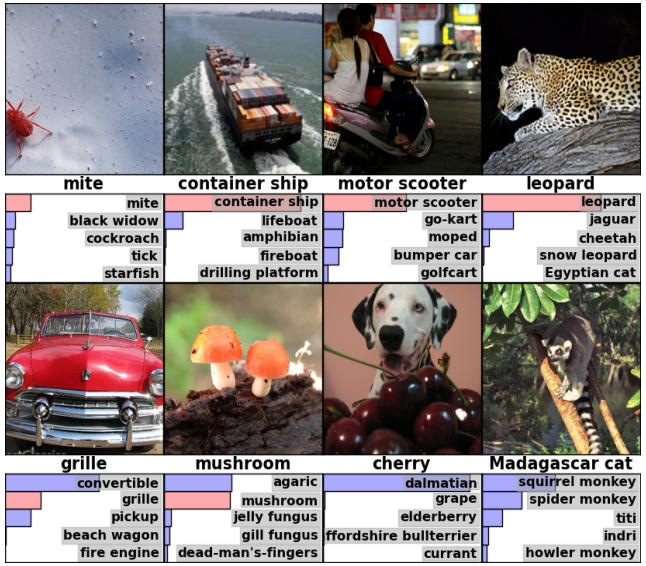
# Aim of this course

This course will provide you will an introduction to the functioning of modern deep learning systems

You will learn about the underlying concepts of modern deep learning systems like automatic differentiation, neural network architectures, optimization, and efficient operations on systems like GPUs

To solidify your understanding, along the way (in your homeworks), you will build (from scratch) needle, a deep learning library loosely similar to PyTorch, and implement many common architectures in the library

# Why study deep learning?

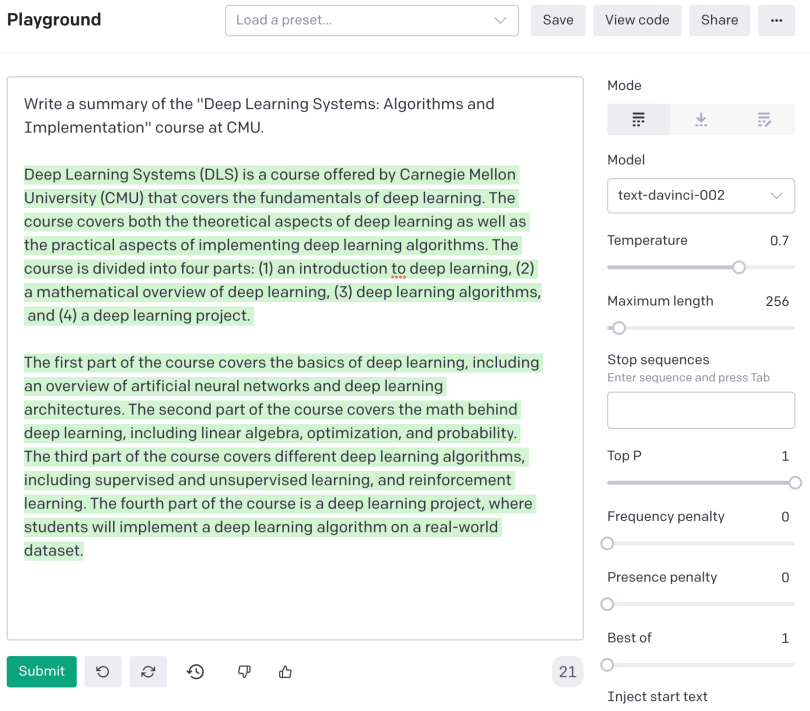



AlexNet
(Krizhevsky et al., 2012)

