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https://github.com/julianmak/OCES5303_ML_ocean

The repository principally contains the compiled products rather than the source for size reasons.

- ▶ Associated Python code (as Jupyter notebooks mostly) will be held on the same repository. The source data however might be big, so I am going to be naughty and possibly just refer you to where you might get the data if that is the case (e.g. JRA-55 data). I know I should make properly reproducible binders etc., but I didn't...
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OCES 5303 : ML methods in Ocean Sciences

Session 4: Neural Networks, PyTorch, and MLPs

Outline

- ▶ anatomy of a **neural network**
 - nodes, weights, hidden layers, activation functions
 - back-propagation
- ▶ **perceptrons**
 - simple perceptrons and interface with linear models
- ▶ **multi-layer perceptrons (MLPs)**
 - set up in **PyTorch** (could actually be done in `sklearn`)
 - solvers, loss curves, various options
- ▶ cats and dogs example: classification and regression

Oceanic application

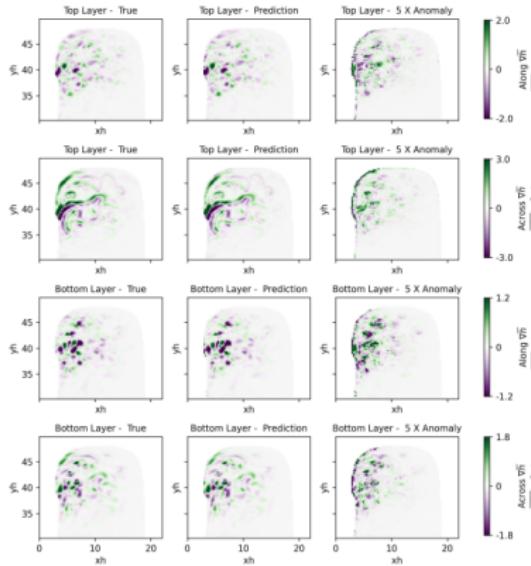


Figure: Model truth, predicted and mismatches in the predicted thickness fluxes from a double gyre calculation. From Balwada *et al.* (submitted).

- ▶ many instances where **neural networks** are used
 - but usually not in the MLP form for reasons to be elaborated
- ▶ example in predicting a spatially varying field, application in parameterisations
 - prediction here for **thickness** fluxes

Oceanic application

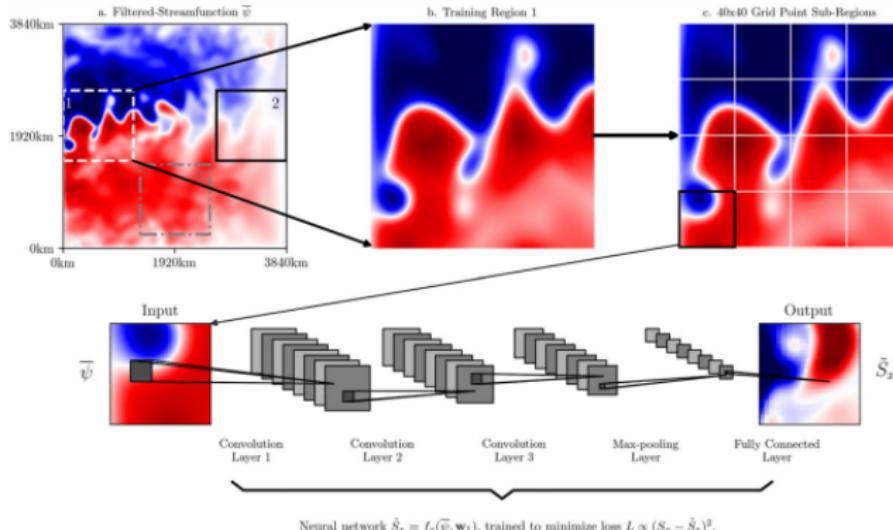


Figure: CNN applied to an eddy parameterisation problem. From Bolton & Zanna (2019).

- eddy parameterisation problem
 - regression: predict one image from another with **CNNs**

Oceanic application

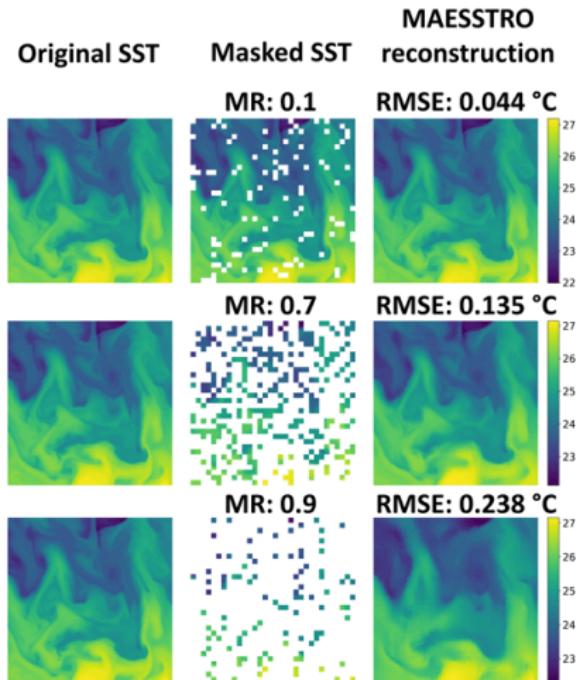


Figure: Reconstruction of SST from occluded data. From Fig. 2 of Goh *et al.* (2024).

