Applied inductive learning - Lecture 5
(Deep) Neural Networks

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Find slides: http://montefiore.ulg.ac.be/∼lwh/AIA/

Introduction

Single neuron models

- Hard threshold unit (LTU) and the perceptron
- Soft threshold unit (STU) and gradient descent
- Theoretical properties

Multilayer perceptron

- Definition and expressiveness
- Learning algorithms
- Overfitting and regularization

Other neural network models

- Radial basis function networks
- Convolutional neural networks
- Recurrent neural networks

Conclusion

Batch-mode vs Online-mode Supervised Learning

- Objects (or observations): $LS = \{o_1, \dots, o_N\}$
- Attribute vector: $\boldsymbol{a}^i = (a_1(o_i), \dots, a_n(o_i))^T$, $\forall i = 1, \dots, N.$
- Outputs: $y^i = y(o_i)$ or $c^i = c(o_i)$, $\forall i = 1, \dots, N.$
- LS Table

o	$a_1(o)$	$a_2(o)$	$\dots$	$a_n(o)$	$y(o)$
1	a_1^1	a_2^1	$\dots$	a_n^1	y^1
2	a_1^2	a_2^2	$\dots$	a_n^2	y^2
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
N	a_1^N	a_2^N	$\dots$	a_n^N	y^N

Focus for this lecture on numerical inputs, and numerical outputs (classes will be encoded numerically if needed).

Batch-mode vs online mode learning

- In batch-mode
  - Samples provided and processed together to construct model
  - Need to store samples (not the model)
  - Classical approach for data mining
- In online-mode
  - Samples provided and processed one by one to update model
  - Need to store the model (not the samples)
  - Classical approach for adaptive systems
- But both approaches can be adapted to handle both contexts
  - Samples available together can be exploited one by one
  - Samples provided one by one can be stored and then exploited together

Motivations for Artificial Neural Networks

Intuition: biological brain can learn, so let's try to be inspired by it to build learning algorithms.

- Starting point: single neuron models
  - perceptron, LTU and STU for linear supervised learning
  - online (biologically plausible) learning algorithms
- Complexify: multilayer perceptrons
  - flexible models for non-linear supervised learning
  - universal approximation property
  - iterative training algorithms based on non-linear optimization
- ...other neural network models of importance

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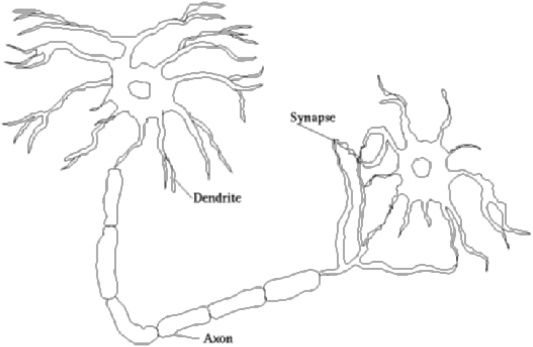
Single neuron models

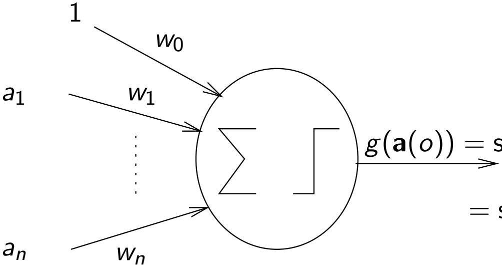
The biological neuron:



Human brain: 10^{11} neurons, each with 10^4 synapses
Memory (knowledge): stored in the synapses

Hard threshold unit...

A simple (simplistic) mathematical model of the biological neuron



$$g(\mathbf{a}(o)) = \text{sgn}\left\{w_0 + \mathbf{w}^T\mathbf{a}(o)\right\}$$

$$= \text{sgn}\left\{\mathbf{w}'^T\mathbf{a}'(o)\right\}$$

Parameters to adapt to problem: $\boldsymbol{w}'$

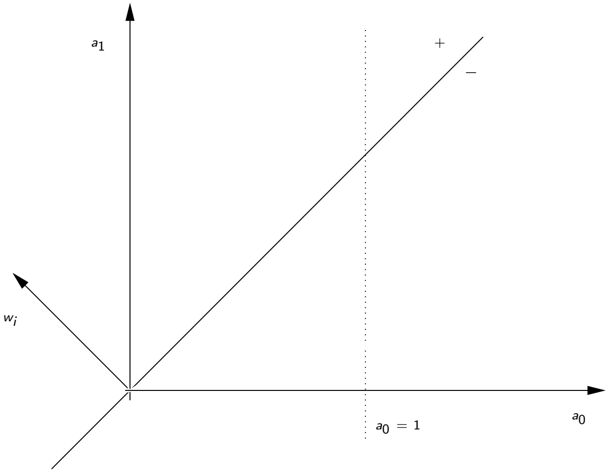
...and the perceptron learning algorithm

1. For binary classification: $c(o) = \pm 1$.
2. Start with an arbitrary initial weight vector, e.g. $\boldsymbol{w}'_0 = \mathbf{0}$.
3. Consider the objects of the LS in a cyclic or random sequence.
4. Let o_i be the object at step i, $c(o_i)$ its class and $\boldsymbol{a}(o_i)$ its attribute vector.
5. Adjust the weight by using the following correction rule,

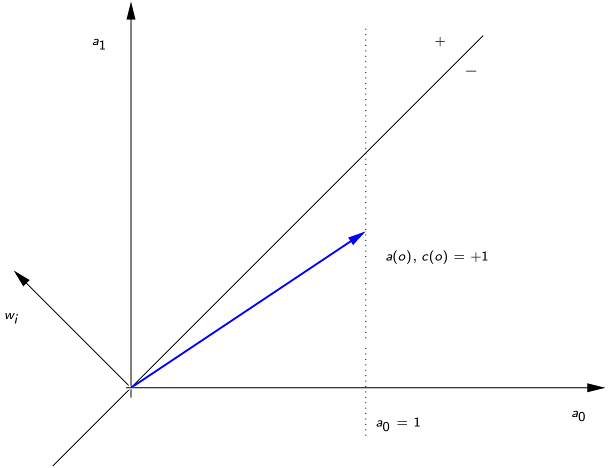
$$\boldsymbol{w}'_{i+1} \quad = \quad \boldsymbol{w}'_i + \eta_i \left(c(o_i) - g_i(\boldsymbol{a}(o_i))\right) \boldsymbol{a}'(o_i).$$

