Real-Time Speech-Driven Facial Animation

ECE417 – Multimedia Signal Processing

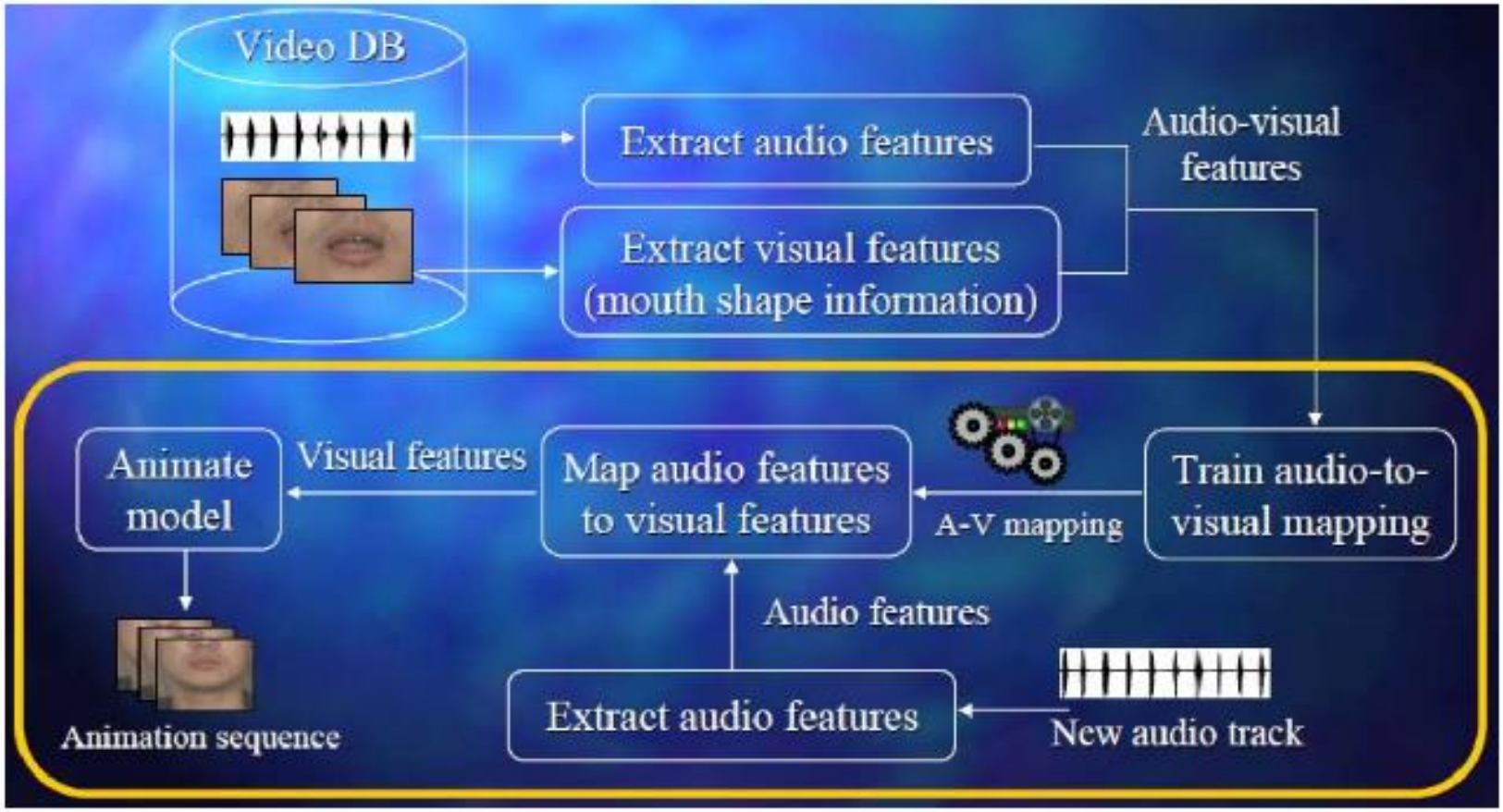
Spring2015

Goal

1. Up to this point, we've worked on recognition and classification. In this MP, we'll switch gears and focus on synethesis (generation).
2. Specifically, we want to generate a "talking head" model.
3. The goal of this machine problem is to use speech data to try to deform a mouth image such that we can give the impression that it is actually speaking the audio data we give it.

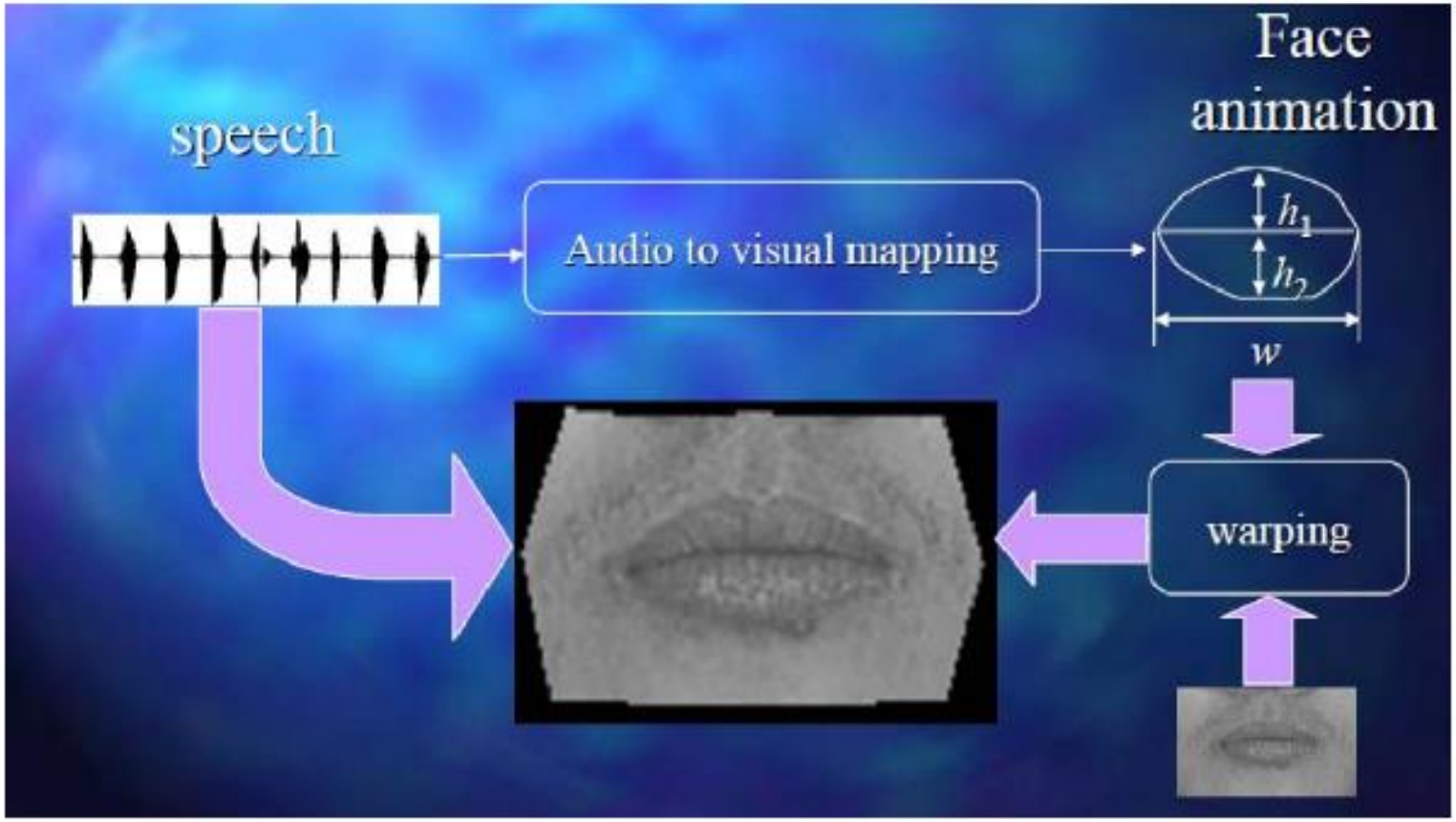
The Basic Idea

Given a set of audio and image features, train a mapping between the two. Then, use said mapping to generate a set of test images given a set of audio features.