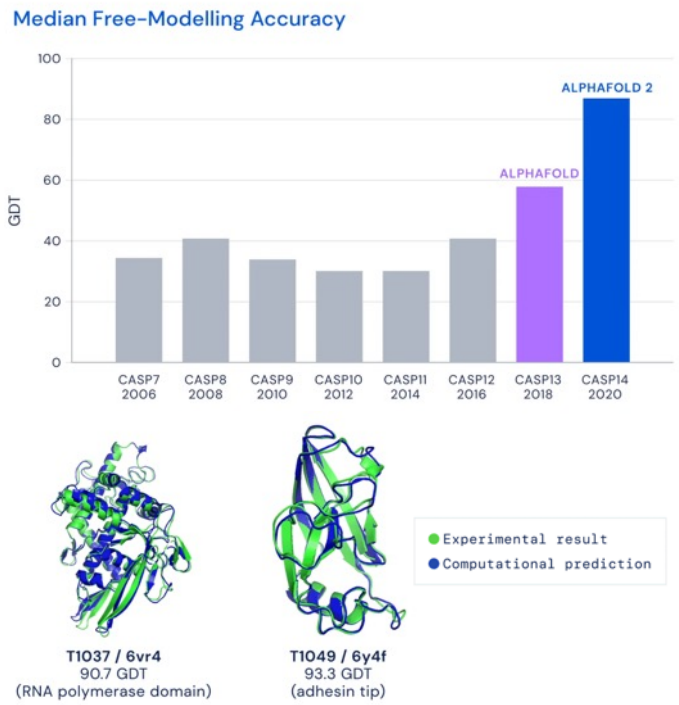

AlphaGo
(Silver et al., 2016)

StyleGAN
(Karras et al., 2018)

# Why study deep learning?




GPT-3
(OpenAI et al., 2021)




AlphaFold 2
(Jumper et al., 2021)

A dog dressed as a university professor nervously preparing his first lecture of the semester, 10 minutes before the start of class. Oil painting on canvas.

Stable Diffusion (see also, DALLE-2)
(Rombach et al., 2022)

# …Not (just) for the “big players”

DeOldify (Antic and Kelley, ~2018)

https://github.com/rwightman/pytorch-image-models

PyTorch Image Models (Wightman, 2021)