► e.g. satellite data

→ masked **auto-encoder** to fill out the gaps

→ model data but masked accordingly (e.g. cover by cloud)

→ don't have to wait for the satellite to pass again

Q. reconstruction to be **constrained** physically?
(e.g. maintain **geostrophy**?)

Oceanic application

- ▶ e.g. oxygen content
 - random forest and MLPs using ship and argo data
 - to interpolate sparse data content
 - reconstruction to quantify rates of deoxygenation

Q. reconstruction to be **constrained** by principles?

(e.g. PINNs later)

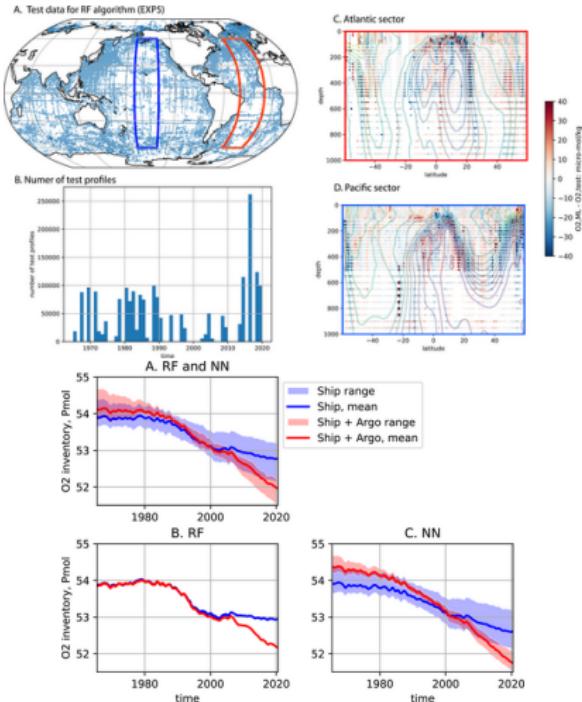


Figure: Reconstruction of observed oxygen content from ship and argo data. From Fig. 8 and 12 of Ito *et al.* (2024).

Recap: classifiers/regressors

- ▶ recall for supervised learning we basically have

$$Y = f(X),$$

and given X and Y we want the classifier/regressor f

- ▶ f can be represented
 - symbolically (e.g. linear models)
 - as decision trees (e.g. random forests)
 - as a chain of elementary operations (e.g. neural networks)

Neural networks: anatomy

- ▶ easiest probably with an example:

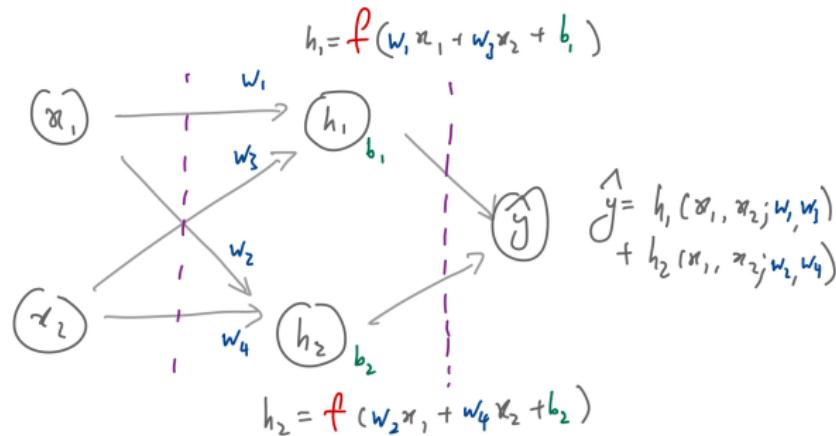


Figure: Made up example of a neural network (that you can code/train up yourself in principle; see notebook).

- ▶ input $X = (x_1, x_2)$ passes through network and gets transformed into prediction $Y = \hat{Y}$

Neural networks: anatomy

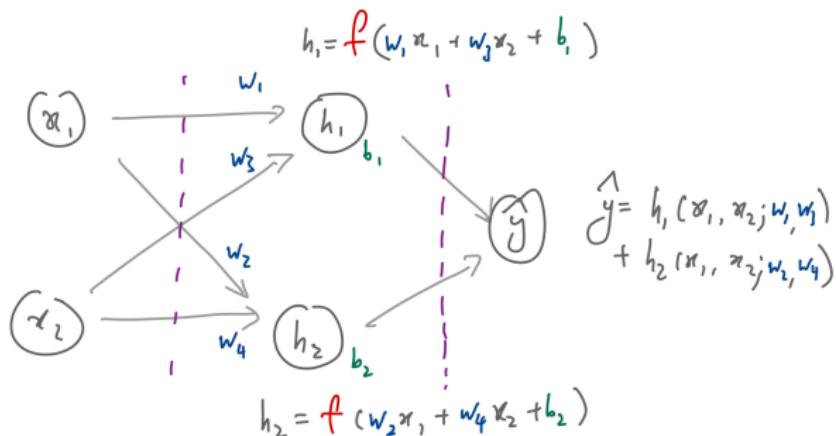


Figure: Made up example of a neural network (that you can code/train up yourself in principle; see notebook).

