

Lecture 11 of 42

Artificial Neural Networks (ANNs): More Perceptrons and Winnow

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<http://www.kddresearch.org/Courses/Spring-2007/CIS732/>

Readings:

Sections 4.1-4.4, Mitchell

Section 2.2.6, Shavlik and Dietterich (Rosenblatt)

Section 2.4.5, Shavlik and Dietterich (Minsky and Papert)



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Lecture Outline

- Textbook Reading: Sections 4.1-4.4, Mitchell
- Read “The Perceptron”, F. Rosenblatt; “Learning”, M. Minsky and S. Papert
- Next Lecture: 4.5-4.9, Mitchell; “The MLP”, Bishop; Chapter 8, RHW
- This Week’s Paper Review: “Discriminative Models for IR”, Nallapati
- This Month: Numerical Learning Models (e.g., Neural/Bayesian Networks)
- The Perceptron
 - Today: as a linear threshold gate/unit (LTG/LTU)
 - Expressive power and limitations; ramifications
 - Convergence theorem
 - Derivation of a gradient learning algorithm and training (Delta aka LMS) rule
 - Next lecture: as a neural network element (especially in multiple layers)
- The Winnow
 - Another linear threshold model
 - Learning algorithm and training rule



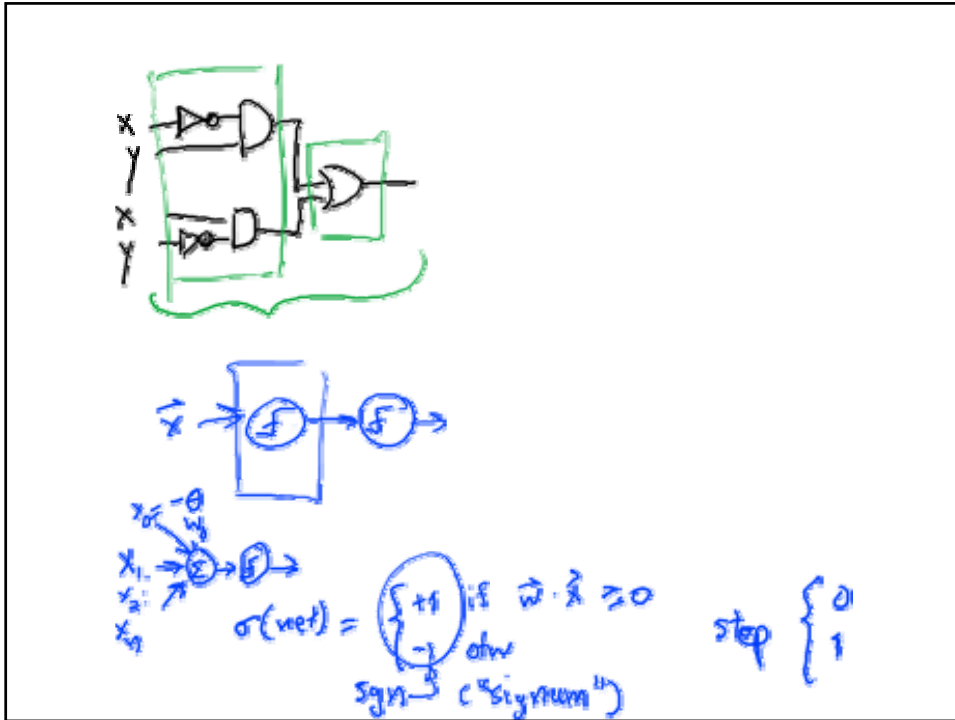
$$(x^A - \gamma)(x^B - \gamma)$$
$$x^A \gamma + x^B \gamma$$

x	y	x ⊗ y
0	0	0
0	1	0
1	0	0
1	1	1



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Review: ALVINN and Feedforward ANN Topology

- Pomerleau et al**
 - <http://www.cs.cmu.edu/afs/cs/project/alv/member/www/projects/ALVINN.html>
 - Drives 70mph on highways

30x32 Sensor Input Retina

Hidden Unit

30 Output Units

Sharp Left, Straight Ahead, Sharp Right

proc units, weights, inhibition, excitation

Hidden diagram

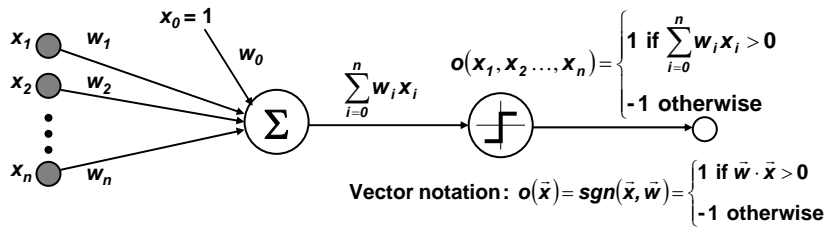
Hidden-to-Output Unit Weight Map (for one hidden unit)