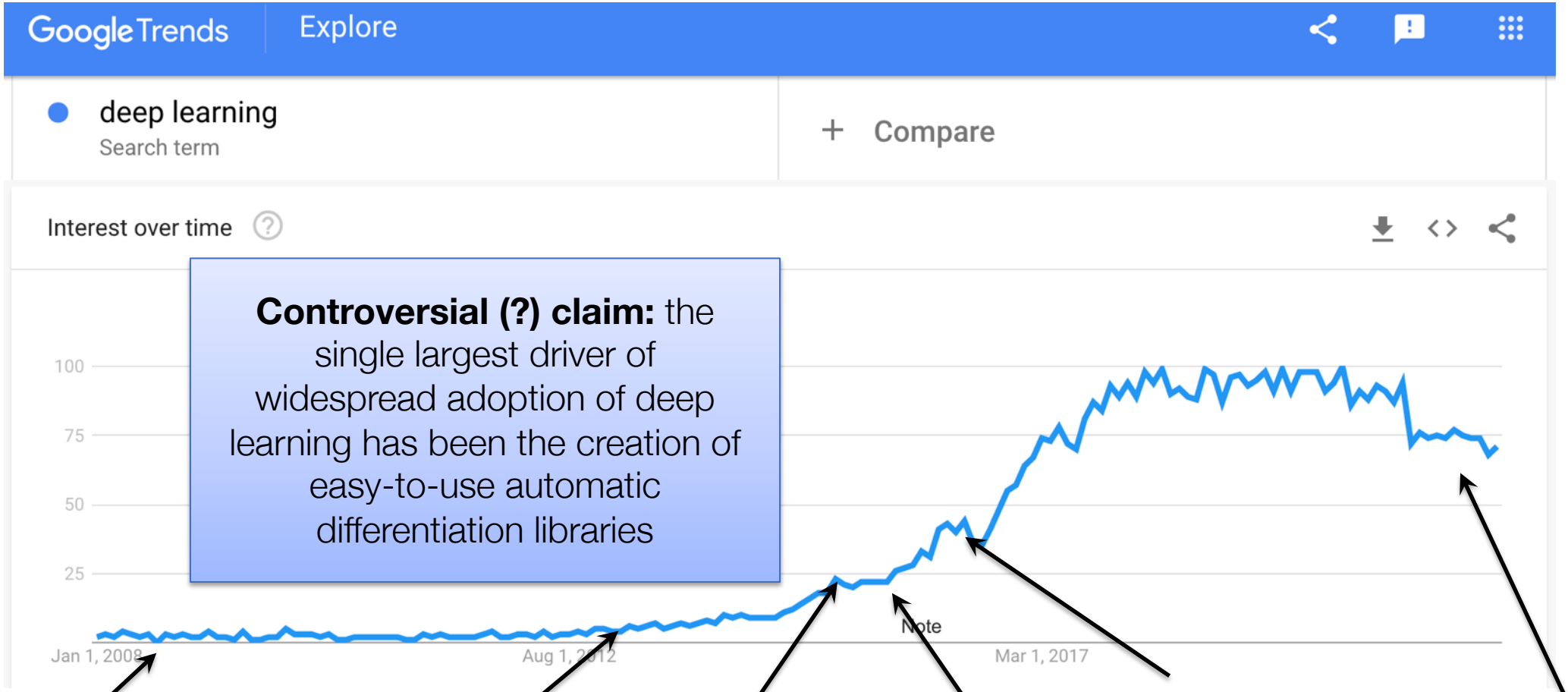
dmlc

mxnet

tvm

..many community-driven libraries/frameworks

# Why study deep learning systems?




**Controversial (?) claim:** the single largest driver of widespread adoption of deep learning has been the creation of easy-to-use automatic differentiation libraries

Deep learning gains traction at NeurIPS

AlexNet

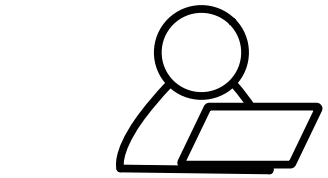
Keras released

TensorFlow released

PyTorch released

(Uh oh?)

# Working on deep learning ten years ago



Researcher

ConvNets

RNNs

...

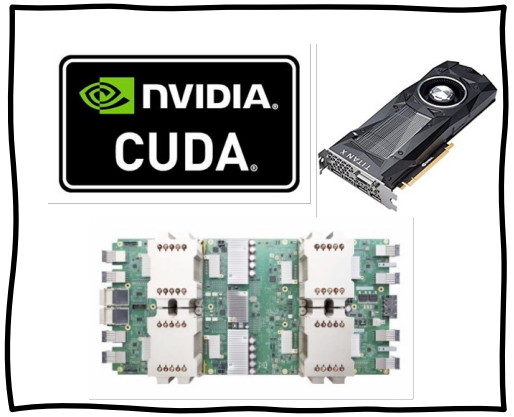
ML Models

44k lines of code

Six months

IMAGENET

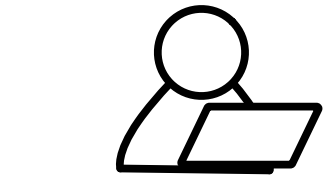
Data




Compute

Based on real story

# Working on deep learning ten years ago



Researcher

ConvNets

RNNs

...

ML Models

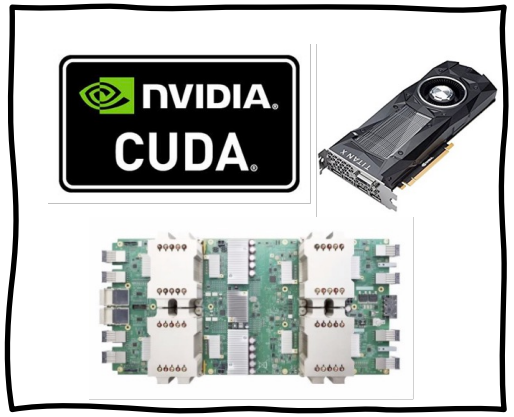
100 lines of code

A few hours

**Deep learning systems**


IMAGENET

Data




Compute

Based on real story

# Reason #1: To build deep learning systems

Despite the dominance of deep learning libraries and TensorFlow and PyTorch, the playing field in this space is remarkably fluid (see e.g., recent emergence of JAX)