- ▶ each **hidden layer** have **nodes**, where we
 - multiply things by **weights** w_i
 - add on **biases** b_i
 - passed through an **activation function** f

Neural networks: anatomy

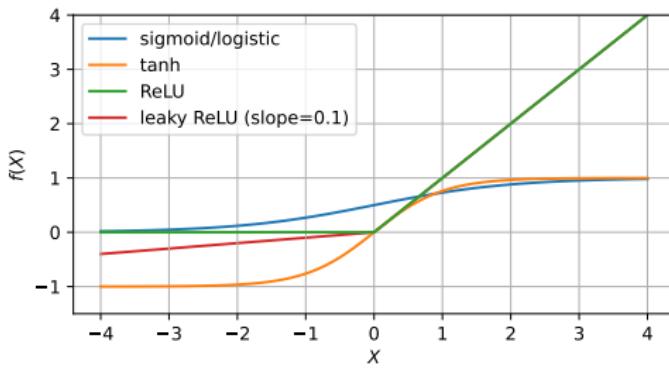


Figure: Samples of common activation functions: sigmoid (bounded between $[0, 1]$), tanh (bounded between $[-1, 1]$) and ReLU (bounded below by 0). Note ReLU is basically hinge loss but flipped the other way around. Leaky ReLU has a slope in the negative part.

- ▶ **activation functions** add nonlinearity to the system (see later)
 - maps the elementary operations to known ranges
 - usually piecewise differentiable (see three slides later for reason)
 - e.g. ReLU controls ‘firing’ of neurons (if $x < 0$)

Neural networks: as approximators

- Q. just a bunch of elementary operations, cannot be complex enough surely?
- ▶ universal approximation theorem for neural networks:
 - ‘sensible’ (!?) functions can be approximated using above operations given sufficient ‘complexity’
 - ‘complexity’ means number of nodes and/or layers
- ▶ note: an **existence** theorem
 - doesn’t tell you how you would train it
 - there are lower/upper bounds for complexity in some cases

Neural networks: training

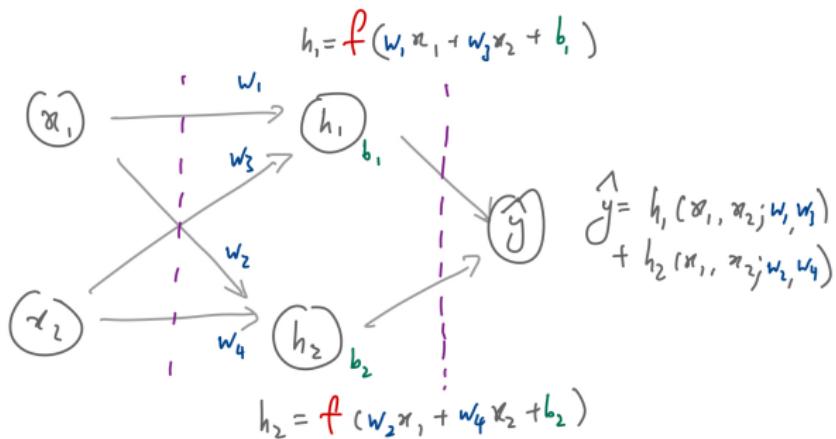


Figure: Made up example of a neural network (that you can code/train up yourself in principle; see notebook).

- ▶ one **feed-forward** results in \hat{y}
 - evaluate a **loss function** $J(Y, \hat{y})$
 - J depends on problem, e.g. one sided for classification, L^2 for regression, information entropy based etc.

Neural networks: training

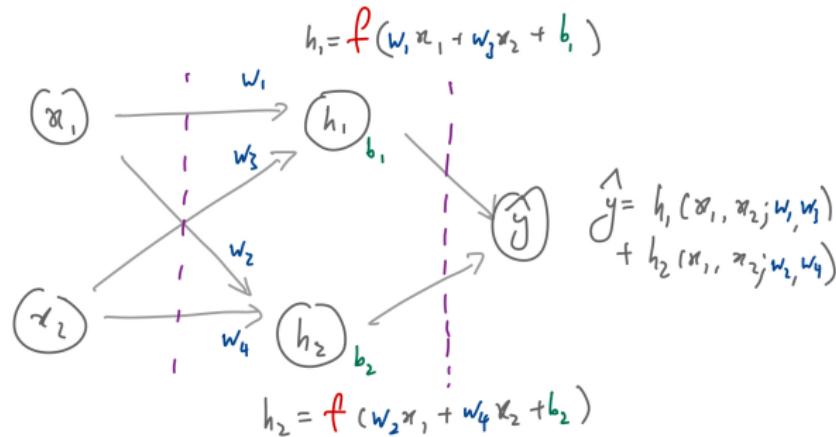


Figure: Made up example of a neural network (that you can code/train up yourself in principle; see notebook).

