Introduction to Convolutional Neural Networks
What is a Neuron?

- A neuron is a computational unit in the neural network that exchanges messages with each other.

Possible activation functions:

- Step function/threshold function
- Sigmoid function (a.k.a, logistic function)
Feed Forward & Backpropagation

Feed forward algorithm:
• Activate the neurons from the left to the right.

Backpropagation:
• Randomly initialize the parameters
• Calculate total error at the right, $f_6(e)$
• Then calculate contributions to error, $\delta_n$, at each step going backwards.
\[ f(x) = \frac{1}{1 + e^{-x}} \]

\[ x = -0.06 \times 2.7 + -2.5 \times -8.6 + 1.4 \times 0.002 = 21.34 \]
**Training data**

<table>
<thead>
<tr>
<th>Fields</th>
<th>class</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4 2.7 1.9</td>
<td>0</td>
</tr>
<tr>
<td>3.8 3.4 3.2</td>
<td>0</td>
</tr>
<tr>
<td>6.4 2.8 1.7</td>
<td>1</td>
</tr>
<tr>
<td>4.1 0.1 0.2</td>
<td>0</td>
</tr>
<tr>
<td>etc …</td>
<td></td>
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**Initialise with random weights**
Training data

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</tr>
<tr>
<td>4.1</td>
<td>0.1</td>
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</table>

etc …

Present a training pattern
Training data

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Feed it through to get output
**Training data**

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</table>

Compare with target output

```
1.4 2.7 0.8 0
1.9 0.8 0 error 0.8
```
### Training data

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#### Adjust weights based on error

1.4
2.7
1.9

error 0.8

0
Training data

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Present a training pattern
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etc …

Feed it through to get output

```
6.4
2.8
1.7
```

```
0.9
```
### Training data

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</tr>
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<td>4.1</td>
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</tr>
<tr>
<td>etc…</td>
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**Compare with target output**

- **error**: -0.1
- **class**: 1
- **output**: 0.9

![Diagram](image)
**Training data**

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</tr>
<tr>
<td>3.8</td>
<td>0</td>
</tr>
<tr>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>0</td>
</tr>
<tr>
<td><strong>6.4</strong></td>
<td><strong>1</strong></td>
</tr>
<tr>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>1.7</td>
<td></td>
</tr>
<tr>
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<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>etc …</td>
<td></td>
</tr>
</tbody>
</table>

Adjust weights based on error

```
6.4 2.8 1.7 1
error -0.1
```
Training data

### Fields | class
--- | ---
1.4 2.7 1.9 | 0
3.8 3.4 3.2 | 0
6.4 2.8 1.7 | 1
4.1 0.1 0.2 | 0
etc …

And so on ….

Repeat this thousands, maybe millions of times – each time taking a random training instance, and making slight weight adjustments.

*Algorithms for weight adjustment are designed to make changes that will reduce the error*
The Main Points to Remember

• weight-learning algorithms for NNs are “simple”

• they work by making thousands and thousands of tiny adjustments, each making the network do better at the most recent pattern, but perhaps a little worse on many others

• but, by “luck”, eventually this tends to be good enough to learn effective classifiers for many real applications
The Decision Boundary Perspective

Initial random weights
The Decision Boundary Perspective

Present a training instance / adjust the weights
The Decision Boundary Perspective

Present a training instance / adjust the weights
The Decision Boundary Perspective

Present a training instance / adjust the weights
The Decision Boundary Perspective

Present a training instance / adjust the weights
The Decision Boundary Perspective

Eventually ....
If \( f(x) \) is linear, the NN can only draw straight decision boundaries (even if there are many layers of units).
NNs use nonlinear $f(x)$ so they can draw complex boundaries, but keep the data unchanged.

SVMs only draw straight lines, but they transform the data first in a way that makes that OK.
**Limitations of Neural Networks**

**Random initialization + densely connected networks** lead to:

- **High cost**
  - Each neuron in the neural network can be considered as a logistic regression.
  - Training the entire neural network is to train all the interconnected logistic regressions.

- **Difficult to train as the number of hidden layers increases**
  - Recall that logistic regression is trained by gradient descent.
  - In backpropagation, gradient is progressively getting more dilute. That is, below top layers, the correction signal $\delta n$ is minimal.

- **Stuck in local optima**
  - The objective function of the neural network is usually not convex.
  - The random initialization does not guarantee starting from the proximity of global optima.

