

Neural Networks

Oxford Spring School in Advanced Research Methods 2025

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Day 4/5

Recap

Yesterday's session, we covered non-parametric ML methods using trees

- ▶ The estimator does not require the model form to be pre-specified
- ▶ Complex relationships can be captured via a conjunction of splits
- ▶ Two different “forest” methods can improve on the performance of CART

Today's session

Explore an even more flexible form of ML:

- ▶ Neural network architectures
- ▶ An “engineering-grade” solution
 - ▶ A lot more flexible in terms of abstract structure than forests
- ▶ Introduce the concept of deep-learning

Remainder of the session:

1. Simple neural networks
2. Deep learning
3. Different types of neural network
4. Example application in social science

Neural network terminology

Basic terminology

Input

- ▶ Data that forms an argument passed to the node

Weight

- ▶ A scalar that is *multiplied* with an input vector

Bias

- ▶ A scalar value *added* to the input vector

Node

- ▶ A computational unit that applies some function f to inputs, weights and bias

Output

- ▶ The result of the function applied at a node – typically another vector

Simple perceptron model

Suppose we have a single vector of input data x , and we want to predict the output y

A simple perceptron model looks like the following:

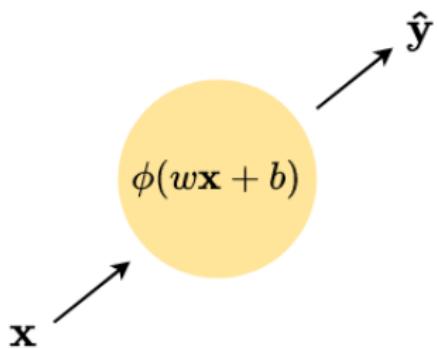


Figure 1: Single node, single layer perceptron model

w is the weight term and b is the bias term – in this simple case, both are scalar.

Activation functions ϕ

The activation function is simply a function applied to the result of $w\mathbf{x} + b$, that controls the range of the output vector

ϕ may simply be the **identity function**:

- ▶ I.e. $\phi(\mathbf{x}) = \mathbf{x}$

Sigmoid function:

- ▶ $\phi(\mathbf{x}) = \frac{1}{1+e^{-\mathbf{x}}}$

Rectified Linear Unit (ReLU):

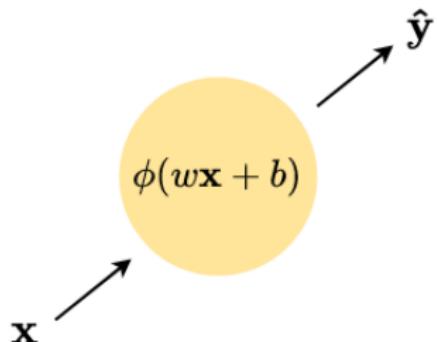
- ▶ $\phi(\mathbf{x}) = \max(0, \mathbf{x})$

Tanh:

- ▶ $\phi(\mathbf{x}) = \frac{e^{\mathbf{x}} - e^{-\mathbf{x}}}{e^{\mathbf{x}} + e^{-\mathbf{x}}}$

These functions (and others) are particularly useful because they have known derivatives – which we'll return to later!

Gaining a prediction from our simple model



Suppose:

- ▶ ϕ is the ReLU function
- ▶ $w = 2, b = 1$

And we observe the following input vector \mathbf{x} :

$$\begin{bmatrix} 5 \\ 1 \\ -1 \end{bmatrix}$$

What is $\hat{\mathbf{y}}$?

Multiple inputs

The first model is very basic, so we can adapt it to accept **multiple** inputs:

- ▶ Let k index input variables, i.e. $\mathbf{X} = \{x_1, \dots, x_k\}$
- ▶ Let \mathbf{w} be a vector of weights, i.e. $\mathbf{w} = \{w_1, \dots, w_k\}$

Inside our activation function we replace $w\mathbf{x} + b$ with

$$w_1\mathbf{x}_1 + \dots + w_k\mathbf{x}_k + b \equiv \sum_k w_k \mathbf{x}_k + b$$

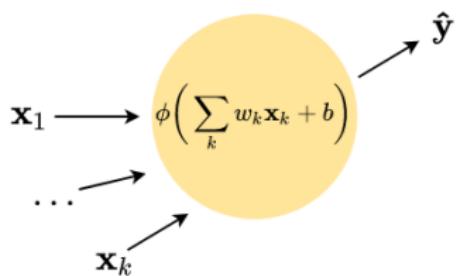


Figure 2: Single node, multiple input perceptron model

Initialisation

Like BART (and unlike CART/RF) prior to training we build the model network

For a single-node perceptron model with k inputs, that means instantiating the weights and biases

- ▶ A naive option sets $w = \mathbf{0}$
 - ▶ This is rarely optimal – it can lead to significantly slower convergence (and can even disrupt convergence entirely)

A now standard approach is to use **Xavier initialisation** where:

$$w_k \sim \mathcal{N}(0, \frac{1}{k})$$

- ▶ where k is the number of inputs to the node
- ▶ Typically used when ϕ is tanh or sigmoidal
- ▶ Bias terms are instantiated at zero

Loss functions

The goal of the perceptron is to minimise the predictive error between y and $\hat{y} = \phi(\sum_k w_k x_k + b)$

Depending on the type of prediction problem, we want to use a different function:

Continuous y

- ▶ ϕ will be linear or ReLU
- ▶ Minimise the mean squared error
- ▶ I.e. $\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2$

Binary y

- ▶ ϕ will be sigmoid
- ▶ Minimise using **cross-entropy** loss function
- ▶ I.e. $= -\frac{1}{N} \sum_{i=1}^n \sum_{c=1}^C y_{ic} \log(\hat{y}_{ic})$
 - ▶ where c indexes the classes within the binary/categorical variable

OLS/Logistic regression as a single-layer perceptron

We can construe OLS as a single-node perceptron model,

$$\mathbf{y} = \phi(b + w_1 \mathbf{x}_1 + \dots + w_k \mathbf{x}_k),$$

when:

- ▶ ϕ is the identity function
- ▶ w is the regression coefficient vector
- ▶ b is the intercept

and solved via MLE.

Similarly logistic regression is where ϕ is the sigmoid activation function.