- ▶ aim: find minimum J by changing model parameters
 $\theta = (w_i, b_i)$
→ want to solve something like $\partial J / \partial \theta = 0$ (abusing notation here...)

Neural networks: training

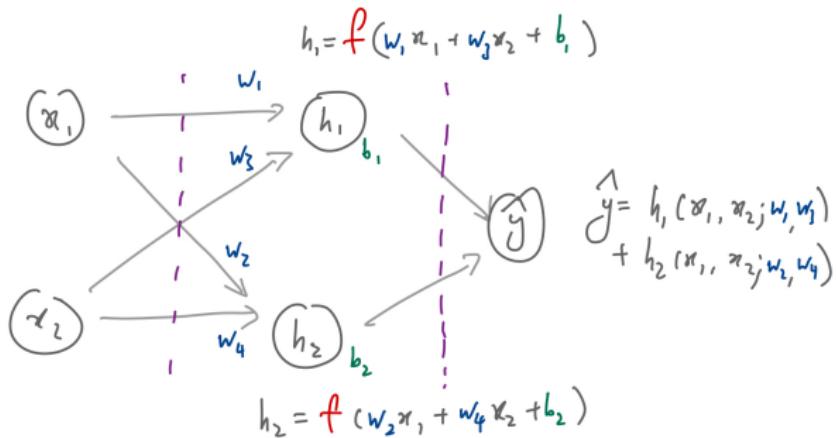


Figure: Made up example of a neural network (that you can code/train up yourself in principle; see notebook).

► back-propagation (chain rule basically): e.g.,

$$\frac{\partial J}{\partial w_1} = \frac{\partial J}{\partial h_1} \frac{\partial h_1}{\partial w_1} = \frac{\partial J}{\partial h_1} f'(w_1 x_1 + \dots) x_1.$$

→ do for all, SGD etc. and iterate until convergence/bored

Neural networks: training

- ▶ more nodes?
 - more equations
- ▶ more layers?
 - longer chains
- ▶ activation functions?
 - choose piecewise differentiable and 'easy' functions
- ▶ other components within the hidden layer?
 - (e.g. convolutional kernels in CNNs, hidden states in RNNs)
 - assume differentiability but proceed as usual
- ▶ constraint and/or dynamical layers?
 - can deal with in principle (e.g. adjoints)...

Perceptrons

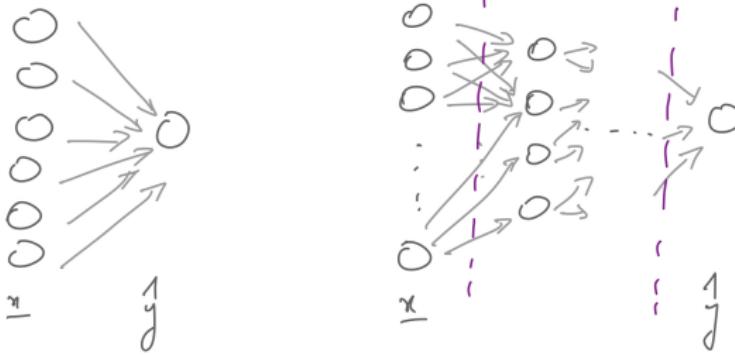


Figure: Schematic of perceptrons (no hidden layers) and MLPs (at least one hidden layer).