Input-to-Hidden Unit Weight Map (for one hidden unit)

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Review: The Perceptron



- **Perceptron: Single Neuron Model**
 - aka Linear Threshold Unit (LTU) or Linear Threshold Gate (LTG)
 - Net input to unit: defined as linear combination $net = \sum_{i=0}^n w_i x_i$
 - Output of unit: threshold (activation) function on net input (threshold $\theta = w_0$)
- **Perceptron Networks**
 - Neuron is modeled using a unit connected by weighted links w_i to other units
 - Multi-Layer Perceptron (MLP): next lecture

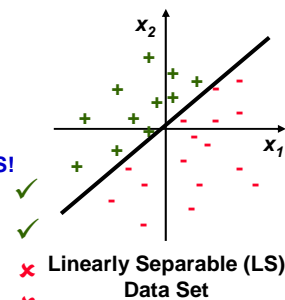


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Review: Linear Separators

- **Functional Definition**
 - $f(x) = 1$ if $w_1 x_1 + w_2 x_2 + \dots + w_n x_n \geq \theta$, 0 otherwise
 - θ : threshold value
- **Linearly Separable Functions**
 - NB: D is LS does not necessarily imply $c(x) = f(x)$ is LS!
 - Disjunctions: $c(x) = x_1' \vee x_2' \vee \dots \vee x_m'$
 - m of n : $c(x) =$ at least 3 of $(x_1', x_2', \dots, x_m')$
 - Exclusive OR (XOR): $c(x) = x_1 \oplus x_2$
 - General DNF: $c(x) = T_1 \vee T_2 \vee \dots \vee T_m$; $T_i = l_1 \wedge l_2 \wedge \dots \wedge l_k$
- **Change of Representation Problem**
 - Can we transform non-LS problems into LS ones?
 - Is this meaningful? Practical?
 - Does it represent a significant fraction of real-world problems?

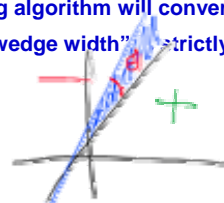


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Review: Perceptron Convergence

- **Perceptron Convergence Theorem**
 - **Claim:** If there exist a set of weights that are consistent with the data (i.e., the data is linearly separable), the perceptron learning algorithm will converge
 - **Proof:** well-founded ordering on search region (“wedge width” strictly decreasing) - see Minsky and Papert, 11.2-11.3
 - **Caveat 1:** How long will this take?
 - **Caveat 2:** What happens if the data is *not* LS?
- **Perceptron Cycling Theorem**
 - **Claim:** If the training data is not LS the perceptron learning algorithm will eventually repeat the same set of weights and thereby enter an infinite loop
 - **Proof:** bound on number of weight changes until repetition; induction on n , the dimension of the training example vector - MP, 11.10
- **How to Provide More Robustness, Expressivity?**
 - **Objective 1:** develop algorithm that will find closest approximation (today)
 - **Objective 2:** develop architecture to overcome representational limitation (next lecture)



Gradient Descent: Principle

- **Understanding Gradient Descent for Linear Units**
 - Consider simpler, unthresholded linear unit:
- $$o(\vec{x}) = \text{net}(\vec{x}) = \sum_{i=0}^n w_i x_i$$
-
- **Objective:** find “best fit” to D
 - **Approximation Algorithm**
 - **Quantitative objective:** minimize error over training data set D
 - **Error function:** sum squared error (SSE)
- $$E[\vec{w}] = \text{error}_D[\vec{w}] = \frac{1}{2} \sum_{x \in D} (t(x) - o(x))^2$$
-
- **How to Minimize?**
 - Simple optimization
 - Move in direction of steepest gradient in weight-error space
 - Computed by finding tangent
 - i.e. partial derivatives (of E) with respect to weights (w_i)



Gradient Descent: Derivation of Delta/LMS (Widrow-Hoff) Rule

- **Definition: Gradient**

$$\nabla E[\bar{w}] \equiv \left[\frac{\partial E}{\partial w_0}, \frac{\partial E}{\partial w_1}, \dots, \frac{\partial E}{\partial w_n} \right]$$