- $\boldsymbol{w}'_i$ changes only if o_i is not correctly classified
- it is changed in the right direction ($\eta_i > 0$ is the learning rate)
- at any stage, $\boldsymbol{w}'_i$ is a linear combination of the $\boldsymbol{a}(o_i)$ vectors

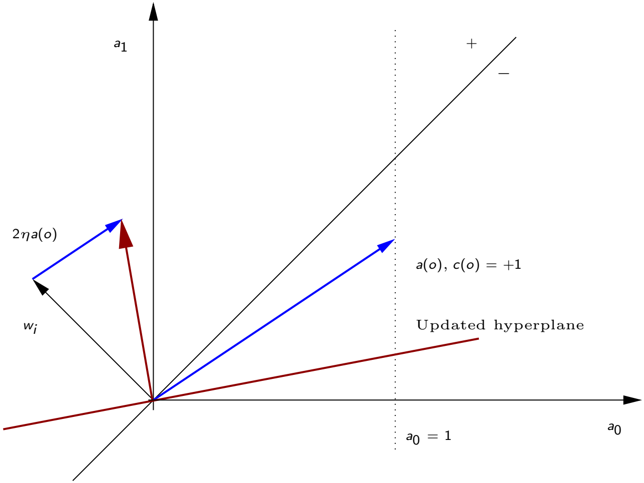
Geometrical view of update equation



Geometrical view of update equation



Geometrical view of update equation



Soft threshold units (STU)...

The input/output function $g(\boldsymbol{a})$ of such a device is computed by

$$g(\boldsymbol{a}(o)) \overset{\triangle}{=} f(w_0 + \boldsymbol{w}^T \boldsymbol{a}(o)) = f(\boldsymbol{w}'^T \boldsymbol{a}'(o))$$

where the *activation* function $f(\cdot)$ is assumed to be differentiable. Classical examples of activation functions are the sigmoid

$$\text{sigmoid}(x) = \frac{1}{1 + \exp(-x)},$$

and the hyperbolic tangent

$$\tanh(x) = \frac{\exp(x) - \exp(-x)}{\exp(x) + \exp(-x)},$$

... and gradient descent

Find vector $\boldsymbol{w}'^T = (w_0, \boldsymbol{w}^T)$ minimizing the square error (TSE)

$$TSE(LS, \boldsymbol{w}') = \sum_{o \in LS} (g(\boldsymbol{a}(o)) - y(o))^2 = \sum_{o \in LS} \left(f(\boldsymbol{w}'^T \boldsymbol{a}'(o)) - y(o) \right)^2 .$$

The gradient with respect to $\boldsymbol{w}'$ is computed by

$$\nabla_{\boldsymbol{w}'} TSE(LS, \boldsymbol{w}') = 2 \sum_{o \in LS} (g(\boldsymbol{a}(o)) - y(o))\, f'(\boldsymbol{w}'^T \boldsymbol{a}'(o))\boldsymbol{a}'(o),$$

where $f'(\cdot)$ denotes the derivative of the activation function $f(\cdot)$.

The gradient descent method works by iteratively changing the weight vector by a term proportional to $-\nabla_{\boldsymbol{w}'} TSE(LS, \boldsymbol{w}')$.

... and stochastic online gradient descent

Fixed step gradient descent in online-mode:

1. For binary classification: $c(o) = \pm 1$.
2. Start with an arbitrary initial weight vector, e.g. $\boldsymbol{w}'_0 = \mathbf{0}$.
3. Consider the objects of the LS in a cyclic or random sequence.
4. Let o_i be the object at step i, $c(o_i)$ its class and $\boldsymbol{a}(o_i)$ its attribute vector.
5. Adjust the weight by using the following correction rule,

$$\begin{aligned}\boldsymbol{w}'_{i+1} &= \boldsymbol{w}'_i - \eta_i \nabla_{\boldsymbol{w}'} SE(o_i, \boldsymbol{w}'_i) \\ &= \boldsymbol{w}'_i + 2\eta_i \left[c(o_i) - g_i(\boldsymbol{a}(o_i))\right] f'(\boldsymbol{w}'^T_i \boldsymbol{a}'(o_i))\boldsymbol{a}'(o),\end{aligned}$$

($SE(o, \boldsymbol{w}')$ is the contribution of object o in $TSE(LS, \boldsymbol{w}')$.)

Theoretical properties

- Convergence of the perceptron learning algorithm
  - If *LS* is linearly separable: converges in a finite number of steps.
  - Otherwise: converges with infinite number of steps, if $\eta_i \to 0$.
- Convergence of the online or batch gradient descent algorithm
  - if $\eta_i \to 0$ (slowly), and infinite number of steps, same solution
  - if $f(\cdot)$ linear, finds same solution as linear regression

NB: slow $\eta_i \to 0$ means

- $\lim_{m\to\infty} \sum_{i=1}^{m} \eta_i = +\infty$
- $\lim_{m\to\infty} \sum_{i=1}^{m} \eta_i^2 < +\infty$

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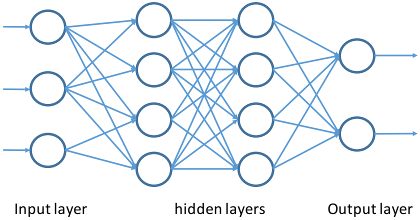
Multilayer perceptron

- Single neuron models are not more expressive than linear models
- Solution: connect several neurons to form a potentially complex non-linear parametric model
- Most common non-linear ANN structure is multilayer perceptron, i.e., multiple layers of neurons, with each layer fully connected to the next.
- E.g., MLP with 3 inputs, 2 hidden layers of 4 neurons each, and 2 outputs



Multilayer perceptron: mathematical definition (1/3)

L number of layers

- Layer 1 is the input layer
- Layer L is the output layer
- Layers 2 to $L-1$ are the hidden layers

s_l $(1 \leq l \leq L)$: number of neurons in the lth layer (s_1 $(= n)$ is the number of inputs, s_L is the number of outputs)

$a_i^{(l)}(o)$ $(1 < l \leq L, 1 \leq i \leq s_l)$: the activation (i.e., output) of the ith neuron of layer l for an object o.