► perceptrons

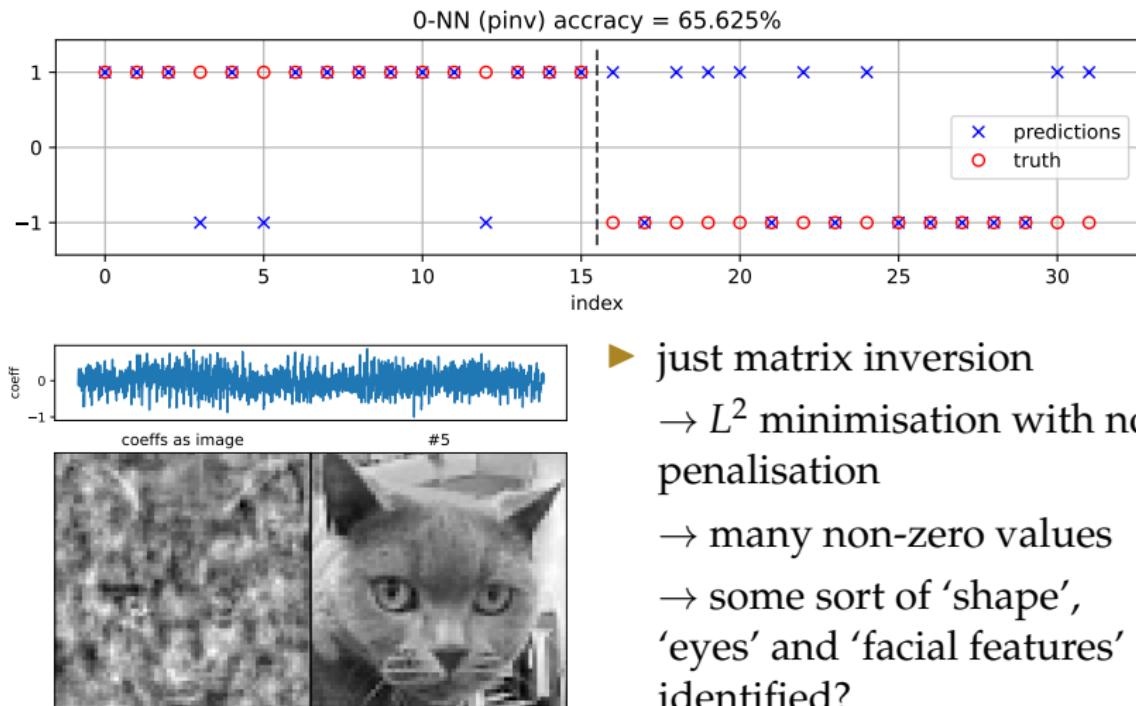
- no hidden layers, may have activation functions
- can only really do binary classification (i.e. 'percept')
- case of no activation function \Rightarrow matrix inversion essentially

Perceptrons: classification



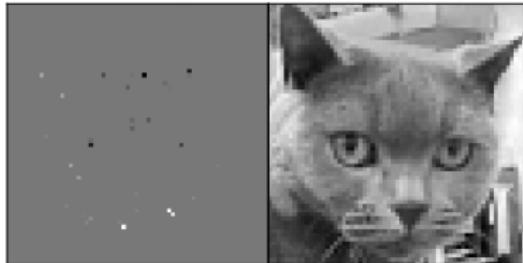
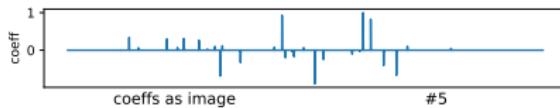
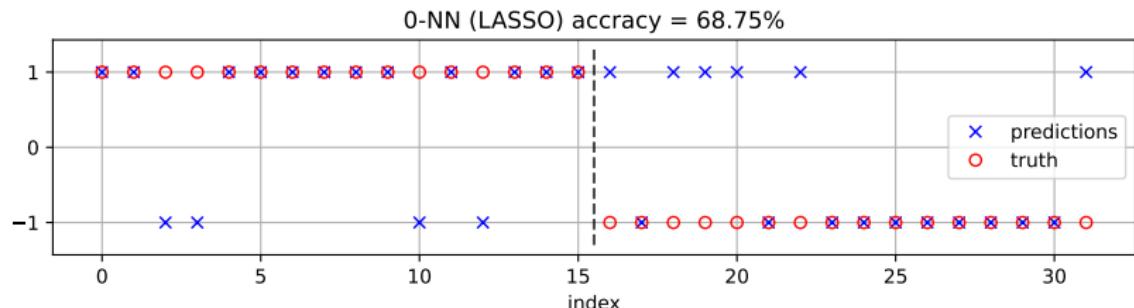
- ▶ classifying cats and dogs
 - this is a hard problem!
 - cats labelled as 1 and dogs as -1
 - throw in full image
 - standardise, train/test split
 - can probe the model in this case, **feature** identification

Perceptrons: classification



- ▶ just matrix inversion
 - L^2 minimisation with no penalisation
 - many non-zero values
 - some sort of 'shape', 'eyes' and 'facial features' identified?

Perceptrons: classification



- ▶ Lasso optimisation instead
 - L^2 minimisation with L^1 penalisation
 - promotes sparsity (but α dependent)
 - 'eyes', 'forehead' and 'mouth' important?

MLPs

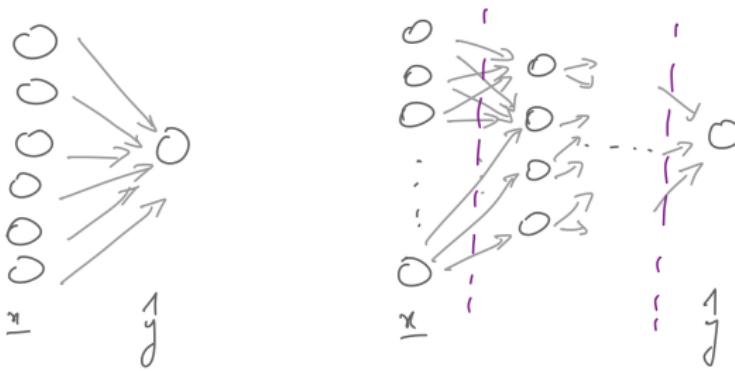


Figure: Schematic of perceptrons (no hidden layers) and MLPs (at least one hidden layer).