The Basic Idea (Specific to MP5)

We can generalize this so that it is specific to the data we will use in MP5. We will use image deformation to warp a base model of a pair of lips based on an audio-image mapping system.



Things You Are Given

1. Code You Are Given
   - 1.1 ECE417_MP5_clean_silence.m - finds unvoiced sections in the speech and eliminates them
   - 1.2 ECE417_MP5_smooth.m - frame-by-frame smoothing after silence deletion
   - 1.3 ECE417_MP5_test.m - estimates visual features for test audio data
   - 1.4 ECE417_MP5_train.m - Trains a 3 layer nueral network for audio-image map (requires Neural Network Toolbox, which EWS computers should have)
   - 1.5 interpVert.m - generate output vertices (x, y) based on (w, h_1, h_2).
   - 1.6 DxBMP.exe - executable file that generates movie based on indivdual image frames
2. Data You Are Given
   - 2.1 mouth.jpg - a base (neutral) image of the mouth that you will deform.
   - 2.2 mesh.txt - L vertices with coordinates (x, y), M mesh triangles with vertices (v_1, v_2, v_3).
   - 2.3 ECE417_MP5_AV_Data.mat - contains the audio features (N cepstral coefficients) for T frames.
   - 2.4 test.wav - audio file used to generate the audio features. Use it to overlay audio in your final movie.

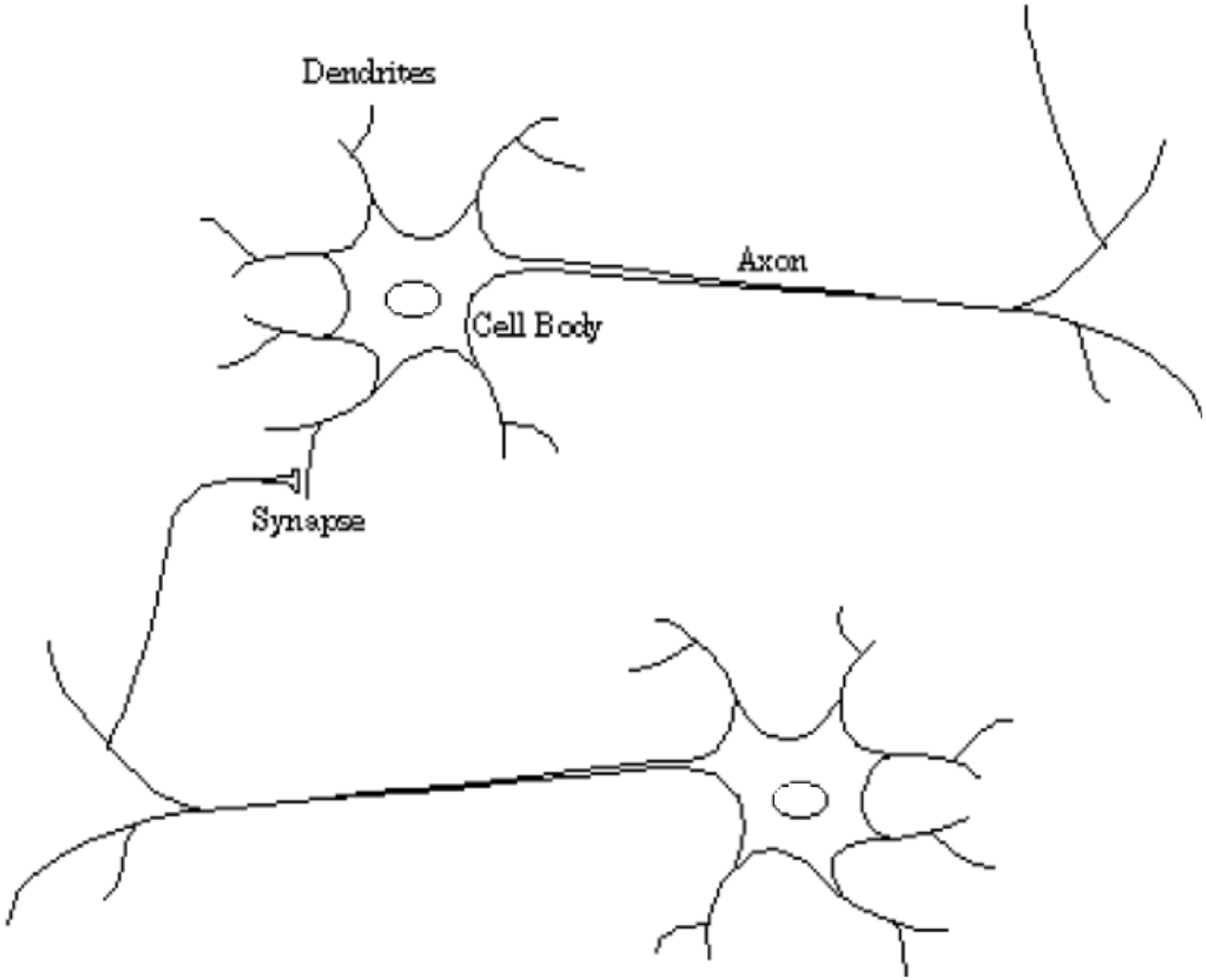
High-Level Approach

1. Use 3 neural networks to create 3 image coordinates (w, h_1, h_2) for a frame based on audio cepstral coefficients.
2. Generate deformed mesh vertices using interpVert.m.
3. Generate new image coordinates using image warping based on deformed mesh vertices for every frame.
4. Generate movie from warped frames and overlay given audio track using given executable file or using Matlab.

Biological Inspirations

- Humans perform complex tasks like vision, motor control, or language understanding very well
- One way to build intelligent machines is to try to imitate the (organizational principles of) human brain

Biological Neuron

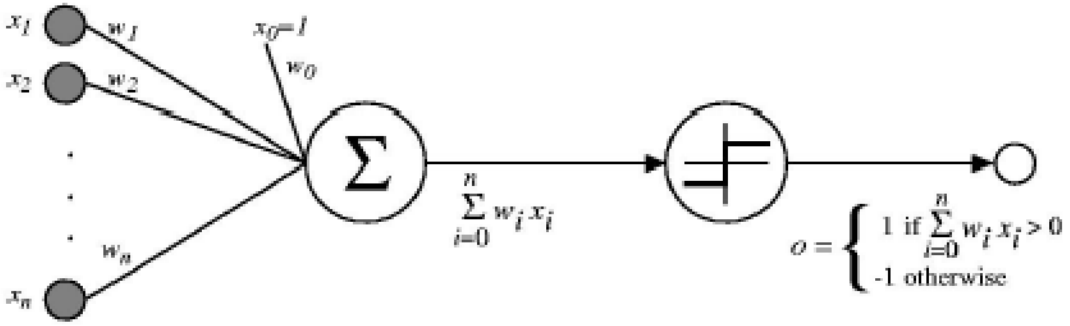


Artificial Neural Networks

- ANNs have been widely used in various domains for:
  - Pattern recognition
  - Function approximation
  - Etc.