$f^{(l)}$ $(2 \leq l \leq L)$: the activation function of layer l

$w_{i,j}^{(l)}$ $(1 \leq i \leq s_{l+1}, 1 \leq j \leq s_l)$: the weight of the edge from neuron j in layer l to neuron i in layer $l+1$

$w_{i,0}^{(l)}$ $(1 \leq i \leq s_{l+1})$: the bias/intercept of neuron i in layer $l+1$.

Multilayer perceptron: mathematical definition (2/3)

Predictions can be computed recursively:

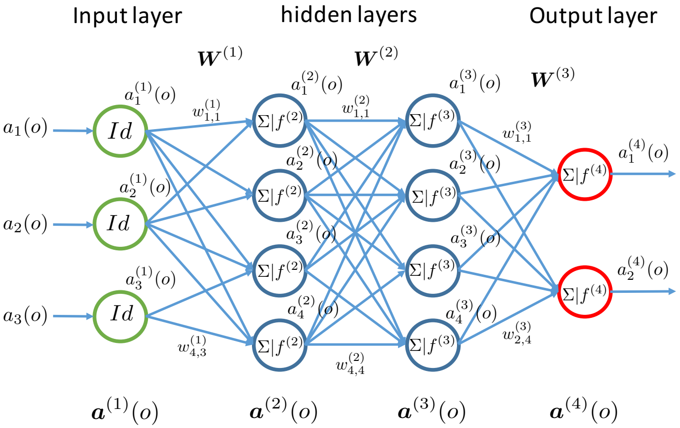
$$
\begin{aligned}
a_i^{(1)}(o) &= a_i(o), & \forall i : 1 \leq i \leq n \\
a_i^{(l+1)}(o) &= f^{(l+1)}(w_{i,0}^{(l)} + \sum_{j=1}^{s_l} w_{i,j}^{(l)} a_k^{(l)}(o)), & \forall 1 < l < L, 1 \leq i \leq s_l
\end{aligned}
\tag{1}
$$

Or in matrix notation:

$$
\begin{aligned}
\boldsymbol{a}^{(1)}(o) &= \boldsymbol{a}(o), \\
\boldsymbol{a}^{(l+1)}(o) &= f^{(l+1)}(\boldsymbol{W}'^{(l)} \boldsymbol{a}'^{(l)}(o)) & \forall 1 < l < L,
\end{aligned}
$$

with $\boldsymbol{W}'^{(l)} \in I\!R^{s_{l+1} \times s_l + 1}$ defined as $(\boldsymbol{W}'^{(l)})_{i,j} = w_{i,j-1}^{(l)}$ and $\boldsymbol{a}'$ defined as previously.

Multilayer perceptron: mathematical definition (3/3)



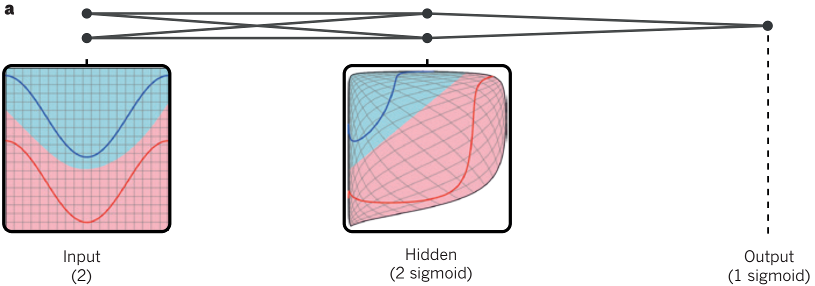
$$\boldsymbol{a}^{(l+1)}(o) = f^{(l+1)}(\boldsymbol{W}'^{(l)}\boldsymbol{a}'^{(l)}(o))$$

($w_{i,0}^{(l)}$ weights are omitted from all figures)

Representation capacity of MLP: classification (1/2)

- Geometrical insight in the representation capacity
- Two hidden layers of hard threshold units
  - First hidden layer: can define a collection of hyperplanes/semiplanes
  - Second hidden layer: can define arbitrary intersections of semiplanes
  - Output layer: can define abitrary union of intersections of semi-planes
  - Conclusion: with a sufficient number of units, very complex regions can be described
- Soft threshold units:
  - hidden layers can distort the input space to make the classes linearly separable by the output layer

Representation capacity of MLP: classification (2/2)



(lecun et al., Nature, 2015)

`http://cs.stanford.edu/people/karpathy/convnetjs/demo/classify2d.html`

Representation capacity of MLP: regression

- Function approximation insight
- One hidden layer of soft threshold units
  - One-dimensional input space illustration
  - Hidden layer defines K offset and scale parameters $\alpha_i, \beta_i, i = 1 \ldots K$: responses $f(\alpha_i x + \beta_i)$
  - Output layer (linear): $\hat{y}(x) = b_0 + \sum_{i=1}^{K} b_i f(\alpha_i x + \beta_i)$
- Theoretical results:
  - Every bounded continuous function can be approximated with arbitrary small error
  - Any function can be approximated to arbitrary accuracy by a network with two hidden layers

http://cs.stanford.edu/people/karpathy/convnetjs/demo/regression.html

Learning algorithms for multilayer perceptrons

Main idea:

- Define a loss function that compares the output layer predictions (for an object o) to the true outputs (with $\mathcal{W}$ all network weights):

$$L(\boldsymbol{g}(\boldsymbol{a}(o);\mathcal{W}),\boldsymbol{y}(o))$$

- Training = finding the parameters $\mathcal{W}$ that minimizes average loss over the training data

$$\mathcal{W}^* = \arg\min_{\mathcal{W}} \frac{1}{N} \sum_{o\in LS} L(\boldsymbol{g}(\boldsymbol{a}(o);\mathcal{W}),\boldsymbol{y}(o))$$

- Use gradient descent to iteratively improve an initial value of $\mathcal{W}$.