You may want to work on developing existing frameworks (virtually all of which are open source), or developing your own new frameworks for specific tasks

This class (and some practice) will prepare you to do this

# Reason #2: To use existing systems more effectively

Understanding how the internals of existing deep learning systems work let you use them *much* more efficiently

Want to make your custom non-standard layer run (much) faster in TensorFlow/PyTorch? … you're going to want to understand how these operations are executed

Understanding deep learning systems is a "superpower" that will let you accomplish your research aims much more efficiently

# Reason #3: Deep learning systems are fun!

Despite their seeming complexity, the core underlying algorithms behind deep learning systems (automatic differentiation + gradient-based optimization) are extremely simple

Unlike (say) operating systems, you could probably write a “reasonable” deep learning library in <2000 lines of (dense) code

The first time you build your automatic differentiation library, and realize you can take gradient of a gradient without actually knowing how you would even go about deriving that mathematically…

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# Course instructors

**Zico Kolter**

https://zicokolter.com/

Professor (2012-present)

LocusLab

Carnegie Mellon University
School of Computer Science

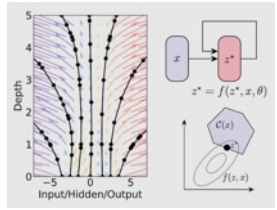
Industry, past + current

C3.ai BOSCH

Research focus on new algorithms and techniques in deep learning


Adversarial robustness
http://adversarial-ml-tutorial.org

Implicit layers
http://implicit-layers-tutorial.org




Early PyTorch adopter…

The first community package based on PyTorch came from Brandon Amos, titled Block, and helped with easier manipulation of block matrices. The Locus Lab at **CMU** subsequently went on to publish PyTorch packages and implementations for most of their research. The first research paper code came from Sergey Zagoruyko titled Paying more attention to attention.

# Course instructors

**Tianqi Chen**

https://tqchen.com/

Professor

catalyst

Carnegie Mellon University
School of Computer Science

Co-founder

OctoML

Creator of Major Learning Systems

tvm

mxnet

dmlc XGBoost

Cook and Foodie

# Big bold disclaimer

**We are offering this course online for the *first time.* A lot of the material (especially assignments) is being revamped from the previous version, and thus being released for the first time. There will almost certainly be some bugs in the content or assignments, or in the course logistics. Please bear with us.**

# Learning objects of the course

By the end of this course, you will …

… understand the basic functioning of modern deep learning libraries, including concepts like automatic differentiation, gradient-based optimization

… be able to implement several standard deep learning architectures (MLPs, ConvNets, RNNs, Transformers), *truly* from scratch

… understand how hardware acceleration (e.g., on GPUs) works under the hood for modern deep learning architectures, and be able to develop your own highly efficient code

# Tentative schedule of topics

| Date | Lecture | Instructor | Slides | Comments |
|---|---|---|---|---|
| 8/30 | 1 - Introduction / Logistics | Kolter | | HW0 Out |
| 9/1 | 2 - ML Refresher / Softmax Regression | Kolter | | |
| 9/6 | 3 - Manual Neural Networks / Backprop | Kolter | | |
| 9/8 | 4 - Automatic Differentiation | Chen | | |
| 9/13 | 5 - Automatic Differentiation Implementation | Chen | | HW0 Due |
| 9/15 | 6 - Optimization | Kolter | | |
| 9/20 | 7 - NN Library Implementation 1 | Chen | | |
| 9/22 | 8 - NN Library Implementation 2 | Chen | | |
| 9/27 | 9 - Normalization, Dropout, + Implementation | Kolter | | |
| 9/29 | 10 - Convolutional Networks | Kolter | | |
| 10/4 | 11 - Convoluations Network Implementation | Kolter | | |
| 10/6 | 12 - Hardware Acceleration for Linear Algebra | Chen | | |
| 10/11 | 13 - Hardware Acceleration + GPUs | Chen | | |
| 10/13 | 14 - Hardware Acceleration Implementation | Chen | | |
| 10/18 | *Fall Break* | | | |
| 10/20 | *Fall Break* | | | |
| 10/25 | 15 - Training Large Models | Chen | | |
| 10/27 | 16 - Architecture Overview Hardware Acceleration | Chen | | |
| 11/1 | 17 - Generative Adversarial Networks | Chen | | |
| 11/3 | 18 - Generative Adversarial Networks Implementation | Chen | | |
| 11/8 | 19 - Sequence Modeling + RNNs | Kolter | | |
| 11/10 | 20 - Sequence Modeling Implementation | Kolter | | |
| 11/15 | 21 - Transformers + Attention | Kolter | | |
| 11/17 | 22 - Transformers + Attention Implementation | Kolter | | |
| 11/22 | 23 - Implicit Layers | Kolter | | |
| 11/29 | 24 - Model Deployment | Chen | | |
| 12/1 | 25 - Machine Learning Compilation and Deployment Implementation | Chen | | |
| 12/6 | 26 - Future Directions / Q&A | Both | | |
| 12/8 | 27 - Student project presentations | Students | | |