Perceptron (Artificial Neuron)

- A perceptron
  - takes a vector of real-valued inputs
  - calculates a linear combination of the inputs
  - outputs +1 if the result is greater than some threshold and -1 (or 0) otherwise



$$o(x_1, \ldots, x_n) = \begin{cases} 1 & \text{if } w_0 + w_1 x_1 + \cdots + w_n x_n > 0 \\ -1 & \text{otherwise.} \end{cases}$$

Perceptron

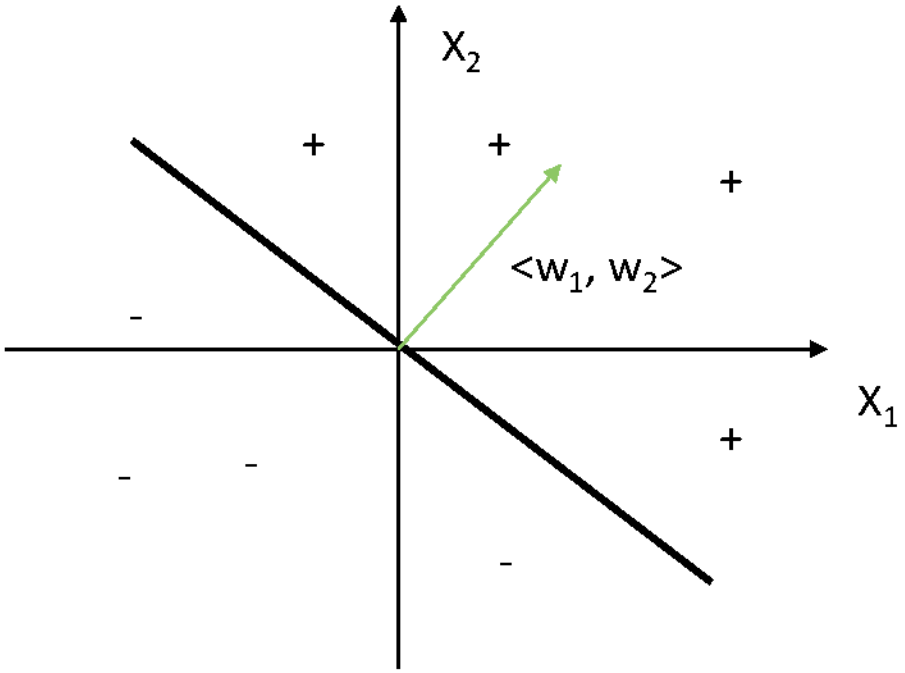
- To simplify notation, assume an additional constant input x_0=1. We can write the perceptron function as

$$o(\vec{x}) = sgn(\vec{w} \cdot \vec{x})$$

$$sgn(y) = \begin{cases} 1 & \text{if } y > 0 \\ -1 & \text{otherwise} \end{cases}$$

Representational Power of Perceptron

- The perceptron ~ a hyperplane decision surface in the n-dimensional space of instances

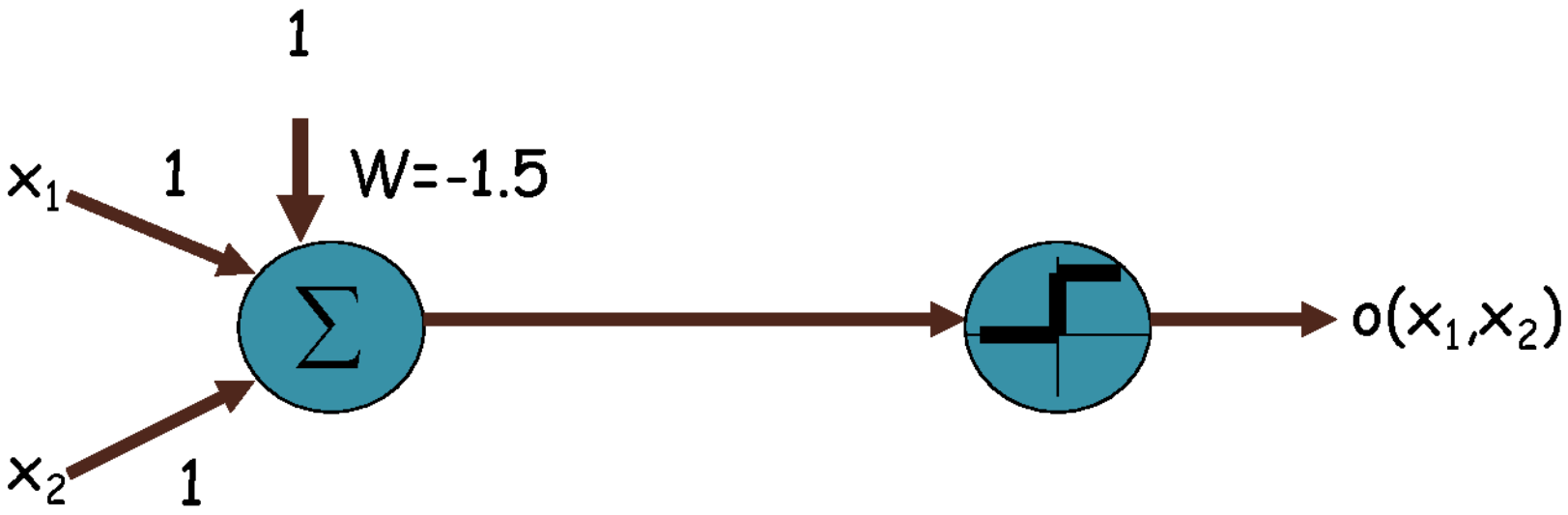


Linearly separable data

Boolean Functions

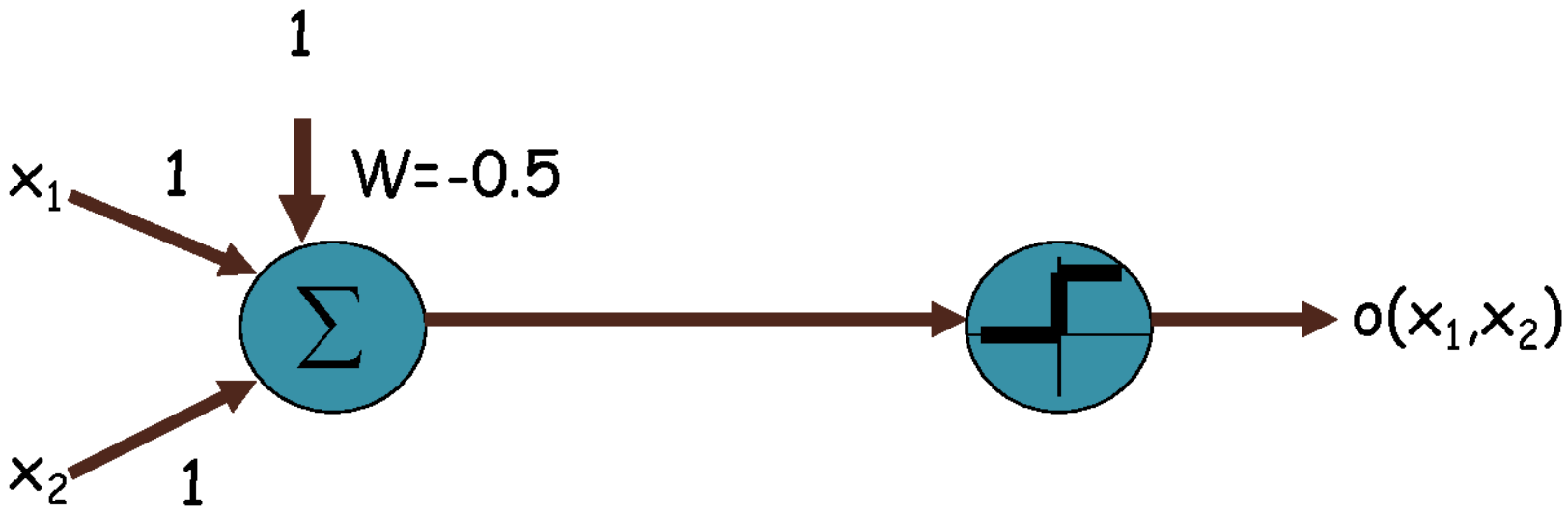
- A single perceptron can be used to represent many boolean functions
  - 1 (true); 0 (false)
- Perceptrons can represent all of the primitive boolean functions
  - AND, OR, NOT