Limitations and extensions

A single-node perceptron model is not particularly exciting:

- ▶ With identity/sigmoid activation functions we get conventional estimators
- ▶ The model is linear in inputs

To complicate our models we need to think about creating a **network** of nodes

- ▶ Increase the number of computational units
- ▶ Determine the flow of information along the network

Similar to how tree-based methods add complexity by branching

- ▶ Multiple nodes, and interactions between nodes, allow us to model complicated relationships

Deep learning

Complicating the network

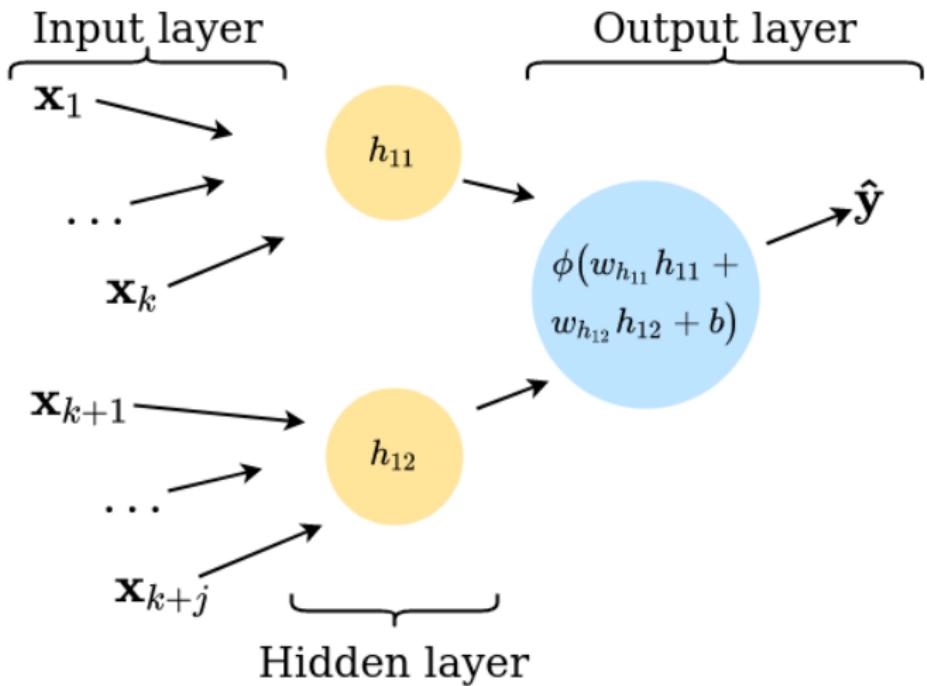


Figure 3: Multi-layer (but not deep) network

Deep neural network

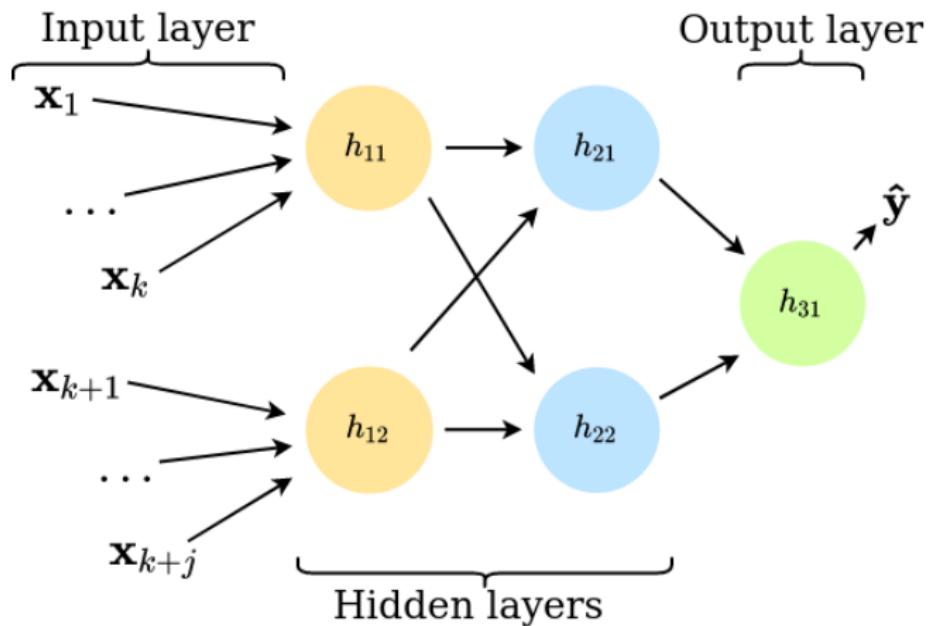


Figure 4: Multi-layer **deep** network

Multi-layer network notation

The computation of outputs through layer h of a neural network is:

$$\mathbf{y}^{(h)} = \sigma(\mathbf{W}^{(h)}\mathbf{y}^{(h-1)} + \mathbf{b}^{(h)}),$$

where:

- ▶ $\mathbf{y}^{(h)}$ is a vector of outputs from layer h
- ▶ $\mathbf{W}^{(h)}$ is a matrix of weights for layer h
- ▶ \mathbf{b} is a vector of biases for layer h
- ▶ σ is an activation function

This model can be generalized to an arbitrary number of hidden layers H :

$$\mathbf{y} = \Phi(\mathbf{W}^{(H)}[\dots[\sigma(\mathbf{W}^{(2)}[\sigma(\mathbf{W}^{(1)}\mathbf{x} + \mathbf{b}^{(1)})] + \mathbf{b}^{(2)})]\dots] + \mathbf{b}^{(H)}),$$

where \mathbf{x} is a vector of inputs and Φ is a final-layer activation function.

Fully-connected networks

In a fully connected network:

- ▶ Every output from layer h is an input to every node in layer $h + 1$

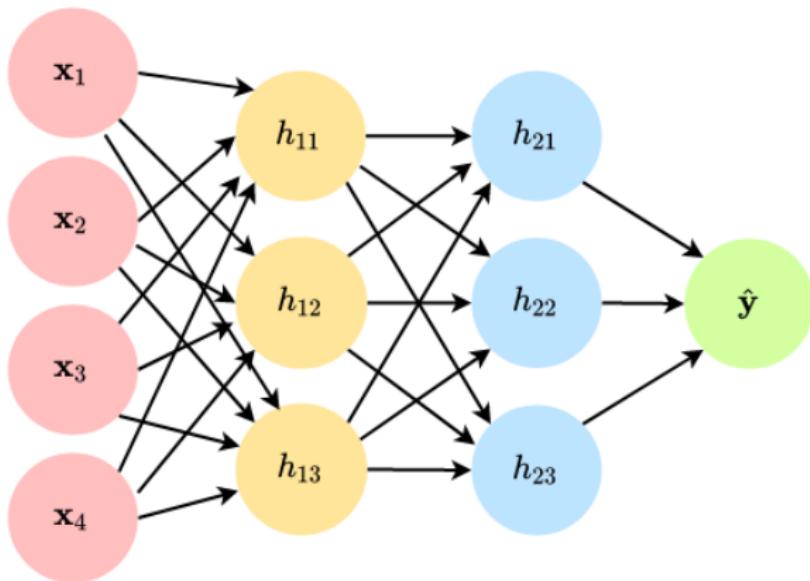


Figure 5: Fully-connected neural network

Feed-forward training

We initialise a multi-layer model like a single-layer model:

1. Set weight terms for each node within each layer via some initialisation function

During training, an **epoch** consists of:

2. Feeding every observation through the model
 - ▶ When there are no cycles in the network, this is called “feed-forward”
3. Calculate the loss associated with the prediction
4. Adjust weights and biases based on the gradient of the loss
 - ▶ This is complicated with multiple layers
 - ▶ Adjusting the weights and bias affects the output of a node.
 - ▶ ... and the input of the nodes (plural!) that it feeds into!