Require to compute the following gradient (for all i, j, l, o):

$$\frac{\partial}{\partial w_{i,j}^{(l)}} L(g(\boldsymbol{a}(o);\mathcal{W}),\boldsymbol{y}(o))$$

Backpropagation of derivatives

- These derivatives can be computed efficiently using the backpropagation algorithm.
- Let us derive this algorithm in the case of a single regression output, square error, and assuming that all activation functions are similar:

$$L(g(\boldsymbol{a}(o);\mathcal{W}),y(o)) = \frac{1}{2}(g(\boldsymbol{a}(o);\mathcal{W})-y(o))^2 = \frac{1}{2}(a_1^{(L)}(o)-y(o))^2$$

- In the following, we will denote by $z_i^{(l)}(o)$ $(1 < l \leq L,\ 1 \leq i \leq s_l)$ the values sent through the activation functions:

$$z_i^{(l)}(o) = w_{i,0}^{(l-1)} + \sum_{j=1}^{s_{l-1}} w_{i,j}^{(l-1)} a_j^{(l-1)}(o) \qquad \boldsymbol{z}^{(l)}(o) = \boldsymbol{W}'^{(l-1)}\boldsymbol{a}'^{(l-1)}(o) \quad (2)$$

(We thus have $a_i^{(l)}(o) = f(z_i^{(l)}(o))$)

Backpropagation of derivatives

Using the chain rule of partial derivatives, we have[1]:

$$\frac{\partial}{\partial w_{i,j}^{(l)}} L(g(\boldsymbol{a};\mathcal{W}),y) = \frac{\partial L(\dots)}{\partial a_i^{(l+1)}} \frac{\partial a_i^{(l+1)}}{\partial z_i^{(l+1)}} \frac{\partial z_i^{(l+1)}}{\partial w_{i,j}^{(l)}}$$

Given the definitions of $a_i^{(l+1)}$ and $z_i^{(l+1)}$, the last two factors are computed as:

$$\frac{\partial a_i^{(l+1)}}{\partial z_i^{(l+1)}} = f'(z_i^{(l+1)}) \qquad \frac{\partial z_i^{(l+1)}}{\partial w_{i,j}^{(l)}} = a_j^{(l)} \text{ (with } a_0^{(l)} = 1)$$

and thus:

$$\frac{\partial}{\partial w_{i,j}^{(l)}} L(\dots) = \frac{\partial L(\dots)}{\partial a_i^{(l+1)}} f'(z_i^{(l+1)}) a_j^{(l)}. \tag{3}$$

[1] Object argument $((o))$ is omitted to simplify the notations

Backpropagation of derivatives

For the last (output) layer, we have:

$$\frac{\partial L(\dots)}{\partial a_1^{(L)}} = \frac{\partial}{\partial a_1^{(L)}}\{\frac{1}{2}(a_1^{(L)} - y)^2\} = (a_1^{(L)} - y)$$

For the inner (hidden) layers, we have ($1 \leq l < L$):

$$\begin{aligned}\frac{\partial L(\dots)}{\partial a_i^{(l)}} &= \sum_{j=1}^{s_{l+1}} \frac{\partial L(\dots)}{\partial z_j^{(l+1)}} \frac{\partial z_j^{(l+1)}}{\partial a_i^{(l)}} = \sum_{j=1}^{s_{l+1}} \frac{\partial L(\dots)}{\partial a_j^{(l+1)}} \frac{\partial a_j^{(l+1)}}{\partial z_j^{(l+1)}} \frac{\partial z_j^{(l+1)}}{\partial a_i^{(l)}} \\ &= \sum_{j=1}^{s_{l+1}} \frac{\partial L(\dots)}{\partial a_j^{(l+1)}} f'(z_j^{(l+1)}) w_{j,i}^{(l)}\end{aligned}$$

Defining $\delta_i^{(l)} = \frac{\partial L(\dots)}{\partial a_i^{(l)}} f'(z_i^{(l)})$, we have[2] ($2 \leq l < L$):

$$\delta_1^{(L)}(o) = (a_1^{(L)}(o) - y(o)) f'(z_1^{(L)}(o)) \quad \delta_i^{(l)}(o) = (\sum_{j=1}^{s_{l+1}} \delta_j^{(l+1)}(o) w_{j,i}^{(l)}) f'(z_i^{(l)}(o)) \qquad (4)$$

[2] Reintroducing object argument

Backpropagation of derivatives

Or in matrix notations:

$$\begin{array}{rcl} \boldsymbol{\delta}^{(L)}(o) & = & (\boldsymbol{a}^{(L)}(o) - \boldsymbol{y}(o))f'(\boldsymbol{z}^{(L)}(o)) \\ \boldsymbol{\delta}^{(l)}(o) & = & ((\boldsymbol{W}^{(l)})^T \boldsymbol{\delta}^{(l+1)}(o))f'(\boldsymbol{z}^{(l)}(o)) \qquad 2 \leq l < L, \end{array}$$

with $\boldsymbol{W}^{(l)} \in I\!R^{s_{l+1} \times s_l}$ defined as $(\boldsymbol{W}^{(l)})_{i,j} = w_{i,j}^{(l)}$.

Backpropagation of derivatives: summary

To compute all partial derivatives $\frac{\partial L(g(\boldsymbol{a}(o);\mathcal{W}),y(o))}{\partial w_{i,j}^{(l)}}$ for a given object o:

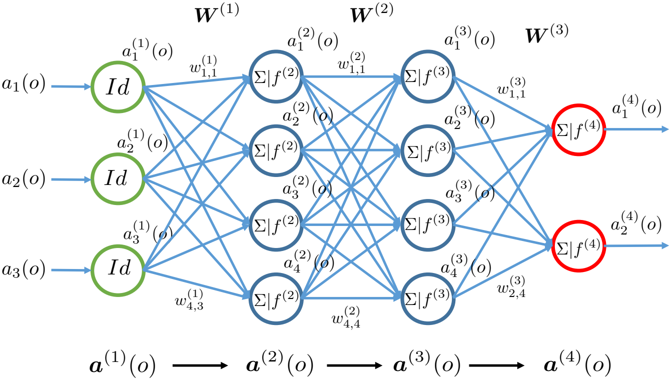
1. compute $a_i^{(l)}(o)$ and $z_i^{(l)}(o)$ for all neurons using (1) and (2)
   (forward propagation)
2. compute $\delta_i^{(l)}(o)$ for all neurons using (4)
   (backward propagation)
3. Compute (using (3)):

$$\frac{\partial L(g(\boldsymbol{a}(o);\mathcal{W}),y(o))}{\partial w_{i,j}^{(l)}} = \delta_i^{(l+1)}(o)a_j^{(l)}(o)$$

NB: Backpropagation can be adapted easily to other (differentiable) loss functions and feedforward (i.e., without cycles) network structure