- **Modified Gradient Descent Training Rule**

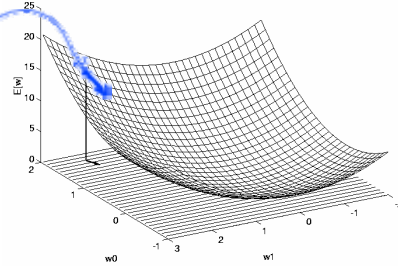
$$\Delta \bar{w} = -r \nabla E[\bar{w}]$$

$$\Delta w_i = -r \frac{\partial E}{\partial w_i}$$

$$\frac{\partial E}{\partial w_i} = \frac{\partial}{\partial w_i} \left[\frac{1}{2} \sum_{x \in D} (t(x) - o(x))^2 \right] = \frac{1}{2} \sum_{x \in D} \left[\frac{\partial}{\partial w_i} (t(x) - o(x))^2 \right]$$

$$= \frac{1}{2} \sum_{x \in D} \left[2(t(x) - o(x)) \frac{\partial}{\partial w_i} (t(x) - o(x)) \right] = \sum_{x \in D} \left[(t(x) - o(x)) \frac{\partial}{\partial w_i} (t(x) - \bar{w} \cdot \bar{x}) \right]$$

$$\frac{\partial E}{\partial w_i} = \sum_{x \in D} [(t(x) - o(x))(-x_i)]$$



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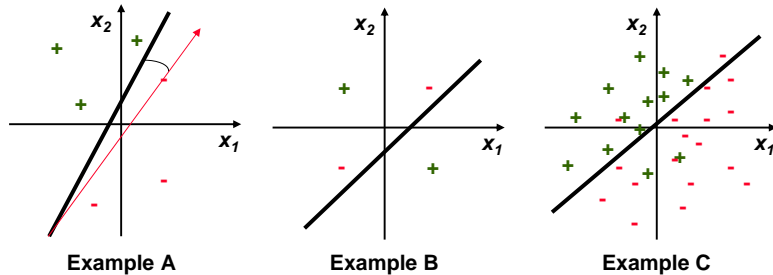
Gradient Descent: Algorithm using Delta/LMS Rule

- **Algorithm Gradient-Descent (D, r)**
 - Each training example is a pair of the form $\langle x, t(x) \rangle$, where x is the vector of input values and $t(x)$ is the output value. r is the learning rate (e.g., 0.05)
 - Initialize all weights w_i to (small) random values
 - UNTIL the termination condition is met, DO
 - Initialize each Δw_i to zero
 - FOR each $\langle x, t(x) \rangle$ in D , DO
 - Input the instance x to the unit and compute the output o
 - FOR each linear unit weight w_i , DO
 - $\Delta w_i \leftarrow \Delta w_i + r(t - o)x_i$
 - $w_i \leftarrow w_i + \Delta w_i$
 - RETURN final w
- **Mechanics of Delta Rule**
 - Gradient is based on a derivative
 - Significance: later, will use nonlinear activation functions (aka transfer functions, squashing functions)

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Gradient Descent: Perceptron Rule versus Delta/LMS Rule



- **LS Concepts: Can Achieve Perfect Classification**
 - Example A: perceptron training rule converges
- **Non-LS Concepts: Can Only Approximate**
 - Example B: not LS; delta rule converges, but can't do better than 3 correct
 - Example C: not LS; better results from delta rule
- **Weight Vector w = Sum of Misclassified $x \in D$**
 - Perceptron: minimize w
 - Delta Rule: minimize error \equiv distance from separator (i.e., maximize $\frac{\partial E}{\partial \bar{w}}$)



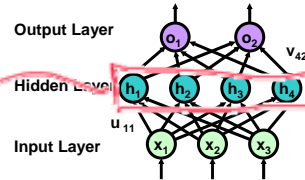
Incremental (Stochastic) Gradient Descent

- **Batch Mode Gradient Descent**
 - UNTIL the termination condition is met, DO
 1. Compute the gradient $\nabla E_D[\bar{w}]$
 2. $\bar{w} \leftarrow \bar{w} - r \nabla E_D[\bar{w}]$
 - RETURN final w
- **Incremental (Online) Mode Gradient Descent**
 - UNTIL the termination condition is met, DO
 - FOR each $\langle x, t(x) \rangle$ in D , DO
 1. Compute the gradient $\nabla E_d[\bar{w}]$
 2. $\bar{w} \leftarrow \bar{w} - r \nabla E_d[\bar{w}]$
 - RETURN final w
- **Emulating Batch Mode**
 - $E_D[\bar{w}] \equiv \frac{1}{2} \left[\sum_{x \in D} (t(x) - o(x))^2 \right]$, $E_d[\bar{w}] \equiv \frac{1}{2} (t(x) - o(x))^2$
 - Incremental gradient descent can approximate batch gradient descent arbitrarily closely if r made small enough