Repeat steps 2-4 multiple times

Backpropagation

We calculate the loss as a function of the known outcomes (y) and predicted output (\hat{y}), plus a weight decay term to prevent overfitting:

$$E = L(\mathbf{y}, \hat{\mathbf{y}}) + \lambda \|\mathbb{E}[\mathbf{W}]\|_2$$

To estimate gradient of the loss function, we can calculate it sequentially from the final layer to the first.

Once the gradient is calculated, we adjust the weights by some scaled amount γ (the learning rate):

$$\Delta \mathbf{W}^{(h)} = -\gamma \frac{\partial E}{\partial \mathbf{W}^{(h)}}$$

Optimisation details

Through two applications of the chain rule, the change in loss due to the weights in layer h is,

$$\frac{\partial E}{\partial \mathbf{W}^{(h)}} = \frac{\partial E}{\partial \mathbf{y}^{(h)}} \cdot \frac{\partial \mathbf{y}^{(h)}}{\partial \mathbf{W}^{(h)}} \quad (1)$$

$$= \frac{\partial E}{\partial \mathbf{y}^{(h+1)}} \cdot \frac{\partial \mathbf{y}^{(h+1)}}{\partial \mathbf{y}^{(h)}} \cdot \frac{\partial \mathbf{y}^{(h)}}{\partial \mathbf{W}^{(h)}}. \quad (2)$$

Estimating the terms:

- ▶ $\frac{\partial E}{\partial \mathbf{y}^{(h+1)}}$ – the derivative w.r.t. the outputs from the next layer
- ▶ $\frac{\partial \mathbf{y}^{(h+1)}}{\partial \mathbf{y}^{(h)}}$ – the derivative of the next layer's activation function
- ▶ $\frac{\partial \mathbf{y}^{(h)}}{\partial \mathbf{W}^{(h)}}$ – equal to $\mathbf{y}^{(h-1)}$, since $\mathbf{y}^{(h)}$ is the weighted sum of the inputs into layer h

Recap of neural networks

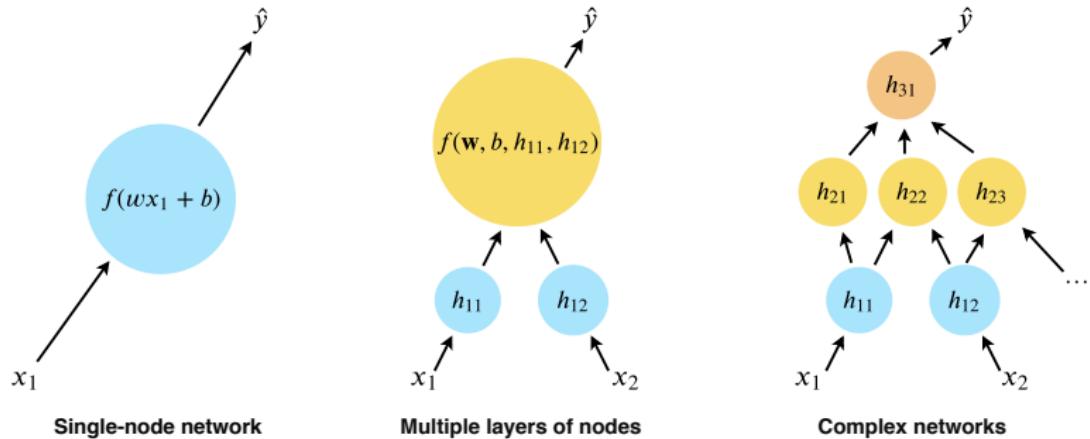


Figure 6: Developing more complex predictive networks

Neural networks in research/production
workflows

Advantages and Limitations

Deep neural networks are extremely powerful

- ▶ Currently in use across industry to solve prediction problems
- ▶ Help make film recommendations, target ads, predict complex physical processes

Neural networks rest on the aggregated power of many simple models

- ▶ Each node is a linear combination of inputs
- ▶ Each activation function will have known derivatives etc.

But deep neural networks are **black boxes**

- ▶ The hidden layers are near-unintelligible in substantive terms
- ▶ We still do not fully understand their performance!

“Engineering-grade” solution: design

Neural networks have huge design degrees of freedom

- ▶ Number of nodes
- ▶ Number of layers
- ▶ Activation functions
- ▶ Connections between nodes
 - ▶ Feed-forward or recurrent?
 - ▶ Fully-connected?
- ▶ The number of networks (!)
- ▶ The number of training epochs

We can construct different structures to help us solve different types of problem

- ▶ We'll explore a few types in remainder of this session

“Engineering-grade” solution: computation (2021)

Neural network technology is rapidly developing

- ▶ We can parallelise operations over CPUs and GPUs
- ▶ Use of algebraic objects like tensors make computation efficient
 - ▶ And corresponding new technology like tensor processing units (TPUs)



Figure 7: Google Tensor Processing Unit rack

“Engineering-grade” solution: computation (2022)

Neural network technology is rapidly developing

- ▶ We can parallelise operations over CPUs and GPUs
- ▶ Use types of algebraic objects like tensors make computation efficient
 - ▶ And corresponding new technology like tensor processing units (TPUs)



Learning data representations: Autoencoders

Classical autoencoders consist of two parts.

An *encoder* deterministically maps an input vector \mathbf{x} to a lower-dimensional representation \mathbf{y} :

$$\mathbf{y} = f_{\theta}(\mathbf{x}) = \sigma(\mathbf{W}^{(B)}[\dots[\sigma(\mathbf{W}^{(2)}[\sigma(\mathbf{W}^{(1)}\mathbf{x} + \mathbf{b}^{(1)})] + \mathbf{b}^{(2)})]\dots] + \mathbf{b}^{(B)}),$$

where B is the “bottleneck” layer consisting of fewer nodes than the input layer.