Backpropagation of derivatives: illustration

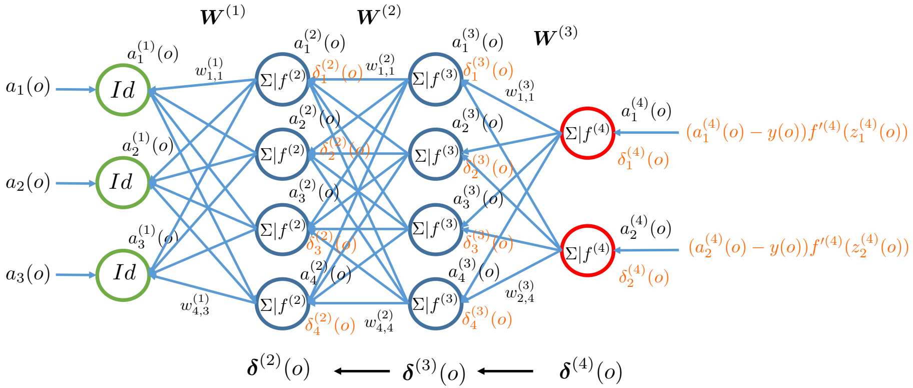
Forward propagation



$$\boldsymbol{a}^{(l+1)}(o) = f^{(l+1)}(\boldsymbol{W}'^{(l)}\boldsymbol{a}'^{(l)}(o))$$

Backpropagation of derivatives: illustration

Backward propagation



$$\boldsymbol{\delta}^{(l)}(o) = ((\boldsymbol{W}^{(l)})^T \boldsymbol{\delta}^{(l+1)}(o))f'(\boldsymbol{z}^{(l)}(o))$$

Online or batch gradient descent with backpropagation

1. Choose a network structure and a loss function L.
2. Initialize all network weights $w_{i,j}^{(l)}$ appropriately.
3. Repeat until some stopping criterion is met:
   3.1 Using backpropagation, compute either (batch mode):

$$\Delta w_{i,j}^{(l)} = \frac{1}{N} \sum_{o \in LS} \frac{\partial L(g(\boldsymbol{a}(o); \mathcal{W}), y(o))}{\partial w_{i,j}^{(l)}},$$

   or (online mode):

$$\Delta w_{i,j}^{(l)} = \frac{\partial L(g(\boldsymbol{a}(o); \mathcal{W}), y(o))}{\partial w_{i,j}^{(l)}}$$

   for a single object $o \in LS$ chosen at random or in a cyclic way.

   3.2 Update the weights according to:

$$w_{i,j}^{(l)} \leftarrow w_{i,j}^{(l)} - \eta \Delta w_{i,j}^{(l)},$$

   with $\eta \in]0, 1]$, the learning rate.

Between online and batch gradient descent

Mini-batch is commonly used

- Compute each gradient over a small subset of q objects
- Between stochastic ($q = 1$) and batch ($q = N$) gradient descent
- Sometimes can provide a better tradeoff in terms of optimality and speed.
- One gradient computation is called an iteration, one sweep over all training examples is called an epoch.
- It's often beneficial to keep original class proportion in mini-batches

Initial values of the weights:

- They have an influence on the final solution
- Not all to zero to break symetry
- Typically: small random weights, so that the network first operates close to linearity and then its non-linearity increases when training proceeds.

More on backpropagation and gradient descent

- Will find a local, not necessarily global, error minimum.
- Computational complexity of gradient computations is low (linear w.r.t. everything) but training can require thousands of iterations.
- Any general technique to make gradient descent converge faster or better can be applied to MLP training (second-order techniques, conjugate gradient, learning rate adaptation, etc.).
- Common improvement of SGD: Momentum update (with $\mu \in [0,1]$)

$$\Delta_{i,j}^{(l)} \leftarrow \mu\Delta_{i,j}^{(l)} - \eta\Delta w_{i,j}^{(l)}; \quad w_{i,j}^{(l)} \leftarrow w_{i,j}^{(l)} + \Delta_{i,j}^{(l)}$$

Multi-class classification

- One-hot encoding: k classes are encoded through k numerical outputs, with $y_i(o) = 1$ if o belongs to the ith class, 0 otherwise
- Loss function could be average square error over all outputs
- A better solution:
  - Transform neural nets outputs using softmax:

$$p_i(o) = \frac{\exp(a_i^{(L)}(o))}{\sum_k exp(a_k^{(L)}(o))}$$

    (such that $p_i(o) \in [0; 1]$ and $\sum_i p_i(o) = 1$).
  - Use cross-entropy as a loss function:

$$L(\boldsymbol{g}(\boldsymbol{a}(o); \mathcal{W}), \boldsymbol{y}(o)) = -\sum_{i=1}^{k} y_i(o) \log p_i(o)$$

Activation functions

As for STU, common activation functions are sigmoid and hyperbolic tangent.

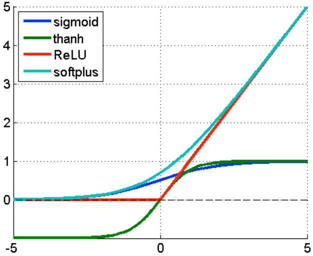
A recent alternative is ReLU (rectifier linear unit):

$$f(x) = \max(0, x).$$

(or its smooth approximation, softplus: $f(x) = \ln(1 + e^x)$)

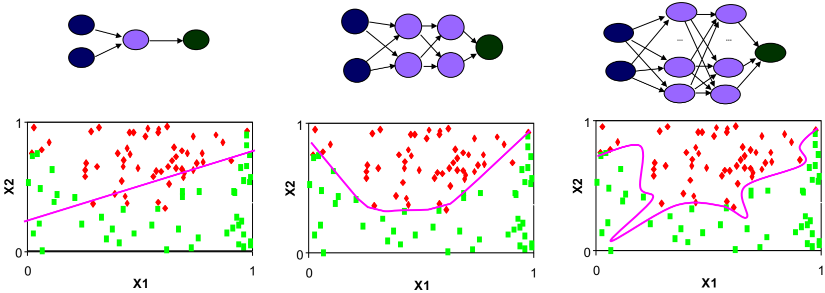
Several advantages:

- Sparse activation (some neurons are inactive)
- Efficient gradient propagation (avoid vanishing or exploding gradient)
- Efficient computation (comparison, addition, and multiplication only)



Overfitting

Too complex networks will clearly overfit.