- ▶ **multi-layer** perceptrons (MLPs)
 - bit of a misnomer, because above limitation with perceptrons do not strictly apply
 - sometimes artificial neural networks (ANNs) (misleading?)
 - can be 'deep' neural networks (DNNs) (misleading?)

How to build the MLPs?

- ▶ single layer is easy (just matrix inversion), but multi-layers?
→ need to perform the **feed-forward** calculations... (easy)

How to build the MLPs?

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 - need to interface with the optimisers...
 - other things like **batching**, **train-test set shuffling**, **CPU/GPU capabilities**, etc...

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 - need to interface with the optimisers...
 - other things like **batching**, **train-test set shuffling**, **CPU/GPU capabilities**, etc...
- ▶ TL;DR: python has a load of packages already set up to do all the above essentially
 - basically just need to know how to call them
 - building neural nets in R actually calls the python packages...

PyTorch

- ▶ PyTorch and TensorFlow the two most popular libraries for neural networks
 - underlying them are procedure to manipulate tensors (multi-dim arrays)
 - links up to solvers and loss functions accordingly
 - have interfaces to help (e.g. Lightning and Keras)
- ▶ JAX (e.g. w/ Keras) could be used in principle



PyTorch: building the MLP

- ▶ need to convert arrays into **tensor** objects
 - so PyTorch library knows what to do with them
 - extra useful functionalities (e.g. reshaping, resizing after manipulation)

- ▶ `FloatTensor`: floats (but float32)
- ▶ `LongTensor`: signed integers
- ▶ `ByteTensor`: unsigned integers

- ▶ in principle will do ‘sane’ things, but best be explicit
 - e.g. `torch.tensor([1., 1., 1.])` will default to `FloatTensor`
 - e.g. `torch.tensor([1, 1, 1])` will default to `ByteTensor`, will **fail** when passed to conv1d

PyTorch: building the MLP

- ▶ specify neural network structure

```
# define the model architecture

class nn_classify_pets(nn.Module):
    def __init__(self): # specify input dims below
        super(nn_classify_pets, self).__init__()

        # nest it in one go
        self.layers = nn.Sequential(
            nn.Linear(64**2, 100), # image is 64**2, 100 nodes (sklearn default)
            # nn.ReLU(),           # no activation function
            nn.Linear(100, 2)     # two possible outputs
        )

    # actual model structure: input -> hidden layer -> outputs, ReLU on input and hidden
    def forward(self, x):
        out = self.layers(x)
        return out
```

- ▶ define as a class, need `__init__`
- ▶ specify network structure
- ▶ need a `forward` to specify the feed-forward
→ this is for internal **taping/annotation** for the **computation graph**, needed for back-propagation later

PyTorch: building the MLP

- ▶ define loss function
 - for binary classification we can choose CrossEntropy
 - others would work too
- ▶ define optimiser
 - use Adam again
 - need to initialise model (e.g. `model = MLP()`) and pass model parameters to the optimiser
 - telling the optimiser what are the control variables
- ▶ sequence of things to do:
 - do a feed-forward
 - evaluate loss function
 - back-propagate
 - update parameters, repeat

PyTorch: building the MLP

```
for epoch in range(num_epochs):

    # iteration step

    model.train() # put the model in training mode (taping is on)
    optimizer.zero_grad() # clear gradients if it exists (from loss.backward())
    Y_pred = model(X_train) # feed-forward
    J_train = J(Y_pred, Y_train) # compute loss
    J_train.backward() # back propagation
    optimizer.step() # iterate
    model.eval() # put the model in evaluation mode (taping is off for diags below)

    # diagnostics: evaluation of metrics as we go along
    with torch.no_grad(): # force no taping just in case
        Y_pred = model(X_valid)
        J_valid = J(Y_pred, Y_valid)
        train_J[epoch] = J_train.item()
        valid_J[epoch] = J_valid.item()
```

- ▶ above subroutine chains it all up, iterates over epochs
 - safety call to clear some calculations to avoid contamination
 - extra diagnostic calls

MLP: classification

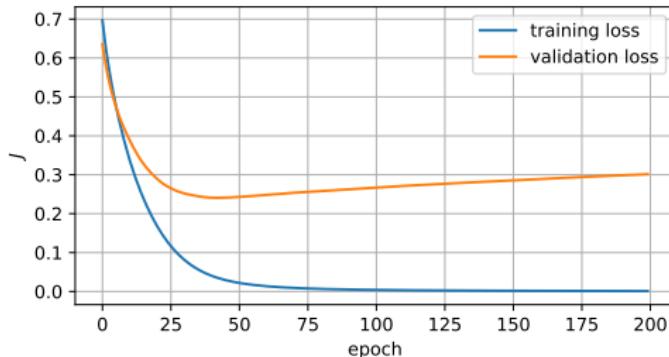


Figure: Example of a loss curve with training epoch.