Multi-Layer Networks of Nonlinear Units

- **Nonlinear Units**
 - Recall: activation function $sgn(w \cdot x)$
 - Nonlinear activation function: generalization of $sgn(w \cdot x)$
- **Multi-Layer Networks**
 - A specific type: Multi-Layer Perceptrons (MLPs)
 - Definition: a multi-layer feedforward network is composed of an input layer, one or more hidden layers, and an output layer
 - “Layers”: counted in weight layers (e.g., 1 hidden layer = 2-layer network)
 - Only hidden and output layers contain perceptrons (threshold or nonlinear units)
- **MLPs in Theory**
 - Network (of 2 or more layers) can represent any function (arbitrarily small error)
 - Training even 3-unit multi-layer ANNs is NP-hard (Blum and Rivest, 1992)
- **MLPs in Practice**
 - Finding or *designing* effective networks for arbitrary functions is difficult
 - Training is very computation-intensive even when structure is “known”

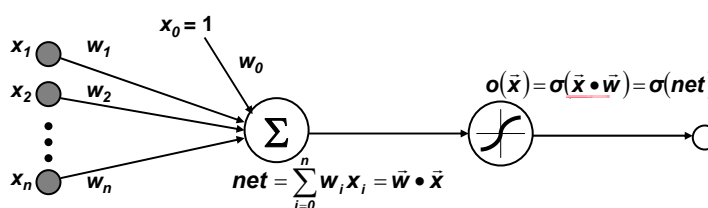


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Nonlinear Activation Functions



- **Sigmoid Activation Function**
 - Linear threshold gate activation function: $sgn(w \cdot x)$
 - Nonlinear activation (aka transfer squashing) function: generalization of sgn
 - σ is the sigmoid function $\sigma(net) = \frac{1}{1 + e^{-net}}$
 - Can derive gradient rules to train:
 - One sigmoid unit
 - Multi-layer, feedforward networks of sigmoid units (using backpropagation)
- **Hyperbolic Tangent Activation Function** $\sigma(net) = \frac{\sinh(net)}{\cosh(net)} = \frac{e^{net} - e^{-net}}{e^{net} + e^{-net}}$



$$\frac{1}{1 + e^{-net}}$$

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Error Gradient for a Sigmoid Unit

• **Recall: Gradient of Error Function** $\nabla E[\vec{w}] = \left[\frac{\partial E}{\partial w_0}, \frac{\partial E}{\partial w_1}, \dots, \frac{\partial E}{\partial w_n} \right]$

• **Gradient of Sigmoid Activation Function**

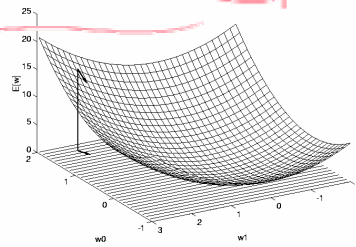
$$\begin{aligned} \frac{\partial E}{\partial w_i} &= \frac{\partial}{\partial w_i} \left[\frac{1}{2} \sum_{\langle \vec{x}, t(\vec{x}) \rangle \in D} (t(\vec{x}) - o(\vec{x}))^2 \right] = \frac{1}{2} \sum_{\langle \vec{x}, t(\vec{x}) \rangle \in D} \left[\frac{\partial}{\partial w_i} (t(\vec{x}) - o(\vec{x}))^2 \right] \\ &= \frac{1}{2} \sum_{\langle \vec{x}, t(\vec{x}) \rangle \in D} \left[2(t(\vec{x}) - o(\vec{x})) \frac{\partial}{\partial w_i} (t(\vec{x}) - o(\vec{x})) \right] = \sum_{\langle \vec{x}, t(\vec{x}) \rangle \in D} \left[(t(\vec{x}) - o(\vec{x})) \frac{\partial o(\vec{x})}{\partial w_i} \right] \\ &= - \sum_{\langle \vec{x}, t(\vec{x}) \rangle \in D} \left[(t(\vec{x}) - o(\vec{x})) \frac{\partial o(\vec{x})}{\partial \text{net}(\vec{x})} \frac{\partial \text{net}(\vec{x})}{\partial w_i} \right] \end{aligned}$$