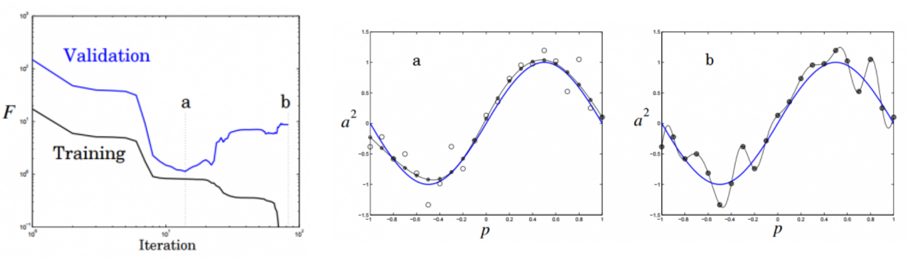


One could select optimal network size using cross-validation but better results are often obtained by carefully training complex networks instead.

Avoiding overfitting with neural networks

Early stopping:

- Stop gradient descent iterations before convergence, by controlling the error on an independent validation set
- If initial weights are small, the more iterations, the more non-linear becomes the model.



Source: `http://www.turingfinance.com/misconceptions-about-neural-networks/`

Avoiding overfitting with neural networks

Weight decay:

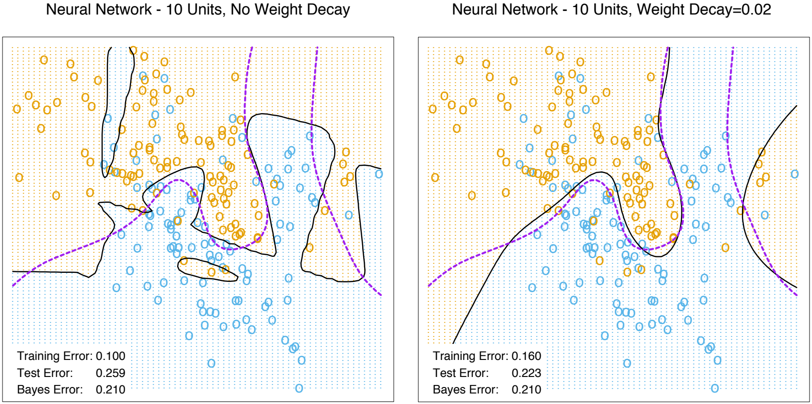
- Add an extra-term to the loss function that penalizes too large weights:

$$\mathcal{W}^* = \arg\min_{\mathcal{W}} \frac{1}{N} \sum_{o \in LS} L(\boldsymbol{g}(\boldsymbol{a}(o); \mathcal{W}), \boldsymbol{y}(o)) + \lambda \frac{1}{2} \sum_{l=1}^{L-1} \sum_{i=1}^{s_{l+1}} \sum_{j=1}^{s_l} (w_{i,j}^{(l)})^2,$$

- λ controls complexity (since larger weights mean more non-linearity) and can be tuned on a validation set
- Modified weight update: $w_{i,j}^{(l)} \leftarrow w_{i,j}^{(l)} - \eta(\Delta w_{i,j}^{(l)} + \lambda w_{i,j}^{(l)})$
- Alternative: L1 penalization: $(w_{i,j}^{(l)})^2 \Rightarrow |w_{i,j}^{(l)}|$.
  Makes some weights exactly equal to zero (a form of edge pruning).

Avoiding overfitting with neural networks

Weight decay:

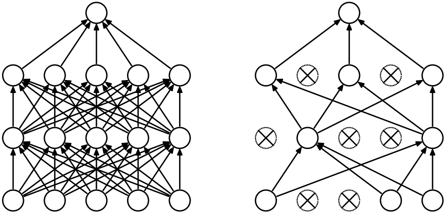


Source: Figure 10.4, Hastie et al., 2009

Avoiding overfitting with neural networks

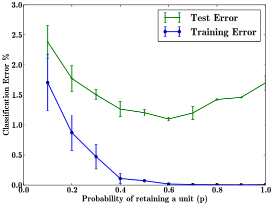
Dropout: (Srivastava et al., JMLR, 2011)

- Randomly drop neurons from each layer with probability Φ and train only the remaining ones
- Make the learned weights of a node more insensitive to the weights of the other nodes.
- This forces the network to learn several independent representations of the patterns and thus decreases overfitting.



(a) Standard Neural Net

(b) After applying dropout.



Avoiding overfitting with neural networks

Unsupervised pretraining:

- Main idea:
  - Train each hidden layer in turn in an unsupervised way, so that it allows to reproduce the input of the previous layer.
  - Introduce the output layer and then fine-tune the whole system using backpropagation
- Allowed in 2006 to train deeper neural networks than before and to obtain excellent performance on several tasks (computer vision, speech recognition).
- Unsupervised pretraining is especially useful when the number of labeled examples is small.

Introduction

Single neuron models

- Hard threshold unit (LTU) and the perceptron
- Soft threshold unit (STU) and gradient descent
- Theoretical properties

Multilayer perceptron

- Definition and expressiveness
- Learning algorithms
- Overfitting and regularization

Other neural network models

- Radial basis function networks
- Convolutional neural networks
- Recurrent neural networks

Conclusion

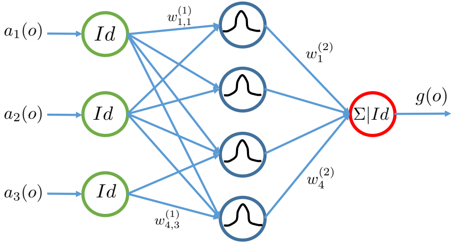
Other neural network models

Beyond MLP, many other neural network structures have been proposed in the literature, among which:

- Radial basis function networks
- Convolutional networks
- Recurrent neural networks
- Restricted Boltzman Machines (RBM)
- Kohonen maps (see lecture on unsupervised learning)
- Auto-encoders (see lecture on unsupervised learning)

Radial basis functions networks

A neural network with a single hidden layer with radial basis functions (RBF) as activation functions



Output is of the following form:

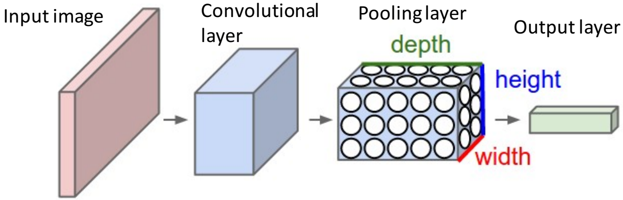
$$g(o) = w_0^{(2)} + \sum_{k=1}^{s_2} w_k^{(2)} \exp\left(-\frac{||\boldsymbol{a}^{(1)}(o) - \boldsymbol{w}_i^{(1)}||^2}{2\sigma^2}\right)$$