Implementing AND



$$o(x_1, x_2) = 1 \text{ if } -1.5 + x_1 + x_2 > 0$$
$$= 0 \text{ otherwise}$$

Implementing OR



$o(x1,x2) = 1$ if $-0.5 + x1 + x2 > 0$

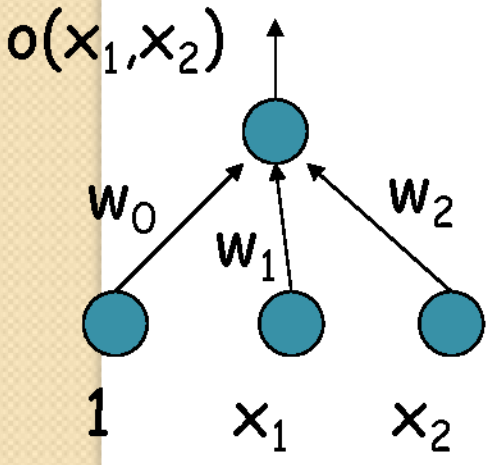
$= 0$ otherwise

Implementing NOT

$$o(x_1) = 1 \text{ if } 0.5 - x_1 > 0$$
$$= 0 \text{ otherwise}$$

The XOR Function

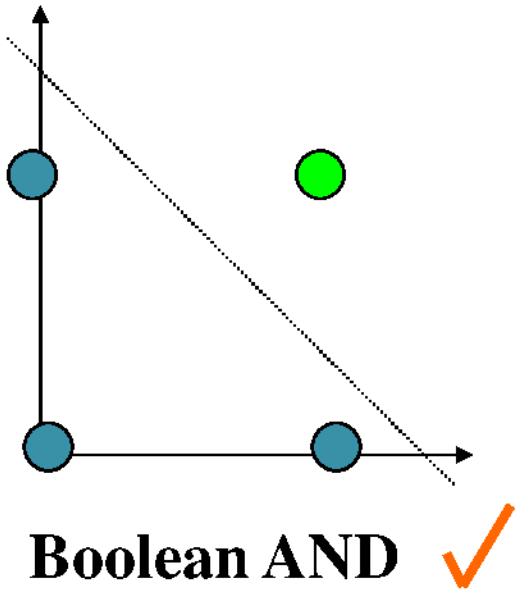
- Unfortunately, some Boolean functions cannot be represented by a single perceptron



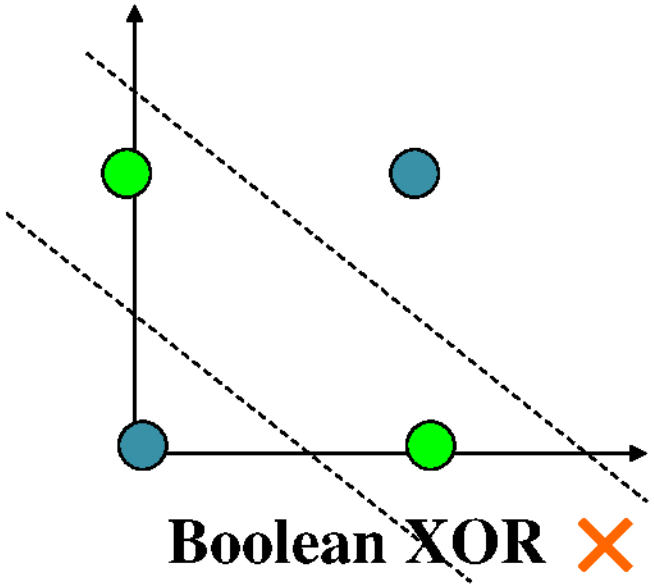
$$
\left.
\begin{aligned}
w_0 + 0 \cdot w_1 + 0 \cdot w_2 &\le 0 \\
w_0 + 0 \cdot w_1 + 1 \cdot w_2 &> 0 \\
w_0 + 1 \cdot w_1 + 0 \cdot w_2 &> 0 \\
w_0 + 1 \cdot w_1 + 1 \cdot w_2 &\le 0
\end{aligned}
\right\} \mathrm{XOR}(x_1, x_2)
$$

There is no assignment of values to w_0,w_1 and w_2 that satisfies above inequalities. XOR cannot be represented!