- ▶ an example of a **loss curve** with training decreasing with iterations (**epoch**)
 - continues until some criterion is reached
 - **early-stopping** is possible (didn't do it here)

MLPs: classification

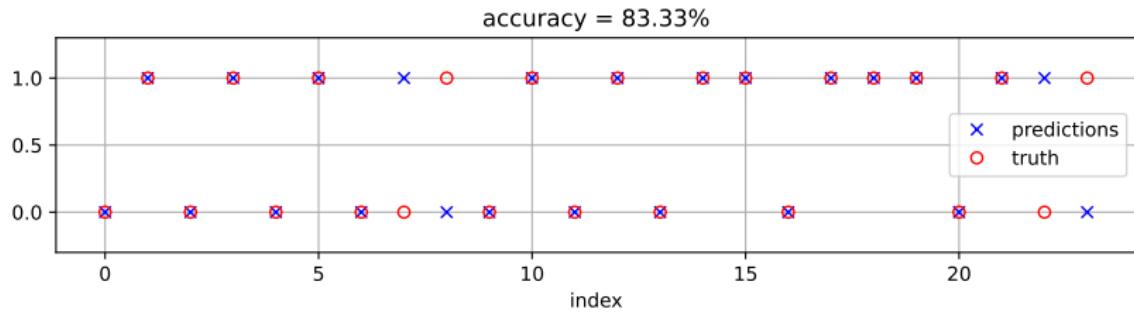


Figure: Perceptron with two hidden layers of size 200 and 50, no activation function.

- ▶ classification skill on test set
→ seems ok?

MLPs: regression problem

- ▶ just using cats
 - predict top half from bottom half (use L^2 /MSE loss)
 - vice-versa might work better?
- ▶ again, this is a hard problem!

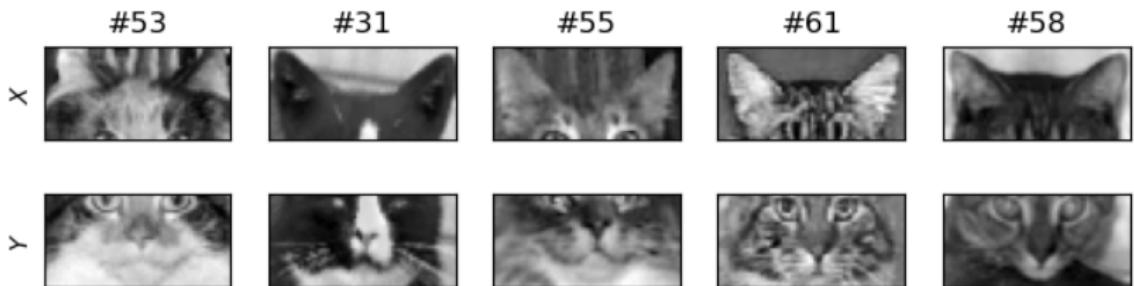


Figure: No animals were hurt in the present demonstration.

MLPs: regression problem

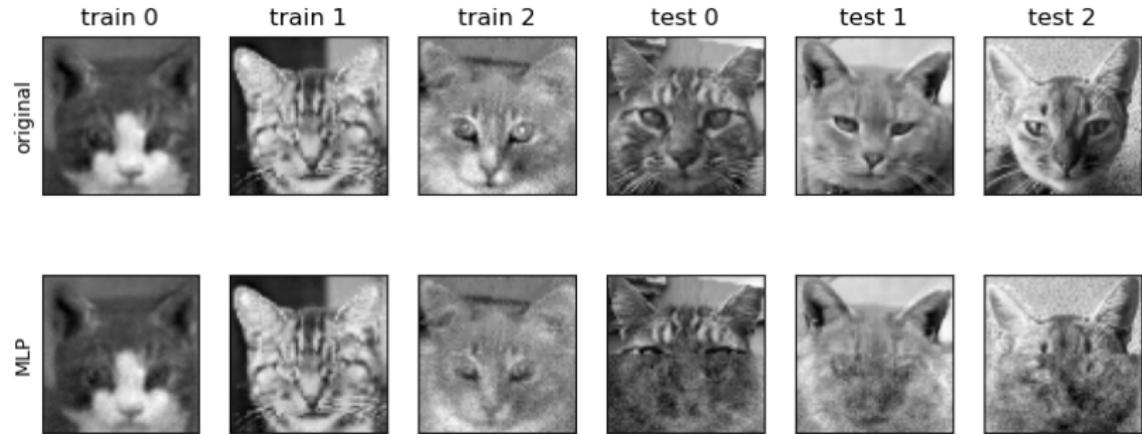


Figure: Predicting bottom half from top half, default settings.