Radial basis function networks

- Training:
  - Input layer: vectors $\boldsymbol{w}_i^{(1)}$ are trained by unsupervised clustering techniques (see later) and σ commonly set to $d/\sqrt(2s_2)$, with d the maximal euclidean distance between two weight vectors.
  - Output layer: can be trained by any linear method (least-square, perceptron...).
  - Size s_2 of hidden layer is determined by cross-validation.
- Much faster to train than MLP
- Similar to the k-NN method

Convolutional neural networks (ConvNets)

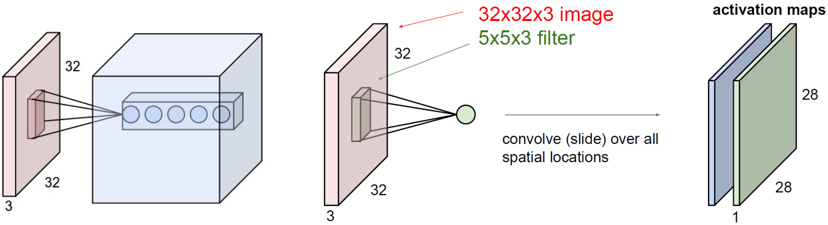
- A (feedforward) neural network structure initially designed for images
  - But can be extended to any input data composed of values that can be arranged in a 1D, 2D, 3D or more structure. E.g., sequences, texts, videos, etc.
- Built using three kinds of hidden layers: convolutional, pooling, and fully-connected
- Neurons in each layer can be arranged into a 3D structure.



Source: `http://cs231n.github.io/convolutional-networks/`

Convolutional layer

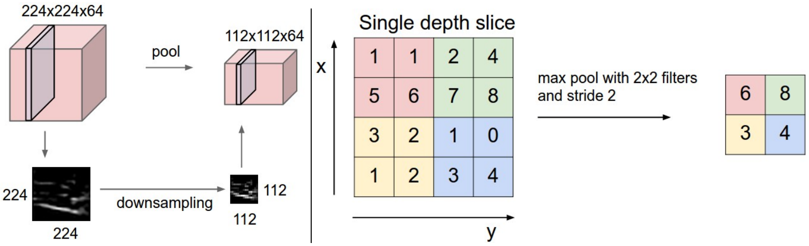
- Each neuron is connected only to a local region (along width and height, not depth) in the previous layer (the receptive field of the neuron)
- The receptive field of neurons at the same depth are slided by some fixed stride along width and height.
- All neurons at the same depth share the same set of weights (and thus detect the same feature at different locations)



Source: http://cs231n.github.io/convolutional-networks/

Pooling (or subsampling) layer

- Each neuron is connected only to a local region (along width and height) at the same depth as its own depth in the previous layer.
- The receptive field of neurons at the same depth are slided by some fixed stride along width and height (stride>1 means subsampling).
- Output of the neuron is an aggregation of the values in the local region. E.g., the maximum or the average in that region.



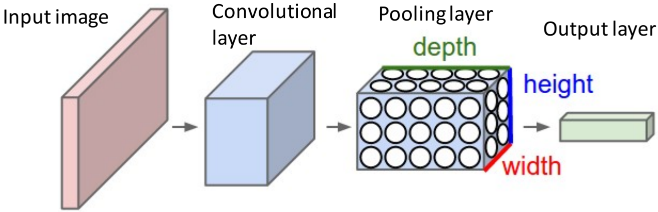
1	1	2	4
5	6	7	8
3	2	1	0
1	2	3	4

6	8
3	4

Source: `http://cs231n.github.io/convolutional-networks/`

Fully connected layer

- Width and height are equal to 1
- Each neuron is connected to all neurons of the previous layer
- At least, the output layer is a fully connected layer, with one neuron per output

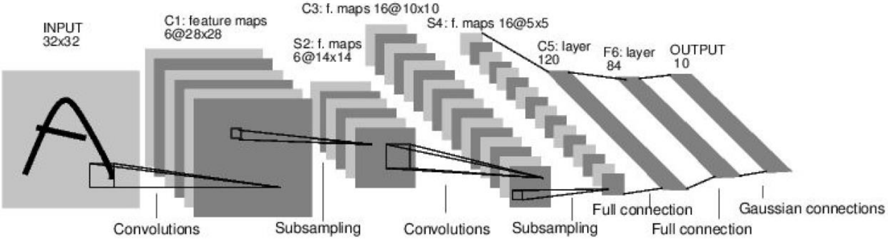


Source: http://cs231n.github.io/convolutional-networks/

Why convolutional networks?

- It's possible to compute the same ouputs in a fully connected MLP, but:
  - The network would be much harder to train.
  - Convolutional networks have much less parameters due to weight sharing.
  - They are less prone to overfitting.
- It makes sense to detect features (by convolution) and to combine them (by pooling). Max pooling allows to detect shift-invariant features.
- It's possible to draw analogy with the way our brain works.

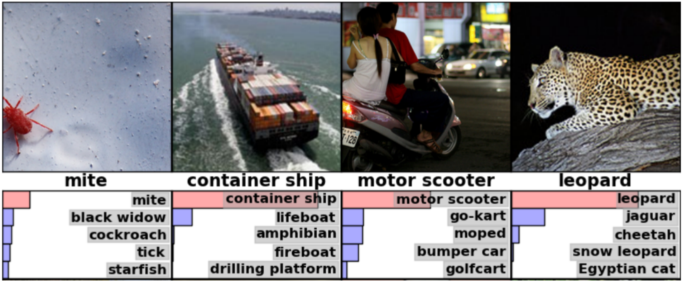
LeNet-5 (Lecun et al., 1998)



5 × 5 convolutional layers at stride 1, 2 × 2 max pooling layers at stride 2.

First successful application of convolutional networks. Used by banks in the US to read cheques.