Linear Seprability



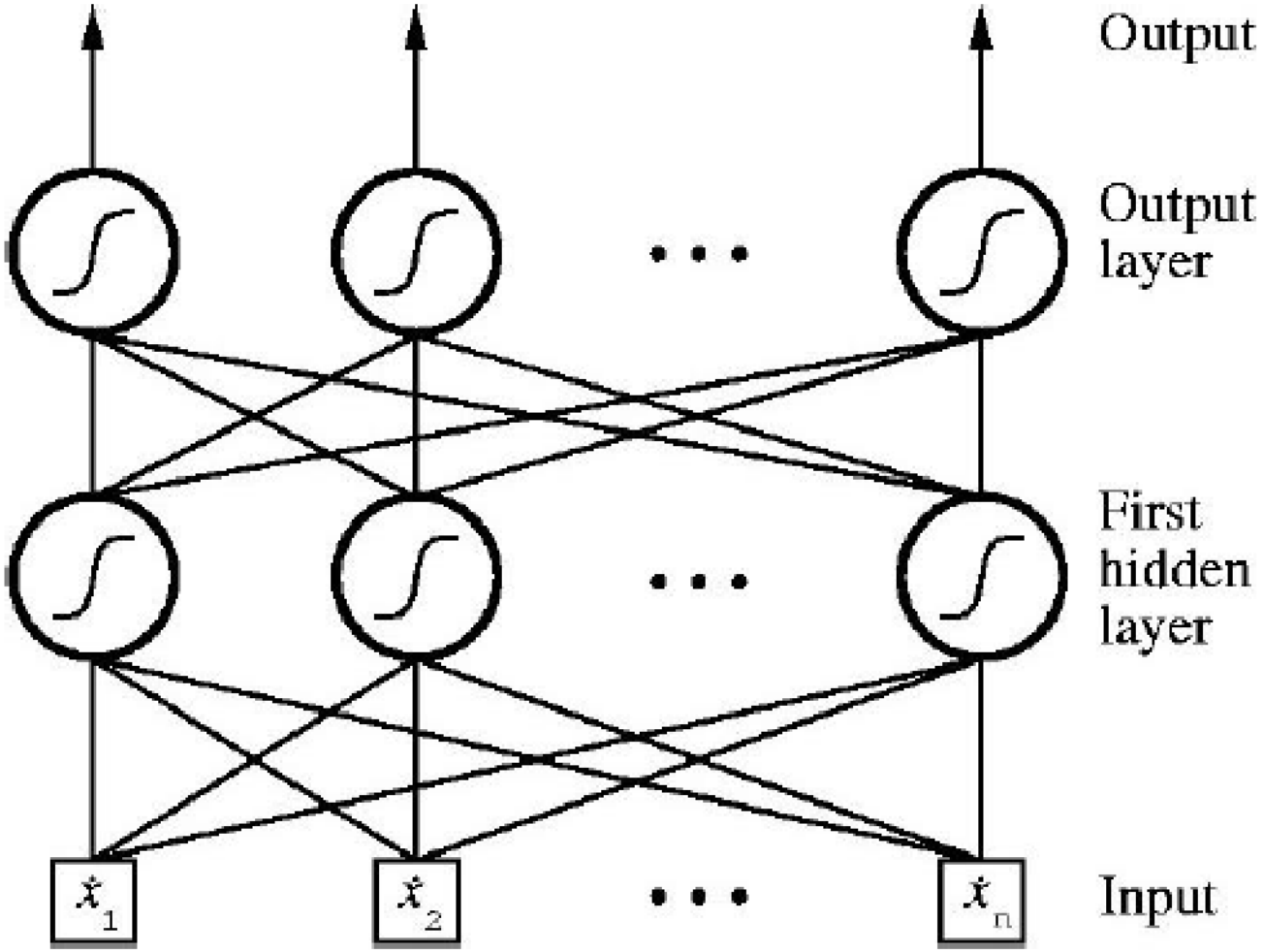
Boolean AND ✓



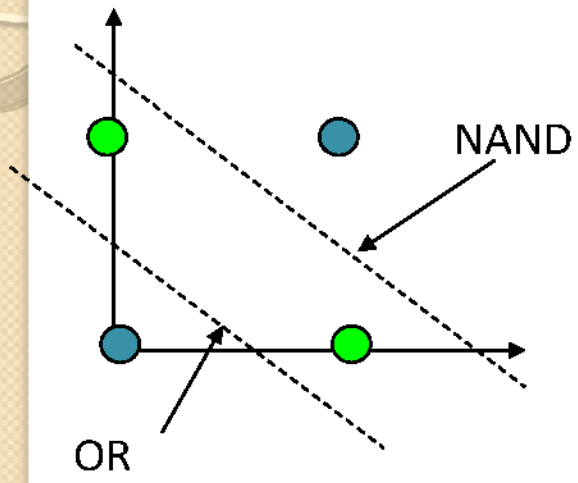
Boolean XOR ✗

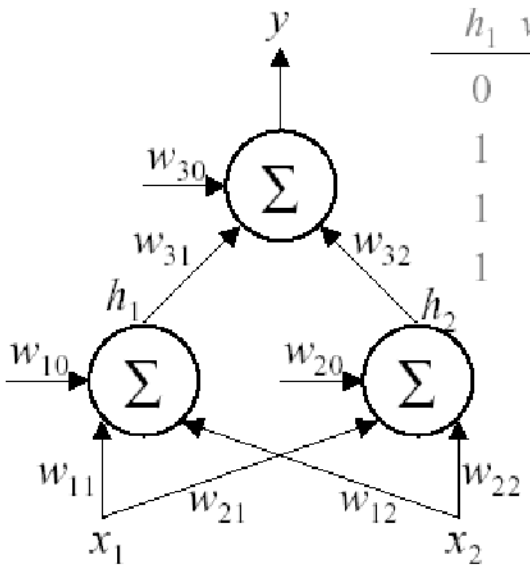
Representation Theorem: Perceptrons can only represent linearly separable functions. That is, the decision surface separating the output values has to be a plane.
(Minsky & Papert, 1969)

Multi-Layer Perceptrons (MLP)



Implementing XOR by Multi-layer perceptron (MLP)





h_1	w_{31}	h_2	w_{32}	Σ	w_{30}	y
0	1	0	-1	0	0.5	0
1	1	0	-1	1	0.5	1
1	1	0	-1	1	0.5	1
1	1	1	-1	0	0.5	0

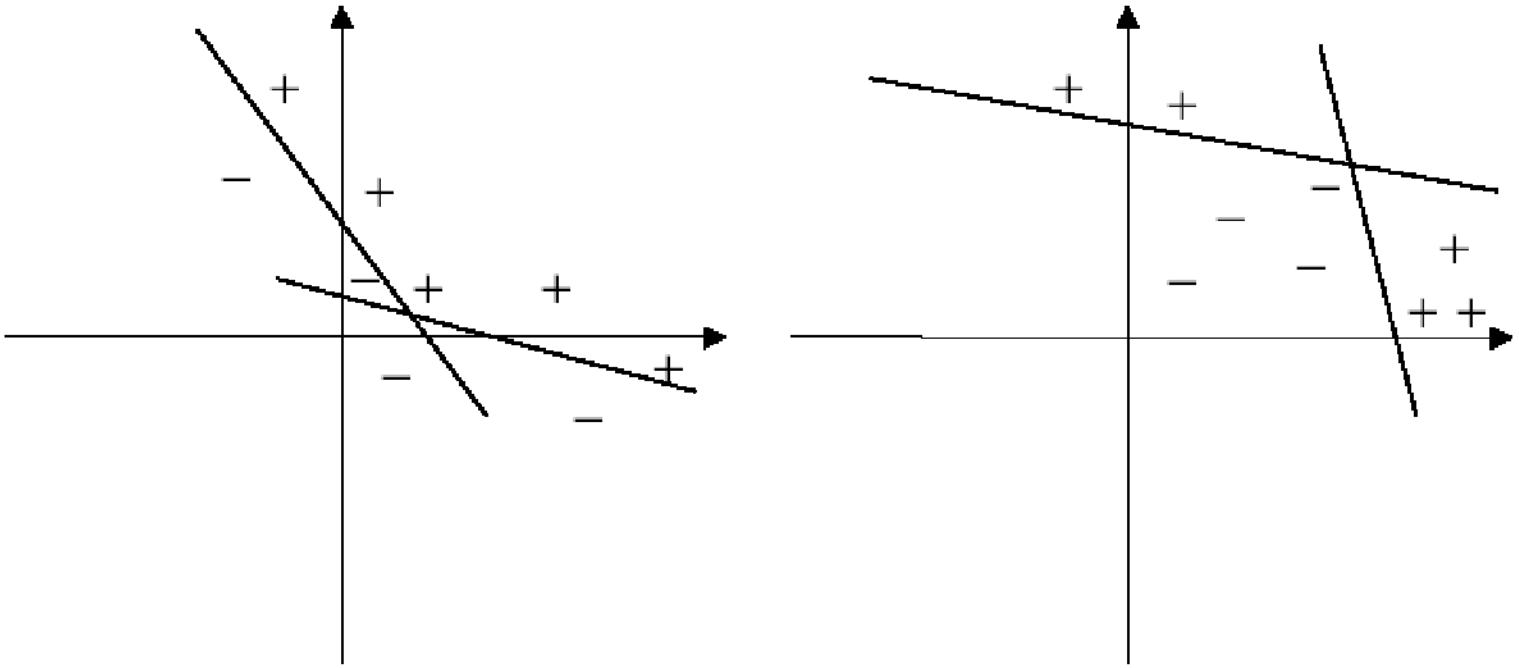
x_1	w_{11}	x_2	w_{12}	Σ	w_{10}	h_1
0	0.5	0	0.5	0	0.3	0
0	0.5	1	0.5	0.5	0.3	1
1	0.5	0	0.5	0.5	0.3	1
1	0.5	1	0.5	1	0.3	1

x_1	w_{21}	x_2	w_{22}	Σ	w_{20}	h_2
0	0.5	0	0.5	0	0.7	0
0	0.5	1	0.5	0.5	0.7	0
1	0.5	0	0.5	0.5	0.7	0
1	0.5	1	0.5	1	0.7	1

x1 XOR x2 = (x1 OR x2) AND (NOT(x1 AND x2))

Representation Power of MLP

- Conjunction of piece-wise hyperplanes



Representation Power of ANN

- Boolean functions: Every Boolean function can be represented exactly by some network with two layers of units
- Continuous functions: Every bounded continuous function can be approximated with arbitrarily small error (under a finite norm) by a network with two layers of units
- Arbitrary functions: Any function can be approximated to arbitrary accuracy by a network with three layers of units