• **But We Know:**

$$\frac{\partial o(\vec{x})}{\partial \text{net}(\vec{x})} = \frac{\partial \sigma(\text{net}(\vec{x}))}{\partial \text{net}(\vec{x})} = o(\vec{x})(1 - o(\vec{x}))$$

$$\frac{\partial \text{net}(\vec{x})}{\partial w_i} = \frac{\partial (\vec{w} \cdot \vec{x})}{\partial w_i} = x_i$$

• **So:** $\frac{\partial E}{\partial w_i} = - \sum_{\langle \vec{x}, t(\vec{x}) \rangle \in D} [(t(\vec{x}) - o(\vec{x})) (o(\vec{x})(1 - o(\vec{x}))) \cdot x_i]$



Learning Disjunctions

• **Hidden Disjunction to Be Learned**

- $c(x) = x_1' \vee x_2' \vee \dots \vee x_m'$ (e.g., $x_2 \vee x_4 \vee x_5 \dots \vee x_{100}$)
- **Number of disjunctions:** 3^n (each x_i : included, negation included, or excluded)
- **Change of representation:** can turn into a monotone disjunctive formula?
 - How?
 - How many disjunctions then?
- Recall from COLT: mistake bounds
 - $\log(|C|) = O(n)$
 - Elimination algorithm makes $O(n)$ mistakes

• **Many Irrelevant Attributes**

- Suppose only $k \ll n$ attributes occur in disjunction c - i.e., $\log(|C|) = O(k \log n)$
- Example: learning natural language (e.g., learning over text)
- Idea: use a Winnow - perceptron-type LTU model (Littlestone, 1988)
 - Strengthen weights for false positives
 - Learn from negative examples too: weaken weights for false negatives



Winnow Algorithm

- **Algorithm *Train-Winnow* (D)**
 - Initialize: $\theta = n$, $w_i = 1$
 - UNTIL the termination condition is met, DO
 - FOR each $\langle x, t(x) \rangle$ in D , DO
 1. CASE 1: no mistake - do nothing
 2. CASE 2: $t(x) = 1$ but $w \cdot x < \theta$ - $w_i \leftarrow 2w_i$ if $x_i = 1$ (promotion/strengthening)
 3. CASE 3: $t(x) = 0$ but $w \cdot x \geq \theta$ - $w_i \leftarrow w_i / 2$ if $x_i = 1$ (demotion/weakening)
 - RETURN final w
- **Winnow Algorithm Learns Linear Threshold (LT) Functions**
- **Converting to Disjunction Learning**
 - Replace demotion with elimination
 - Change weight values to 0 instead of halving
 - Why does this work?



Terminology

- **Neural Networks (NNs): Parallel, Distributed Processing Systems**
 - Biological NNs and artificial NNs (ANNs)
 - Perceptron aka Linear Threshold Gate (LTG), Linear Threshold Unit (LTU)
 - Model neuron
 - Combination and activation (transfer, squashing) functions
- **Single-Layer Networks**
 - Learning rules
 - Hebbian: strengthening connection weights when both endpoints activated
 - Perceptron: minimizing total weight contributing to errors
 - Delta Rule (LMS Rule, Widrow-Hoff): minimizing sum squared error
 - Winnow: minimizing classification mistakes on LTU with multiplicative rule
 - Weight update regime
 - Batch mode: cumulative update (all examples at once)
 - Incremental mode: non-cumulative update (one example at a time)
- **Perceptron Convergence Theorem and Perceptron Cycling Theorem**



Summary Points

- **Neural Networks: Parallel, Distributed Processing Systems**
 - Biological and artificial (ANN) types
 - Perceptron (LTU, LTG): model neuron
- **Single-Layer Networks**
 - Variety of update rules
 - Multiplicative (Hebbian, Winnow), additive (gradient: Perceptron, Delta Rule)
 - Batch versus incremental mode
 - Various convergence and efficiency conditions
 - Other ways to learn linear functions
 - Linear programming (general-purpose)
 - Probabilistic classifiers (some assumptions)
- **Advantages and Disadvantages**
 - “Disadvantage” (tradeoff): simple and restrictive
 - “Advantage”: perform well on many realistic problems (e.g., some text learning)
- **Next: Multi-Layer Perceptrons, Backpropagation, ANN Applications**