Listing of lecturers from course website:
https://dlsyscourse.org

**Broad topics:** ML refresher/background, automatic differentiation, fully connected networks, optimization, NN libraries, convnets, hardware and GPU acceleration, sequence models, training large models, transformers + attention, generative models

(As suggested by course title) lectures are frequently broken down between “algorithm” lectures and “implementation” lecturers (or combined into one)

# Prerequisites

In order to take this course, you need to be proficient with:

- Systems programming
- Linear algebra
- Other mathematical background: e.g., calculus, probability, basic proofs
- Python and C++ development
- Basic prior experience with ML

If you are unsure about your background, take a look at the first three lectures take a look at Homework 0 (released September 15); you *should* be familiar with all the ideas in this homework in order to take the course

# Components of the course

This course will consist of four main elements

1. Video lectures
2. Programming-based (autograded) homeworks
3. (Group) final project
4. Interaction/discussion in course forum

Important to take part in all of these in order to get the full value from the course

There is no formal “credit” for taking the course, but everyone who an average of at least 80% on the homeworks, and submits a final project, will receive a certificate of completion

# Video lectures

Lectures will consist of a mix of slide presentations, mathematical notes / derivations, and live coding illustration

Videos for all lectures will be posted to YouTube or other video sites according to the course schedule; videos will be available to anyone, and do not require registering

# Programming homework assignments

The course will consist of four programming-based homework assignments, plus an additional Homework 0 meant as a review / test of your background

Homeworks are *entirely* coding-based: throughout the assignments you will incrementally develop needle, a PyTorch-like deep learning library, with: automatic differentiation; gradient-based optimization of models; support for standard operators like convolutions, recurrent structure, self-attention; and (manually-written) efficient linear algebra on both CPU and GPU devices

Homeworks will be autograded using a custom system we are developing for this course (demo and illustration during the next lecture); **you need to officially sign up for the course (at http://dlsyscourse.org) to submit assignments**

# Final project

In addition to homeworks, there will also be a final project, done in groups of 2-3 students

Final project should involve developing a substantial new piece of functionality in needle, or implement some new architecture in the framework (note that you *must* implement it in needle, you cannot, e.g., use PyTorch or TensorFlow for the final project)

Prior to the final project proposal/team formation deadline, we will post a collection of possible topics/ideas for the project

# Class forum

All interaction with other students and the instructors/TAs will take place over the course forum:

http://forum.dlsyscourse.org

You should have received an invitation to join the class forum, log in after class if you haven't done so yet

You can (and should) ask for help with assignments on the forum, but we will not be able to answer all questions: upvote (like) questions that you would like to see answered, and help by answering questions from other students

Further are posted in the main welcome message on the forum

# Parting words

We are excited about being able to offer this course publicly, and look forward to having you in the course

If you have any feedback or comments, please let us know (it may not be possible to make changes for this offering, but we want this to be as valuable a resource as possible for the community now and in the future)