Definition of Training Error

- Training error E: a function of weight vector over the training data set D

$$E(w) \equiv \frac{1}{2} \sum_{d \in D} (t_d - o_d)^2$$

$$o(\vec{x}) = \vec{w} \cdot \vec{x}$$

Unthresholded perceptron or linear unit

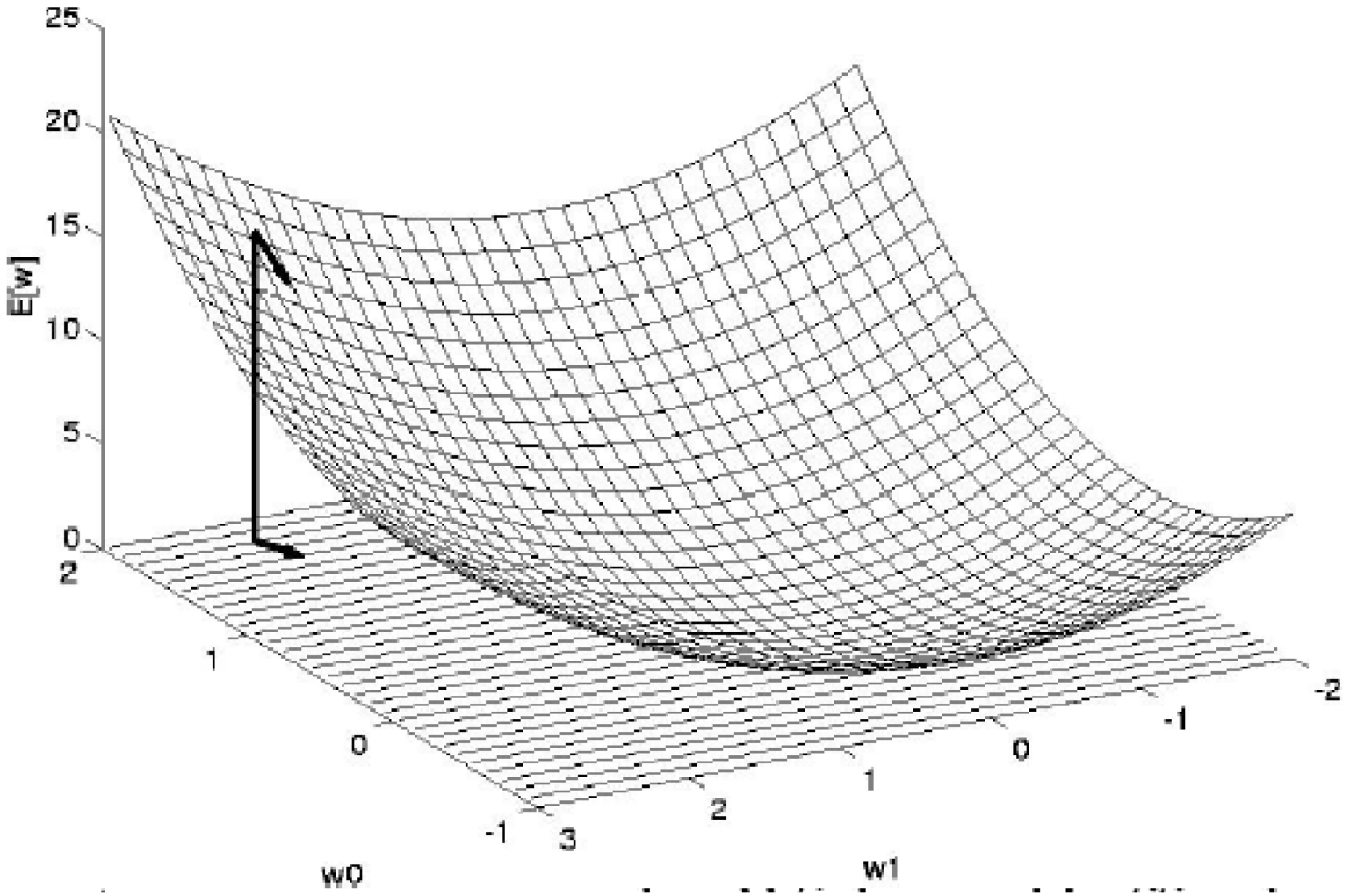
Gradient Descent

- To reduce error E, update the weight vector w in the direction of steepest descent along the error surface

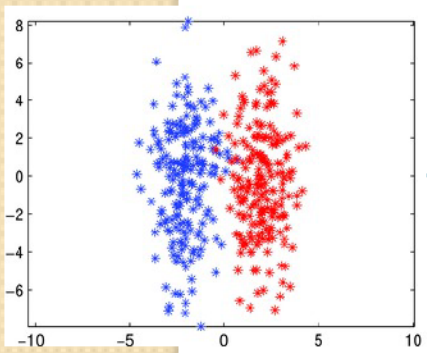
$$\nabla E(w) \equiv \left[\frac{\partial E}{\partial w_0}, \frac{\partial E}{\partial w_1}, \frac{\partial E}{\partial w_2}, \cdots, \frac{\partial E}{\partial w_n} \right]$$

$$w \leftarrow w + (-\eta \nabla E(w))$$

Gradient Descent

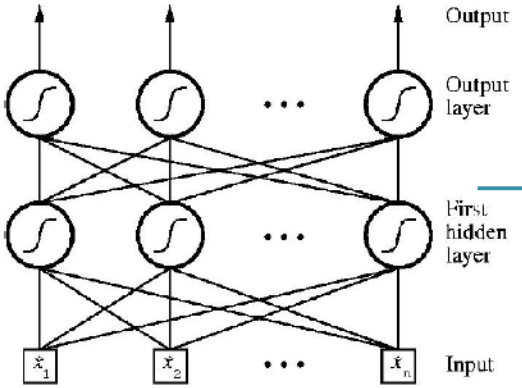


Neuron network design for non-closed form problem



Training data $\{x_i, y_i\}$

Training process



Neuron network

Testing data x^*

Testing process

Result y^*

Neural Network I/O and Method

1. In MP5, use 3-hidden layer neural networks (numN=3) for audio-to-image mapping
2. Training function:
   [mapping] = ECE417_MP5_train (avTrainingData, avValidateData, silenceModel, numN, resultFile)
   - Feedforward neural networks are trained to map input audio features to the corresponding visual coordinate.
   - Train three neural networks for visual dimensions (w, h_1, h_2), respectively.
3. Testing function:
   [results] = ECE417_MP5_test (testAudio, silenceModel, mapping)
   - Given the trained neural networks and audio test features, the neural networks predicts visual coordinates.

Image Deformation/Warping for MP5

1. For each triangle find an affine transformation system deform the triangle.
2. Apply deformation to points inside given triangle.
3. Assign image values to triangle points

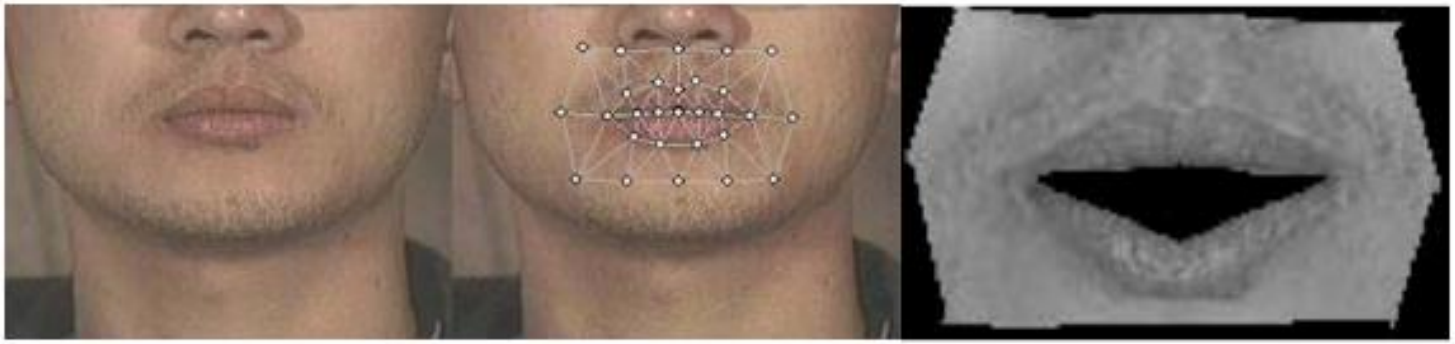


Figure : Neutral Mouth, Mouth Mesh, and Deformed Mouth

Warping for Trianglular Mesh

For each point in the image, you need to figure out which triangle it belongs to and then deform it using the transform that corresponds to that particular triangle in the mesh.