A *decoder* then maps \mathbf{y} back to a reconstructed vector \mathbf{z} of the same dimensions as \mathbf{x} :

$$\mathbf{z} = g_{\theta'}(\mathbf{y}) = \Phi(\mathbf{W}^{(H)'}[\dots[\sigma(\mathbf{W}^{(B+2)'}[\sigma(\mathbf{W}^{(B+1)'}\mathbf{y} + \mathbf{b}^{(B+1)'})] + \mathbf{b}^{(B+2)'})]\dots] + \mathbf{b}^{(H)'})$$

Autoencoder graph

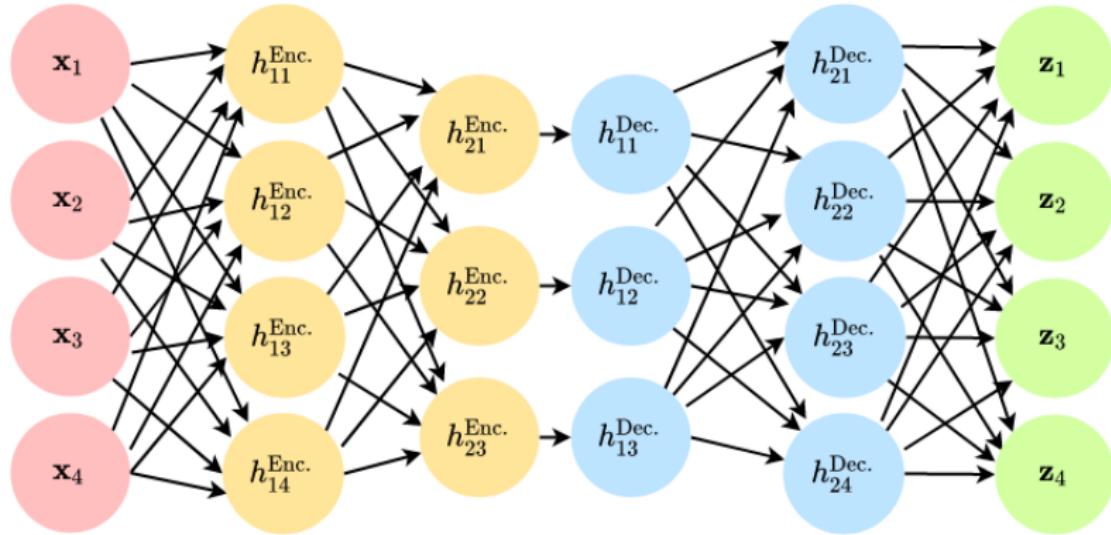


Figure 9: Graphical depiction of an autoencoder network

Uses and limitations of classical autoencoders

Autoencoders perform dimensionality reduction:

- ▶ Find a lower-dimensional representation y that captures the “essence” of x
- ▶ Could be repurposed for finding latent concepts in social science
 - ▶ Where decoding element is not necessary

It is quite easy to learn/approximate the **identity function**:

- ▶ Combination of nodes perfectly reconstructs input through layers of the network
- ▶ Leads to loss values of zero in-training
- ▶ And likely very poor performance out-of-sample
- ▶ I.e. overfitting

When we face a problem of overfitting what do we do?

Denoising autoencoders as regularised autoencoders

Denoising autoencoders corrupt the input:

$$\mathbf{x} \rightarrow \tilde{\mathbf{x}} \sim q_D(\mathbf{x}|\tilde{\mathbf{x}}).$$

The corrupted input is then mapped to a hidden representation

$$\mathbf{y} = f_\theta(\tilde{\mathbf{x}}),$$

from which a clean or “denoised” version is reconstructed:

$$\mathbf{z} = g_{\theta'}(\mathbf{y}).$$

Unlike before, $\hat{\mathbf{y}}$ is now a deterministic function of $\tilde{\mathbf{x}}$ (not \mathbf{x}).

- ▶ Loss is calculated with respect to the original input data \mathbf{x} and “cleaned” data
- ▶ Hence learning identity function is not optimal in training

Dropout as additional regularisation

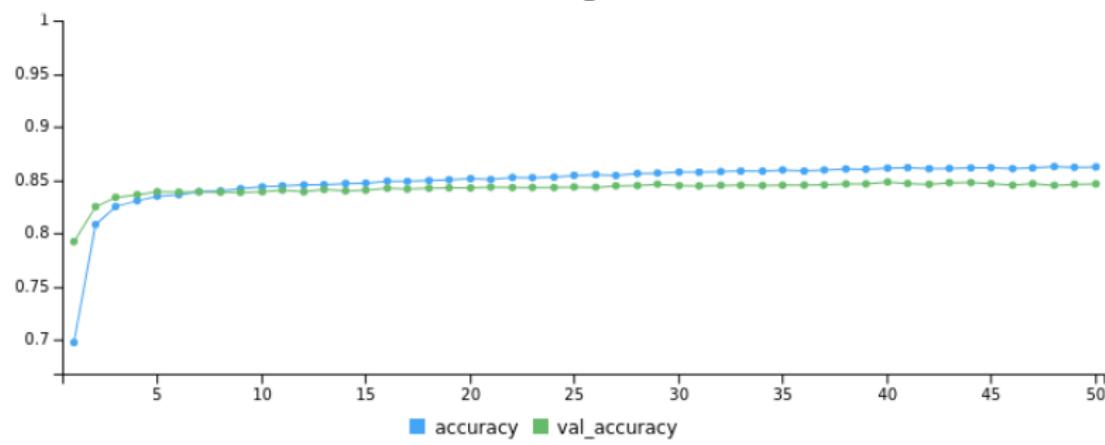
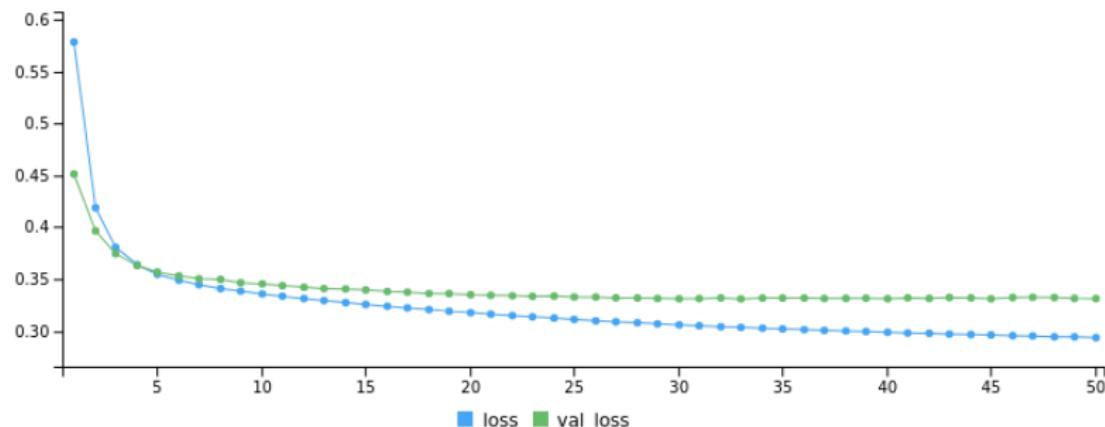
We can also regularise the *nodes* of our network, via a process called **dropout**:

- ▶ We randomly “drop” nodes from the network
- ▶ This occurs randomly for each epoch and draw
- ▶ Goal is to force the network to model a distribution of functions that describe the data

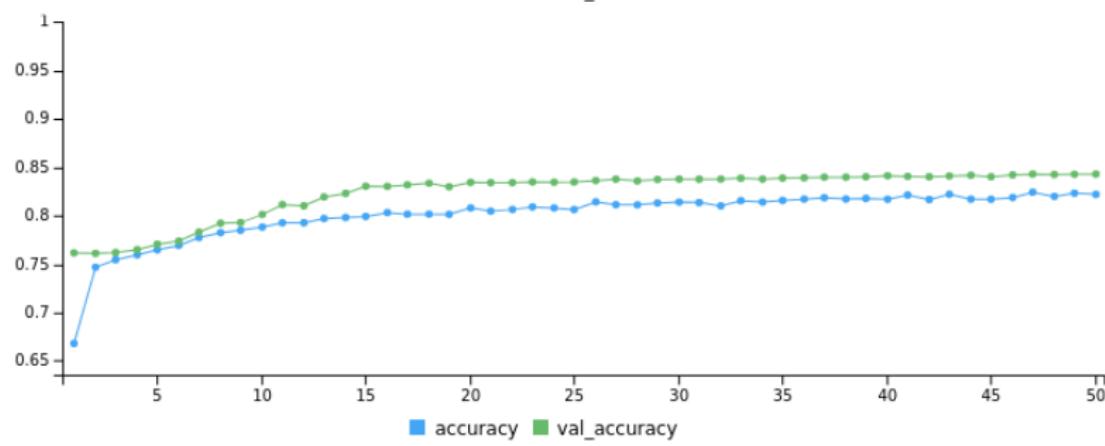
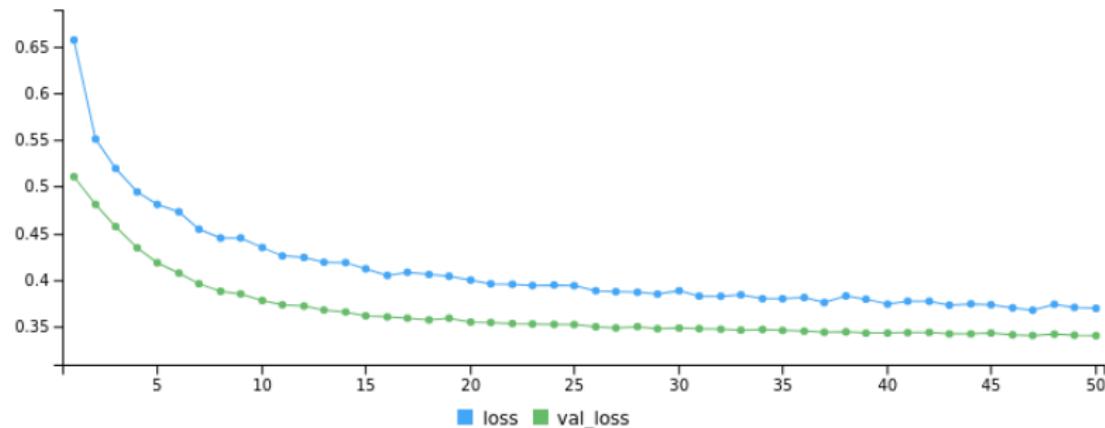
Dropout has the effect of:

- ▶ Increasing the uncertainty of our model
- ▶ Making the predictions *stochastic*
- ▶ Approximating a **Gaussian Process**

Example of training **without** dropout



Example of training **with** dropout



Takeaways

Notice that **without** dropout:

- ▶ Decline in loss is initially steeper
- ▶ Validation loss starts to stabilise while training loss continues to decrease
- ▶ A sign of overfitting!

With dropout:

- ▶ Model takes longer to reduce the loss
- ▶ But we avoid overfitting (over the same number of epochs)
- ▶ Example of better regularisation

MIDAS neural network (Lall and Robinson 2022)

[More information](#)

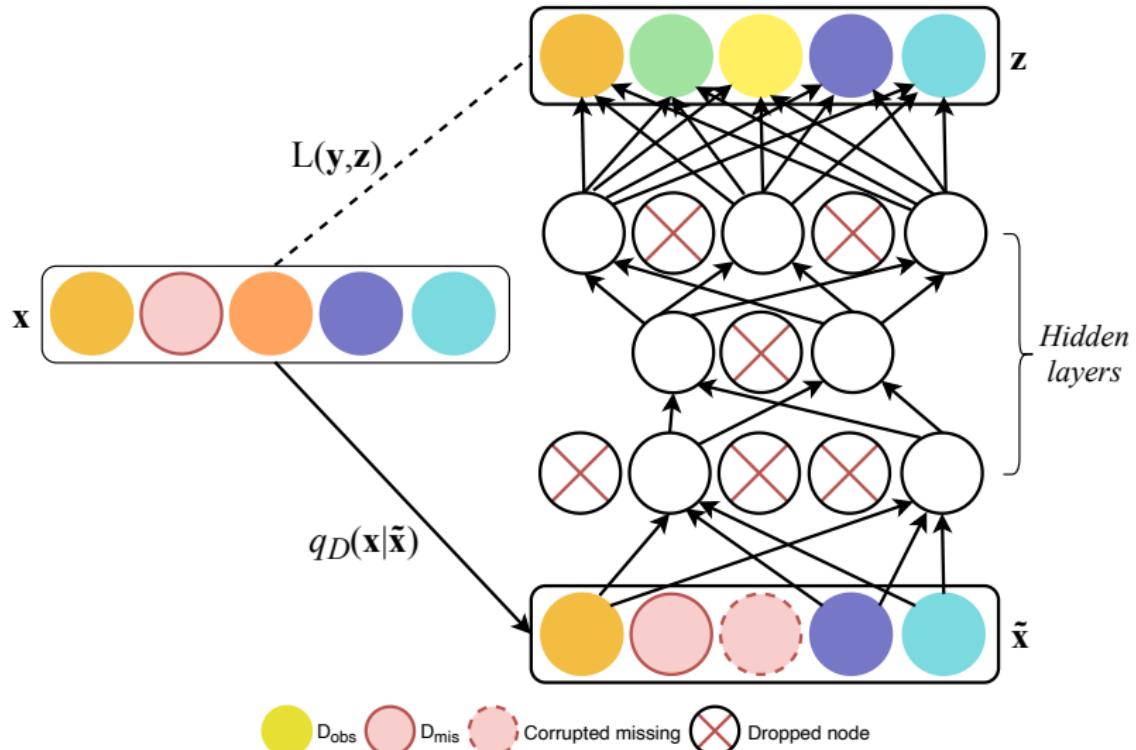
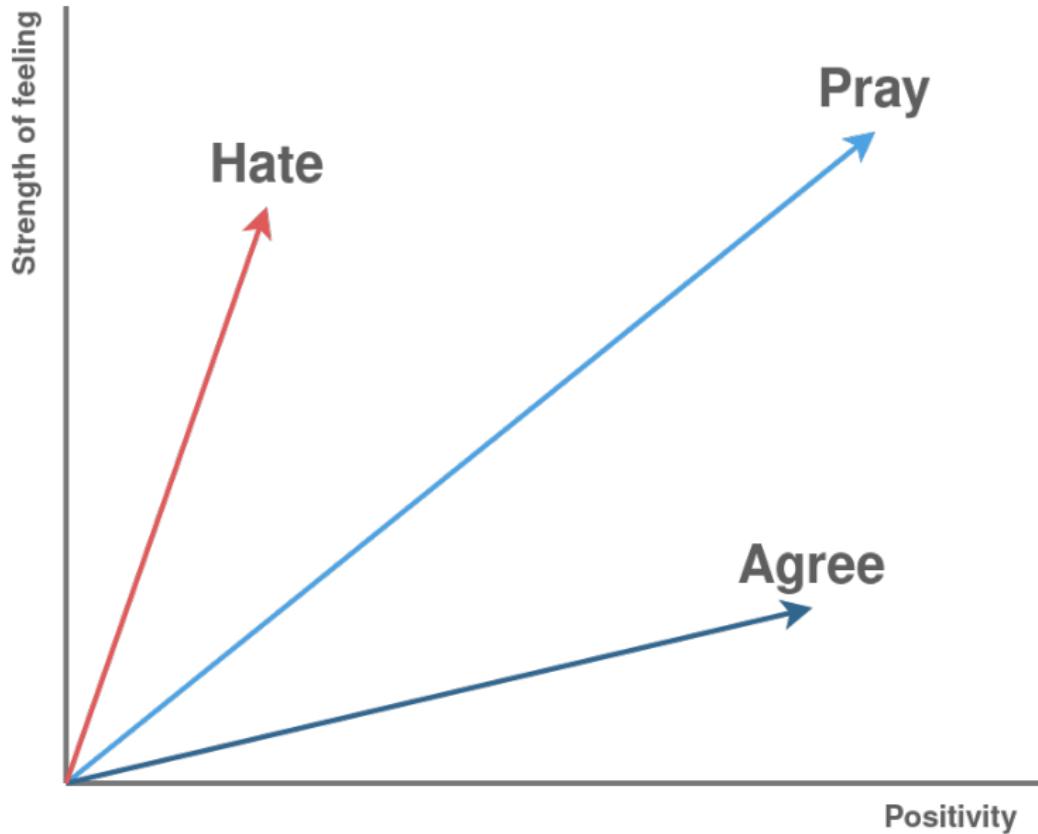