- ▶ note that even the training set had issues doing to the prediction...
 - predictions can be quite cursed if eye happens to be in top half (e.g. grant us eyes)

MLPs: regression problem

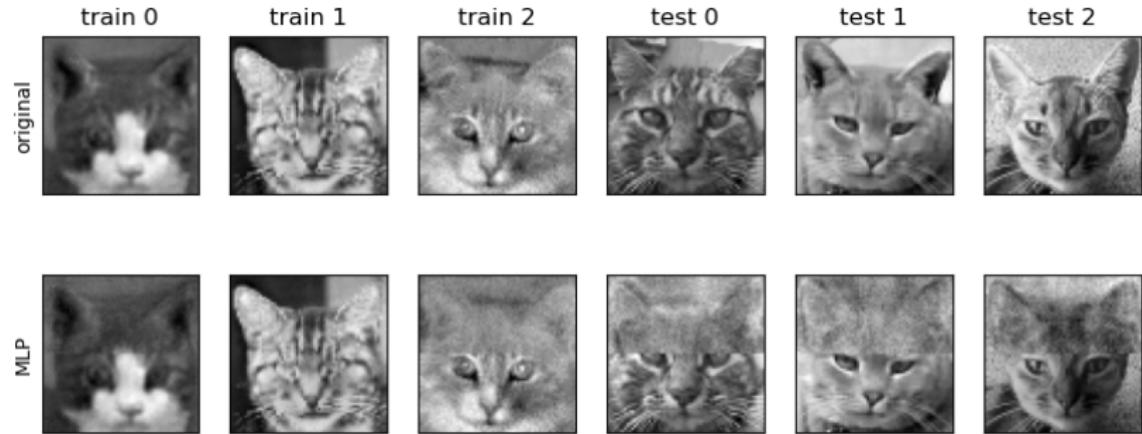


Figure: Predicting top half from bottom half, default settings.

- ▶ note that even the training set had issues doing to the prediction...
 - less cursed at least subjectively
 - at least somewhat continuous predictions?

MLPs: regression problem

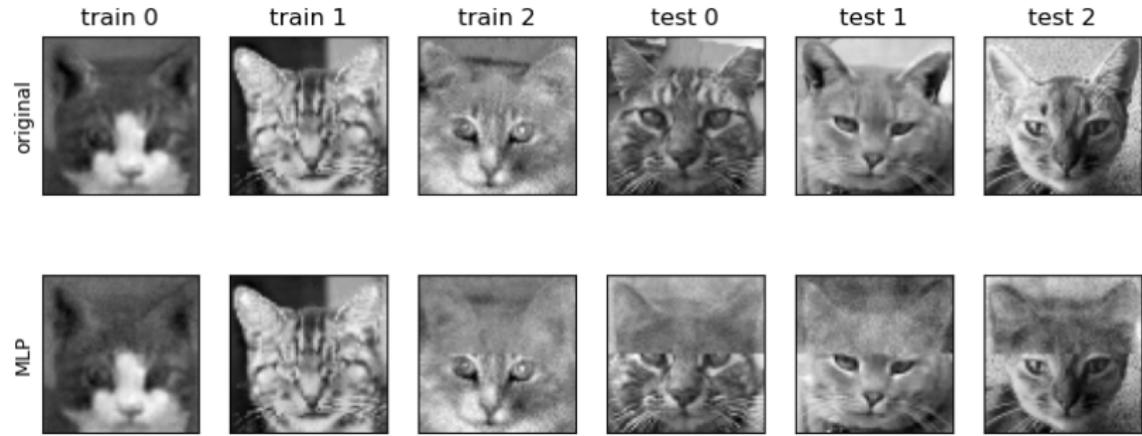


Figure: Predicting top half from bottom half, reasonably complicated.

- ▶ note that even the training set had issues doing the prediction...
 - not doing much better with substantially increased complexity

Demonstration

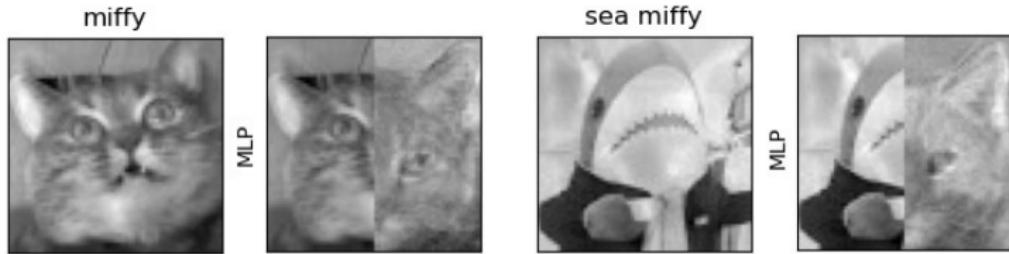


Figure: Cursed beasts reconstruction (out of sample application of MLP).

- ▶ idea behind neural networks
 - ways to control over-fitting (e.g. **dropout**, **regularisation**)
- ▶ MLPs bound by curse of dimensionality!
- ▶ need to cross-validate and tune hyper-parameters!
- ▶ basic use of PyTorch here (more things next time)

Moving to a Jupyter notebook →