- **Solution**
  - Deep Learning/Learning multiple levels of representation
What exactly is deep learning?

Why is it generally better than other methods on image, speech and certain other types of data?

The short answers

“Deep Learning” means using a neural network with several layers of nodes between input and output.

The series of layers between input & output do feature identification and processing in a series of stages, just as our brains seem to.
Multi-layer neural networks have been around for about 25 years. What’s actually new?

We have always had good algorithms for learning the weights in networks with 1 hidden layer. But these algorithms are not good at learning the weights for networks with more hidden layers. What’s new is: algorithms for training many-layer networks.
How to Train a Multi-Layer Network

Train this layer first then this layer then this layer then this layer finally this layer
EACH of the (non-output) layers is trained to be an **auto-encoder**. Basically, it is forced to learn good features that describe what comes from the previous layer.
Networks for Deep Learning

- **Deep Belief Networks** and **Autoencoders** employs layer-wise unsupervised learning to initialize each layer and capture multiple levels of representation simultaneously.


- **Convolutional Neural Network** organizes neurons based on animal’s visual cortex system, which allows for learning patterns at both local level and global level.

**Deep Belief Networks**

- A *deep belief network* (DBN) is a probabilistic, generative model made up of multiple layers of hidden units.
  - A composition of simple learning modules that make up each layer

- A DBN can be used to generatively pre-train a DNN by using the learned DBN weights as the initial DNN weights.
  - Back-propagation or other discriminative algorithms can then be applied for fine-tuning of these weights.

- Advantages:
  - Particularly helpful when limited training data are available
  - These pre-trained weights are closer to the optimal weights than are randomly chosen initial weights.
Convolutional Neural Networks

• Convolutional Neural Networks are inspired by mammalian visual cortex.
  • The visual cortex contains a complex arrangement of cells, which are sensitive to small sub-regions of the visual field, called a receptive field. These cells act as local filters over the input space and are well-suited to exploit the strong spatially local correlation present in natural images.
  • Two basic cell types:
    • Simple cells respond maximally to specific edge-like patterns within their receptive field.
    • Complex cells have larger receptive fields and are locally invariant to the exact position of the pattern.
Yann LeCun

(56, born in Paris, now lives in NYC)

LeNet image recognition
inventor of backpropagation methods for training, and of convolutional neural nets

current director of Artificial Intelligence at Facebook
Convolutional Neural Network for Image Classification
Convolution + ReLU  Pooling  Convolution + ReLU  Pooling  Fully Connected  Fully Connected  Output Predictions

dog (0.01)  cat (0.04)  boat (0.94)  bird (0.02)
Representation of an Image as Pixels
<table>
<thead>
<tr>
<th>Operation</th>
<th>Filter</th>
<th>Convolved Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identity</td>
<td>$\begin{bmatrix} 0 &amp; 0 &amp; 0 \ 0 &amp; 1 &amp; 0 \ 0 &amp; 0 &amp; 0 \end{bmatrix}$</td>
<td><img src="camel_head.jpg" alt="Image" /></td>
</tr>
<tr>
<td>Edge detection</td>
<td>$\begin{bmatrix} 1 &amp; 0 &amp; -1 \ 0 &amp; 0 &amp; 0 \ -1 &amp; 0 &amp; 1 \end{bmatrix}$</td>
<td><img src="camouflage.jpg" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td>$\begin{bmatrix} 0 &amp; 1 &amp; 0 \ 1 &amp; -4 &amp; 1 \ 0 &amp; 1 &amp; 0 \end{bmatrix}$</td>
<td><img src="camouflage.jpg" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td>$\begin{bmatrix} -1 &amp; -1 &amp; -1 \ -1 &amp; 8 &amp; -1 \ -1 &amp; -1 &amp; -1 \end{bmatrix}$</td>
<td><img src="camouflage.jpg" alt="Image" /></td>
</tr>
<tr>
<td>Sharpen</td>
<td>$\begin{bmatrix} 0 &amp; -1 &amp; 0 \ -1 &amp; 5 &amp; -1 \ 0 &amp; -1 &amp; 0 \end{bmatrix}$</td>
<td><img src="camouflage.jpg" alt="Image" /></td>
</tr>
<tr>
<td>Box blur</td>
<td>$\frac{1}{9} \begin{bmatrix} 1 &amp; 1 &amp; 1 \ 1 &amp; 1 &amp; 1 \ 1 &amp; 1 &amp; 1 \end{bmatrix}$</td>
<td><img src="camouflage.jpg" alt="Image" /></td>
</tr>
<tr>
<td>(normalized)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gaussian blur</td>
<td>$\frac{1}{16} \begin{bmatrix} 1 &amp; 2 &amp; 1 \ 2 &amp; 4 &amp; 2 \ 1 &amp; 2 &amp; 1 \end{bmatrix}$</td>
<td><img src="camouflage.jpg" alt="Image" /></td>
</tr>
<tr>
<td>(approximation)</td>
<td></td>
<td></td>
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</tbody>
</table>
The ReLU (Rectified Linear Unit) Operation