Figure 12: MIDAS network structure

Application: Neural networks and text

How similar are two words?



Word embeddings

We can generalise this idea:

- ▶ Represent each word as a vector through K-dimensional space
- ▶ Expect that similar words will have more similar vectors

$$King - Man + Woman = Queen$$

Dimensionality reducing

Embeddings are **dense** representations of words using numbers:

- ▶ Dimensionality-reducing (compared to a sparse representation)

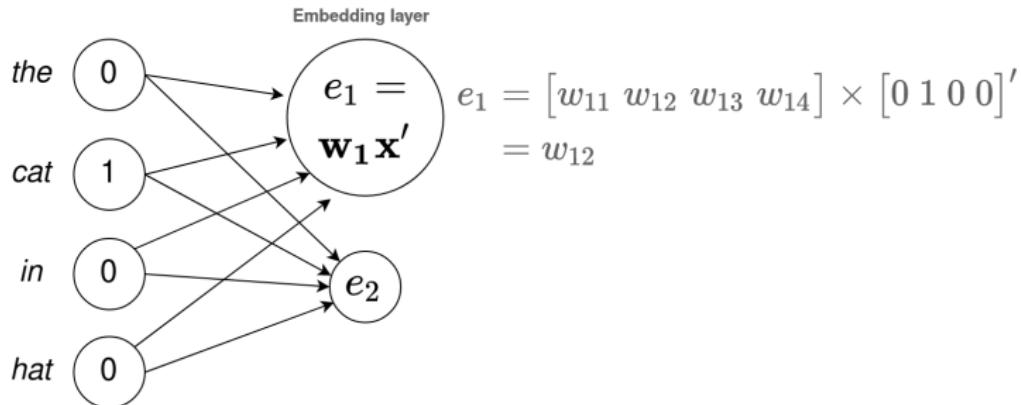
word	Sparse				Dense		
	k_1	k_2	\dots	k_V	e_1	e_2	e_3
a	1	0	\dots	0	0.89	0.5	0.23
aardvark	0	1	\dots	0	0.01	0.88	0.78
...	:	:	\ddots	:	:	:	:
zyzzyva	0	0	\dots	1	0.03	0.79	0.66

Representing an embedding dimension as a network weight

We saw with autoencoders that NN's can be used to perform dimensionality reduction

- ▶ Word embeddings extend this logic
- ▶ Use weight vector in a feed-forward neural network to store embedding values for each word

"The **cat** in the hat"

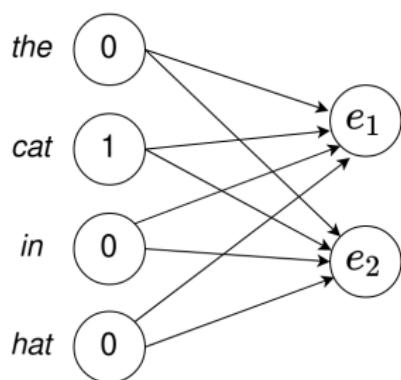


Word embedding as a matrix

This process is repeated for each embedding dimension

- ▶ We can stack the weights for the layer as a matrix
- ▶ Given one-hot input, we return one column per word...
 - ▶ The word embedding vector!