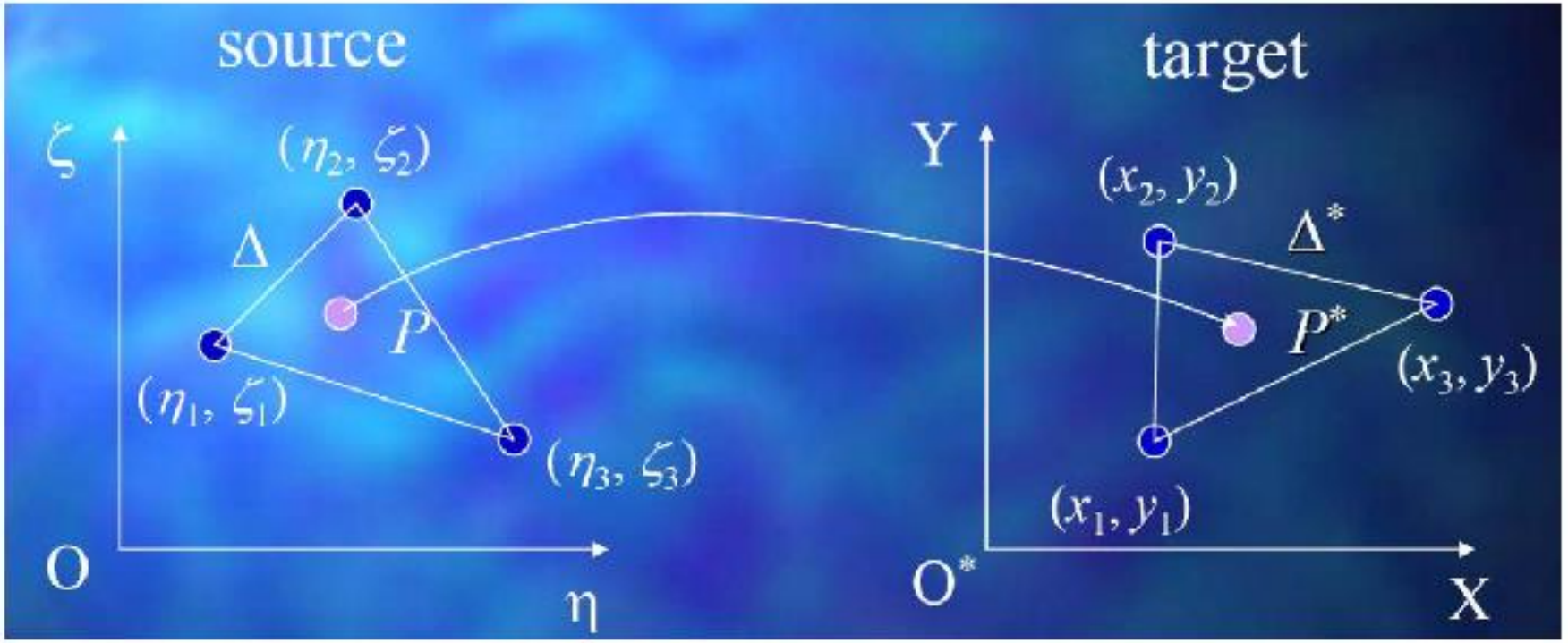


Figure : Triangle Affine Warping

Affine Transformations

The Affine transformation equation is (where the pair (η, ζ) is the source and (x, y) is the warped destination):

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} a_1 & a_2 & a_0 \\ b_1 & b_2 & b_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \eta \\ \zeta \\ 1 \end{bmatrix} \tag{1}$$

Can solve two separate equations for **a** and **b** using Least-Squares.

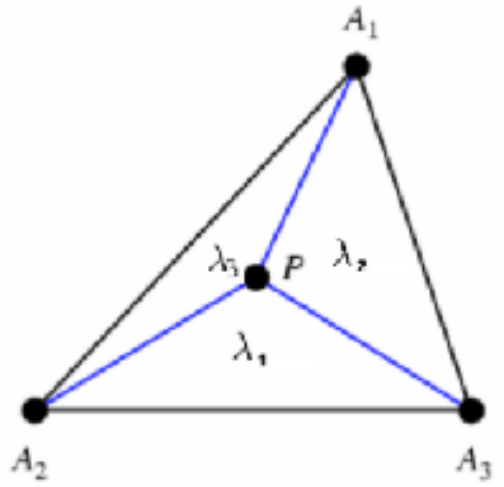
$$\begin{bmatrix} 1 & \eta_1 & \zeta_1 \\ \vdots & \vdots & \vdots \\ 1 & \eta_N & \zeta_N \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} x_1 \\ \vdots \\ x_N \end{bmatrix} \qquad \begin{bmatrix} 1 & \eta_1 & \zeta_1 \\ \vdots & \vdots & \vdots \\ 1 & \eta_N & \zeta_N \end{bmatrix} \begin{bmatrix} b_0 \\ b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} y_1 \\ \vdots \\ y_N \end{bmatrix} \tag{2}$$

Can also just solve for both at once.

$$\begin{bmatrix} \eta_1 & \zeta_1 & 0 & 0 & 1 & 0 \\ 0 & 0 & \eta_1 & \zeta_1 & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \eta_N & \zeta_N & 0 & 0 & 1 & 0 \\ 0 & 0 & \eta_N & \zeta_N & 0 & 1 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ b_1 \\ b_2 \\ a_0 \\ b_0 \end{bmatrix} = \begin{bmatrix} x_1 \\ y_1 \\ \vdots \\ x_N \\ y_N \end{bmatrix} \tag{3}$$

Barycentric Coordinates

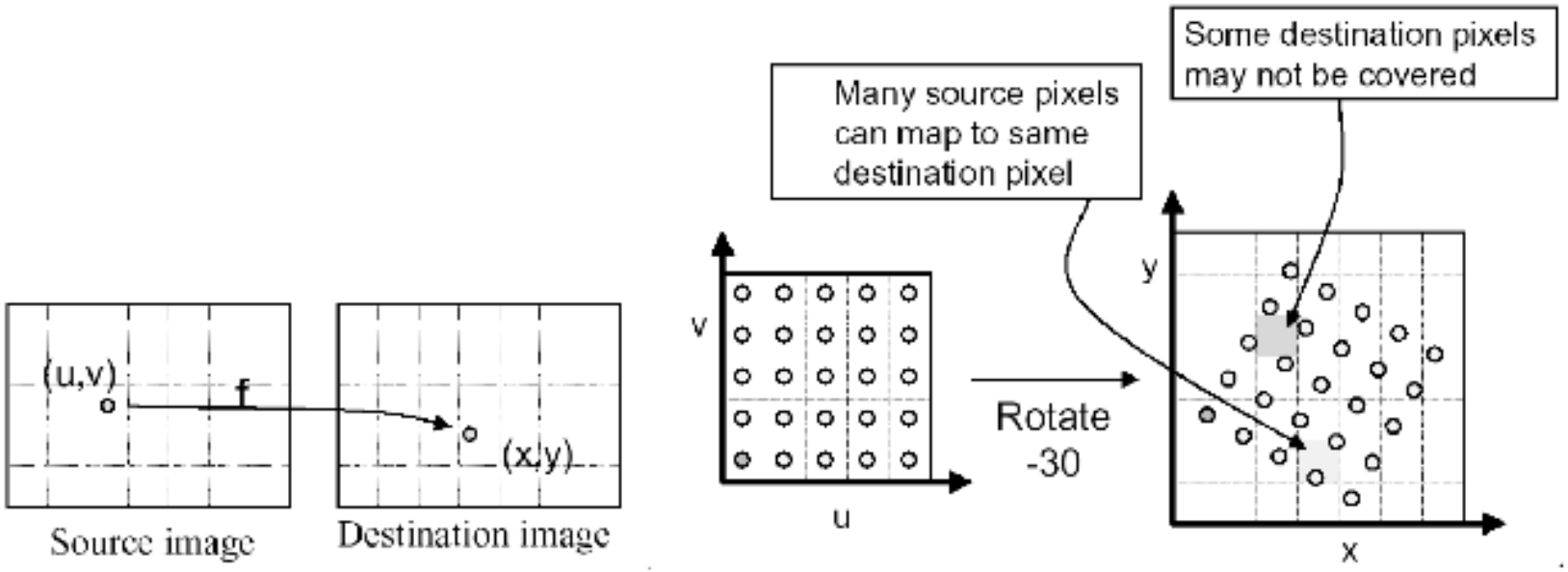
For any (η, ζ) in a given mesh triangle P, we can write the coordinates as a function of the vertices of said triangle. In addition, homogeneous barycentric coordinates are invariant to affine transformations.