Output = Max(zero, Input)
The Max Pooling Operation

Max(1, 1, 5, 6) = 6

Rectified Feature Map
Pooling Applied to Rectified Feature Maps

Convolution using 3 filters + ReLU

Pooling applied separately on each feature map

Input Image

Rectified Feature Maps
Pooling Applied to Rectified Feature Maps
**Training of a Convolutional Neural Net**

**Step 1:** Initialize all filters and parameters / weights with random values.

**Step 2:** The network takes a training image as input, goes through the forward propagation step (convolution, ReLU and pooling operations along with forward propagation in the Fully Connected layer) and finds the output probabilities for each class.

Let's say the output probabilities for the boat image above are [0.2, 0.4, 0.1, 0.3]

Since weights are randomly assigned for the first training example, output probabilities are also random.

**Step 3:** Calculate the total error at the output layer (summation over all 4 classes)

\[
\text{Total Error} = \sum \frac{1}{2} (\text{target probability} - \text{output probability})^2
\]

**Step 4:** Use Backpropagation to calculate the gradients of the error with respect to all weights in the network and use gradient descent to update all filter values / weights and parameter values to minimize the output error.

The weights are adjusted in proportion to their contribution to the total error.

When the same image is input again, output probabilities might now be [0.1, 0.1, 0.7, 0.1], which is closer to the target vector [0, 0, 1, 0].

This means that the network has learnt to classify this particular image correctly by adjusting its weights / filters such that the output error is reduced.

Parameters like number of filters, filter sizes, architecture of the network etc. have all been fixed before Step 1 and do not change during training process – only the values of the filter matrix and connection weights get updated.

**Step 5:** Repeat steps 2-4 with all images in the training set.
Convolutional Neural Nets: Putting It All Together

Feature Extraction from Image

Classification

$E_{\text{total}} = \sum \frac{1}{2}(\text{target} - \text{output})^2$
Figure 4. Historical error rate of the best performing image classification algorithms in the annual ImageNet competition.\textsuperscript{[37]} Established models of computer vision stagnated at 25\% 30\%. The introduction of deep learning in 2012 led to a significant improvement to $\sim$15\%, and human level accuracy ($\sim$5\%) for image classification was achieved by 2015.
TensorFlow is an open source library for machine learning tasks developed by Google and first released in November 2015.

It is a “second generation” system for machine learning, based on deep learning neural networks.

RackBrain now handles a large number of Google searches, and is powered by TensorFlow.

TensorFlow calculations are generally expressed as stateful dataflow graphs. Nodes in the graph represent mathematical operations, while edges are multidimensional arrays ("tensors") communicated between them. The name, TensorFlow, derives from the operations which neural networks perform on the arrays themselves.
DeepDream - Convolutional Neural Network

Original Image

After 10 Iterations of DeepDream
Three Men in a Pool (DeepDream)
In *Nature*, 27 January 2016

• “DeepMind’s program AlphaGo beat Fan Hui, the European Go champion, five times out of five in tournament conditions…”

• “AlphaGo was not preprogrammed to play Go: rather, it learned using a general-purpose algorithm that allowed it to interpret the game’s patterns.”

• “…AlphaGo program applied deep learning in neural networks (convolutional NN) — brain-inspired programs in which connections between layers of simulated neurons are strengthened through examples and experience.”
When a user takes a photo, the app should check whether they're in a national park...

Sure, easy GIS lookup. Gimme a few hours.

...and check whether the photo is of a bird.

I'll need a research team and five years.

In CS, it can be hard to explain the difference between the easy and the virtually impossible.