"The **cat** in the hat"



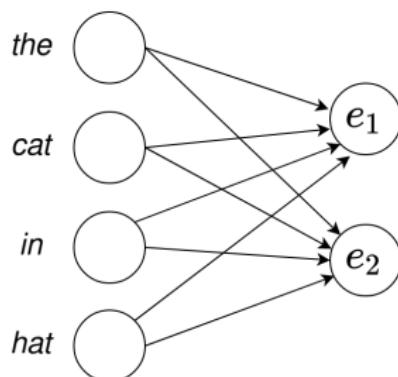
$$\begin{aligned}E^{“cat”} &= \begin{bmatrix} w_{11} & w_{12} & w_{13} & w_{1,4} \\ w_{21} & w_{22} & w_{23} & w_{2,4} \end{bmatrix} \times [0 \ 1 \ 0 \ 0]' \\&= \begin{bmatrix} w_{12} \\ w_{22} \end{bmatrix}\end{aligned}$$

Word embeddings as a lookup table

As we change our input word, we get the corresponding word vector

- ▶ $\mathbf{Ex'}$ is a lookup table

"The **cat** in the hat"



$$E = \begin{bmatrix} w_{11} & w_{12} & w_{13} & w_{1,4} \\ w_{21} & w_{22} & w_{23} & w_{2,4} \end{bmatrix}$$
$$\underbrace{\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}}_{E^{“the”}} \quad \underbrace{\begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}}_{E^{“cat”}} \quad \underbrace{\begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}}_{E^{“in”}} \quad \underbrace{\begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}}_{E^{“hat”}}$$

Estimating the embeddings

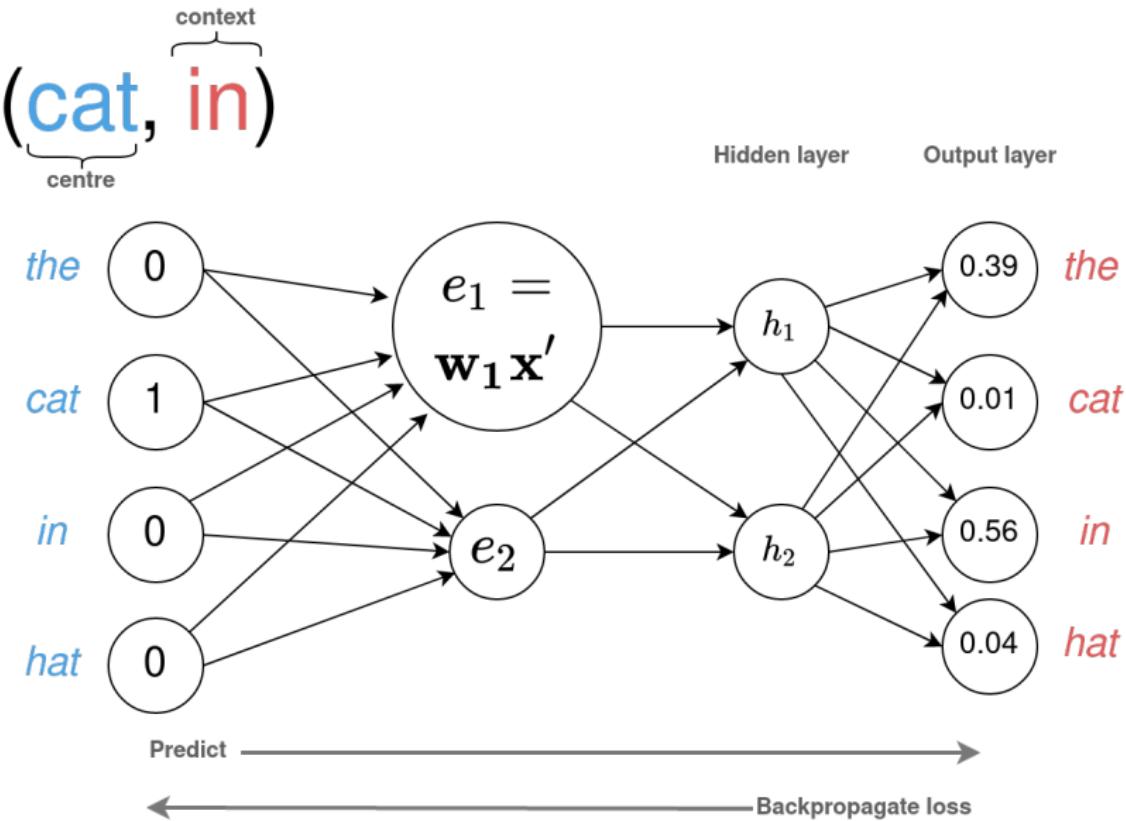
The challenge is to estimate these weights, but at present we have an incomplete model:

- ▶ No output vector
- ▶ No loss function
- ▶ No error to backpropagate

Mikolov et al (2013) come up with innovative solution:

- ▶ Given a **centre** word, predict the **context** word around it – **skipgram** model
- ▶ Sequentially move a **window** through text, creating new (centre, context) pairs
- ▶ Backpropagate loss between predicted and actual context words

A skipgram word embeddings model



Advances and Examples

Rodriguez and Spirling (2022)

- ▶ “What Works, What Doesn’t, and How to Tell the Difference for Applied Research”

Genaro and Ash (2022)

- ▶ “Emotion and Reason in Political Language”

Bellodi (2022)

- ▶ “A Dynamic Measure of Bureaucratic Reputation: New Data for New Theory”

Extra slides

MIDAS software in Python and R



Figure 13: Python instructions



Figure 14: R instructions

MIDAS network with dropout

Dropout involves multiplying outputs from each layer by a Bernoulli vector \mathbf{v} :

$$\tilde{\mathbf{y}}^{(h)} = \mathbf{v}^{(h)} \mathbf{y}^{(h)}, \mathbf{v}^{(h)} \sim \text{Bernoulli}(p).$$

- ▶ When $v_i^{(h)} = 0$ then that output adds nothing to any connected nodes in the next layer

The trained denoising encoder with dropout can thus be described as:

$$\tilde{\mathbf{y}} = f_{\theta}(\tilde{\mathbf{x}}) = \sigma(\mathbf{W}^{(B)} \mathbf{v}^{(B)} [\dots [\sigma(\mathbf{W}^{(2)} \mathbf{v}^{(2)} [\sigma(\mathbf{W}^{(1)} \tilde{\mathbf{x}} + \mathbf{b}^{(1)})] + \mathbf{b}^{(2)})] \dots] + \mathbf{b}^{(B)}).$$

The decoder, in turn, becomes:

$$\mathbf{z} = g_{\theta'}(\tilde{\mathbf{y}}) = \Phi(\mathbf{W}^{(H)'} [\dots [\sigma(\mathbf{W}^{(B+2)'} [\sigma(\mathbf{W}^{(B+1)'} \tilde{\mathbf{y}} + \mathbf{b}^{(B+1)'})] + \mathbf{b}^{(B+2)'})] \dots] + \mathbf{b}^{(H)'})$$

where $g \stackrel{\sim}{\sim} \text{GP}$ and \mathbf{z} represents a fully observed vector containing predictions of $\tilde{\mathbf{x}}_{\text{obs}}$ and $\tilde{\mathbf{x}}_{\text{mis}}$.