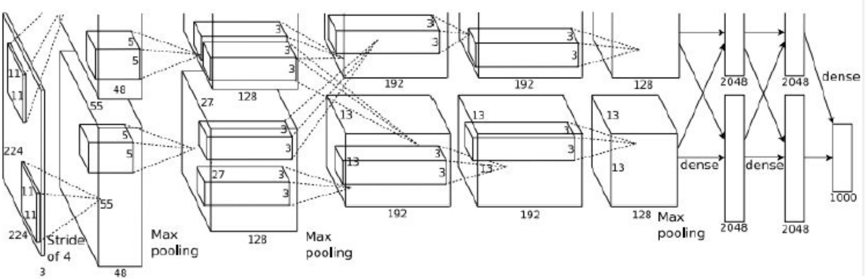
ImageNet - A large scale visual recognition challenge



`http://image-net.org`

- 1.2 million images, 1000 image categories in the training set
- Task: identify the object in the image (ie., a multi-class classification problem with 1000 classes)
- Evaluation: top-5 error ("is one of the best 5 class predictions correct?")
- Human error: 5.1% (`http://cs.stanford.edu/people/karpathy/ilsvrc/`)

Best performer in 2012: AlexNet (Krizhevsky et al., 2012)

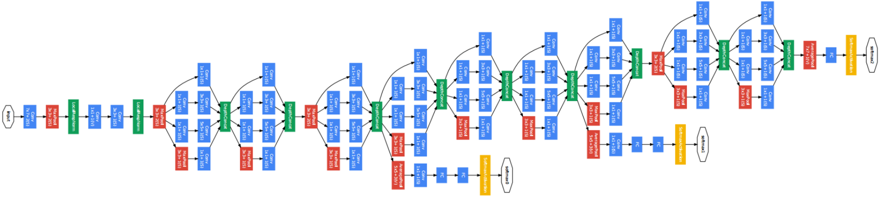


Full (simplified) AlexNet architecture:
[227x227x3] INPUT
[55x55x96] CONV1: 96 11x11 filters at stride 4, pad 0
[27x27x96] MAX POOL1: 3x3 filters at stride 2
[27x27x96] NORM1: Normalization layer
[27x27x256] CONV2: 256 5x5 filters at stride 1, pad 2
[13x13x256] MAX POOL2: 3x3 filters at stride 2
[13x13x256] NORM2: Normalization layer
[13x13x384] CONV3: 384 3x3 filters at stride 1, pad 1
[13x13x384] CONV4: 384 3x3 filters at stride 1, pad 1
[13x13x256] CONV5: 256 3x3 filters at stride 1, pad 1
[6x6x256] MAX POOL3: 3x3 filters at stride 2
[4096] FC6: 4096 neurons
[4096] FC7: 4096 neurons
[1000] FC8: 1000 neurons (class scores)

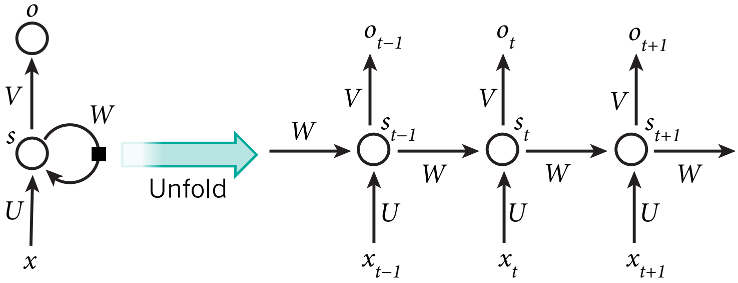
Details/Retrospectives:
- first use of ReLU
- used Norm layers (not common anymore)
- heavy data augmentation
- dropout 0.5
- batch size 128
- SGD Momentum 0.9
- Learning rate 1e-2, reduced by 10 manually when val accuracy plateaus
- L2 weight decay 5e-4
- 7 CNN ensemble: 18.2% -> 15.4%

Best performer in 2014: GoogLeNet (Szegedy et al., 2014)

- 6.7% top-5 error. Very close to human performance.
- Very deep: 100 layers (22 with tuned parameters), more than 4M parameters
- Several neat tricks (heterogeneous set of convolutions, inception modules, softmax outputs in the middle of the network, etc.)



Recurrent neural networks



- Neural networks with feedback connections
- When unfolded, can be trained using back-propagation
- Allows to model non-linear dynamical phenomenon
- Best approach for language modeling (e.g., word prediction)

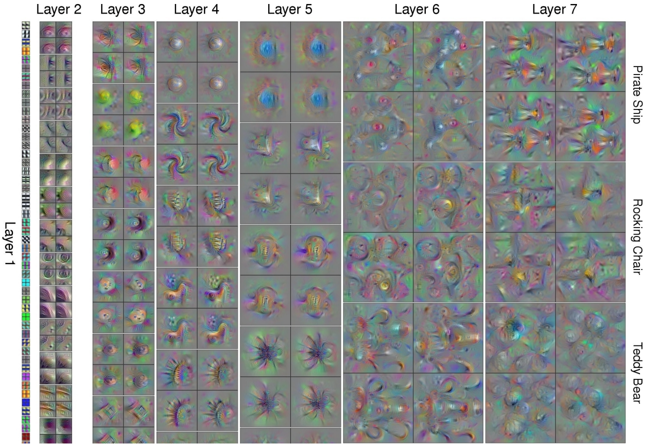
E.g., `http://twitter.com/DeepDrumpf`

Conclusions

- Neural networks are universal (parametric) approximators
- Deep (convolutional) neural networks provide state-of-the-art performance in several application domains (speech recognition, computer vision, texts...)
- Training deep networks is very expensive and requires a lot of data...
- ...but the use of (dedicated) GPUs reduce strongly computing times
- Often presented as automatic feature extraction techniques...
- ...but a lot of engineering (or art) is required to tune their hyper-parameters (structure, regularization, activation and loss functions, weight initialization, etc.).
- ...but researchers try to find automatic ways to tune them

Conclusions

- Essentially black-box models although some model inspection is possible



http://yosinski.com/deepvis

References and softwares

References:

- Hastie et al.: Chapter 11 (11.3-11.7)
- Goodfellow, Bengio, and Courville, Deep Learning, MIT Press, 2016 `http://www.deeplearningbook.org`
- Many tutorials on the web and also videos on Youtube: Andrew Ng, Hugo Larochelle...

Main toolboxes:

- Tensorflow (Google), Python, `https://www.tensorflow.org`
- Theano (U. Montreal), Python, `http://deeplearning.net/software/theano/index.html`
- Caffe (U. Berkeley), Python), `http://caffe.berkeleyvision.org/`
- Torch (Facebook, Twitter), Lua, `http://torch.ch`