MIDAS activation functions

MIDAS uses the exponential linear unit as its default activation function

- ▶ Facilitates efficient training in deep neural networks

The final-layer activation function is:

- ▶ Identity if \mathbf{x} is continuous
- ▶ Logistic if \mathbf{x} is binary
- ▶ Softmax if \mathbf{x} is categorical

MIDAS measures loss with respect to deliberately corrupted values only ($\tilde{\mathbf{x}}_{\text{obs}}$) by multiplying by the corruption indicator \mathbf{r}

Loss calculations:

$$L(\mathbf{x}, \mathbf{z}, \mathbf{r}) = \begin{cases} \left[\frac{1}{J} \sum_{j=1}^J \mathbf{r}_j (\mathbf{x}_j - \mathbf{z}_j)^2 \right]^{\frac{1}{2}} & \text{if } \mathbf{x} \text{ is continuous} \\ -\frac{1}{J} \sum_{j=1}^J \mathbf{r}_j [\mathbf{x}_j \log \mathbf{z}_j + (1 - \mathbf{x}_j) \log(1 - \mathbf{z}_j)] & \text{if } \mathbf{x} \text{ is categorical.} \end{cases}$$

MIDAS algorithm

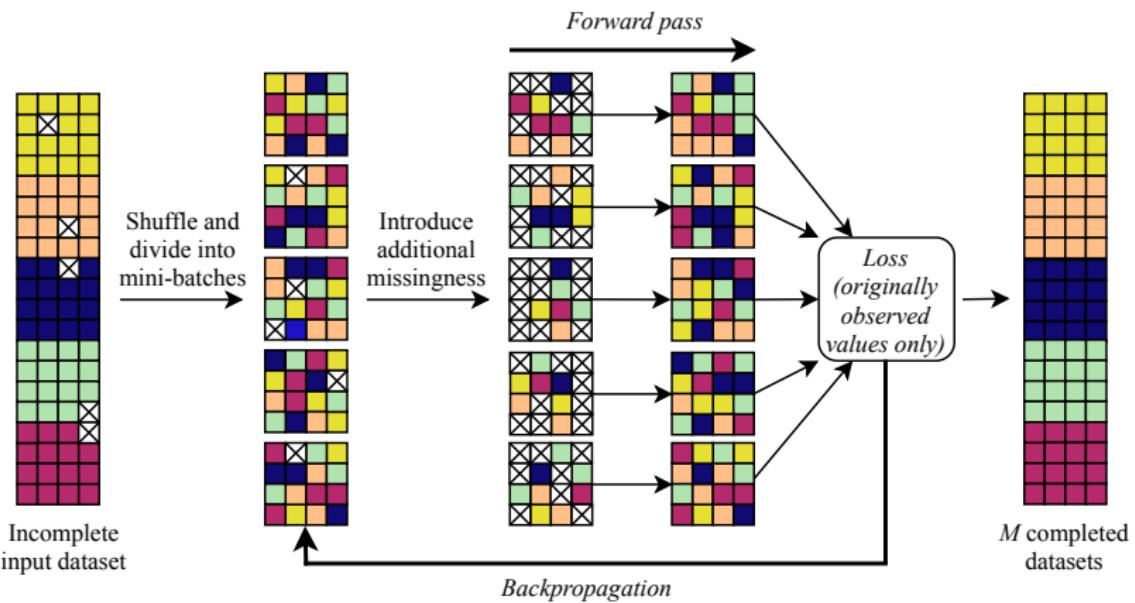


Figure 15: Algorithm Steps for training a MIDAS network

Flexibly impute time trends

Existing strategies also struggle with non-exchangeable data

- ▶ E.g. panel data
- ▶ Most assume linear independence between observations
- ▶ Or require additional time polynomial terms
- ▶ MIDAS is complex enough to implicitly detect these trends

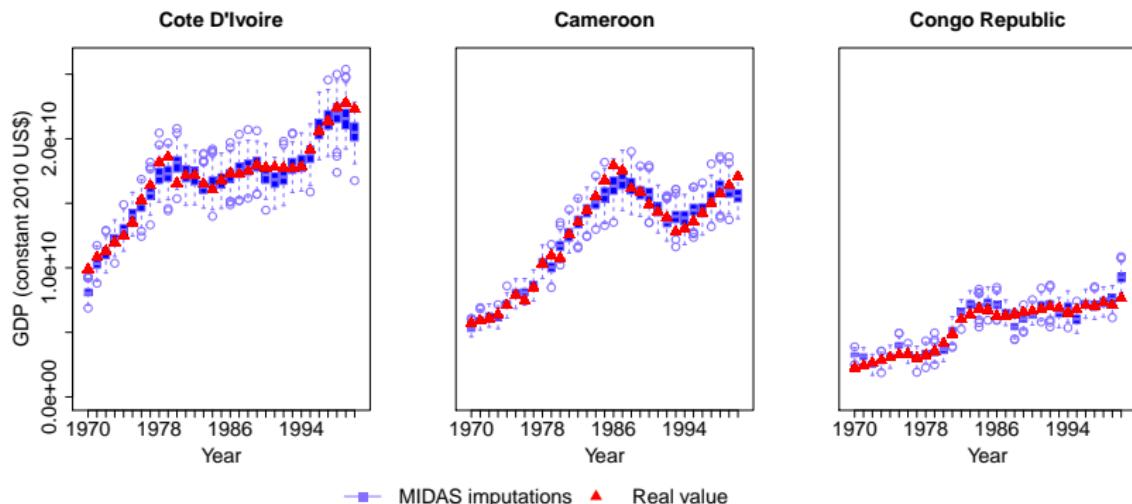


Figure 16: WDI Imputation

Synthetic data

One particularly exciting avenue for neural net. applications is in “creative” tasks:

- ▶ Constructing more realistic vignettes
- ▶ Synthesizing data

Given some training data, how might we produce new data that have similar features (and covariances):

- ▶ Given a series of text, can we produce new “sensible” text?
- ▶ Given a set of images, can we create new and plausible images?

Generative Adversarial Networks

The problem with synthetic data is that it requires labelling “on the fly”:

- ▶ What we want to validate is produced by the model itself
- ▶ Training would be slow if we have to hand-label the outputs!

Generative adversarial networks solve this problem by splitting in two:

- ▶ **Model A** is trained to *generate* new content based on some real examples \mathbf{X}
 - ▶ Denote this $\mathbf{X}'^{\text{Gen.}}$.
 - ▶ Let \mathbf{X}' be the set $\{\mathbf{X}'^{\text{Real}}, \mathbf{X}'^{\text{Gen.}}\}$
- ▶ **Model B** is trained to detect whether some $x' \in \mathbf{X}'$ is “Gen.” or “Real”
 - ▶ Called the Discriminator model

GAN optimisation

We have two networks with **competing** (hence adversarial) goals:

- ▶ **Model A** wants to maximise the error of **Model B**
- ▶ **Model B** wants to minimise its prediction error

When trained in tandem, **Model A** tries to create ever more realistic new observations that **Model B** cannot distinguish

- ▶ In turn, **Model B** gets more discriminant over time
- ▶ Forcing **Model A** to improve!

GAN-generated portraits:



Figure 17: NVidia StyleGAN2 synthetic images