$$\begin{bmatrix} \zeta \\ \eta \\ 1 \end{bmatrix} = \begin{bmatrix} \zeta_1 & \zeta_2 & \zeta_3 \\ \eta_1 & \eta_2 & \eta_3 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{bmatrix} \qquad \begin{bmatrix} \zeta \\ \eta \\ 1 \end{bmatrix} = \begin{bmatrix} x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{bmatrix} \tag{4}$$

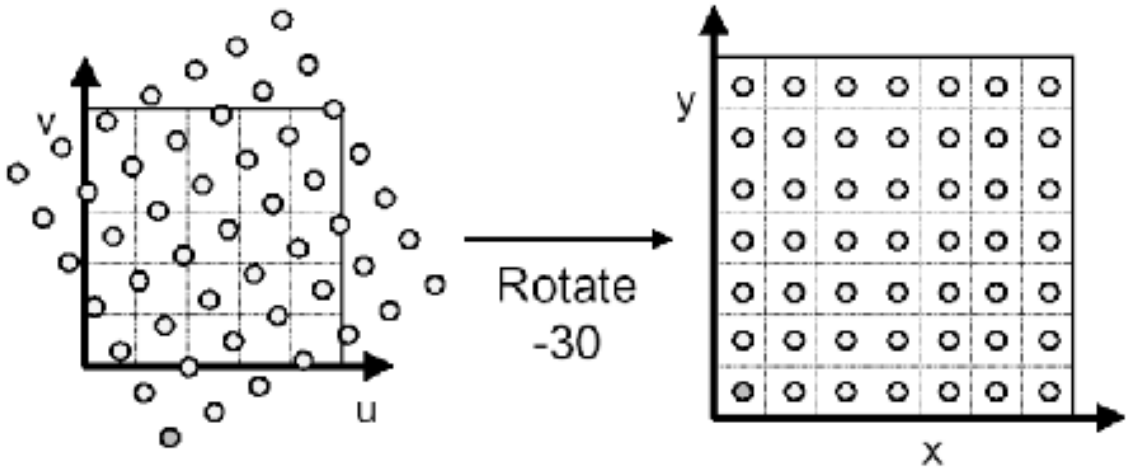
Forward Mapping

Forward: iterate over source image and map pixels in the source image to the destination image.



Backward Mapping

1. Backward: iterate over destination image and map pixels in the destination image back to original image.
2. may oversample, and will have to resample (interpolate) source (because non-integer index returns)

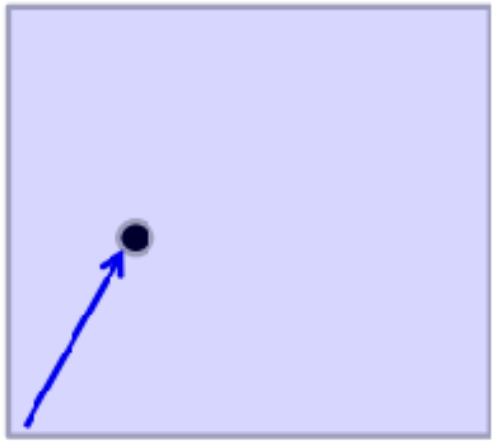


Resampling

1. Evaluate source image at arbitrary (u, v)
   - (u, v) does not usually have integer coordinates
2. Some kinds of resampling
   - Nearest neighbor
   - Bilinear interpolation
   - Gaussian filter

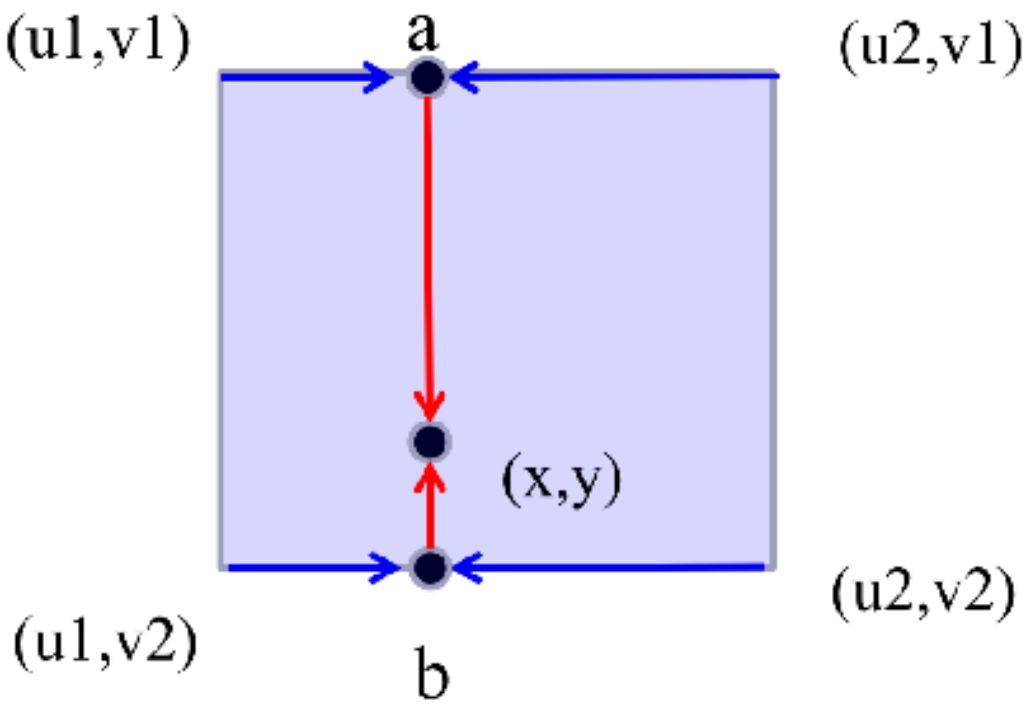
Nearest Neighbor Interpolation

1. Take value at closest pixel
   - int iu = trunc(u + 0.5);
   - int iv = trunc(v + 0.5);
   - dst(x, y) = src(iu, iv);
2. Simple, but causes aliasing



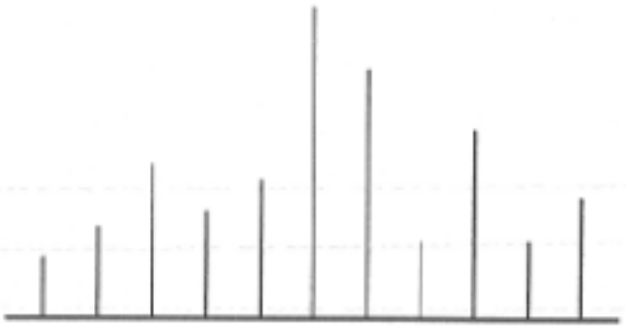
Bilinear Interpolation

1. Bilinearly interpolate four surrounding pixels
   - a = linear interpolation of src(u_1 , v_1) and src(u_2 , v_1)
   - b = linear interpolation of src(u_1 , v_2) and src(u_2 , v_2)
   - dst(x, y) = linear interpolation of 'a' and 'b'

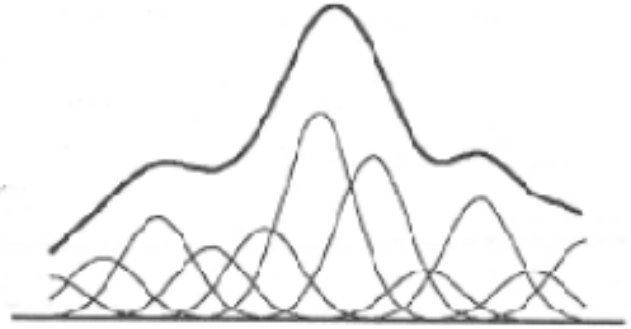


Gaussian Kernel Interpolation

Convolve with Gaussian filter



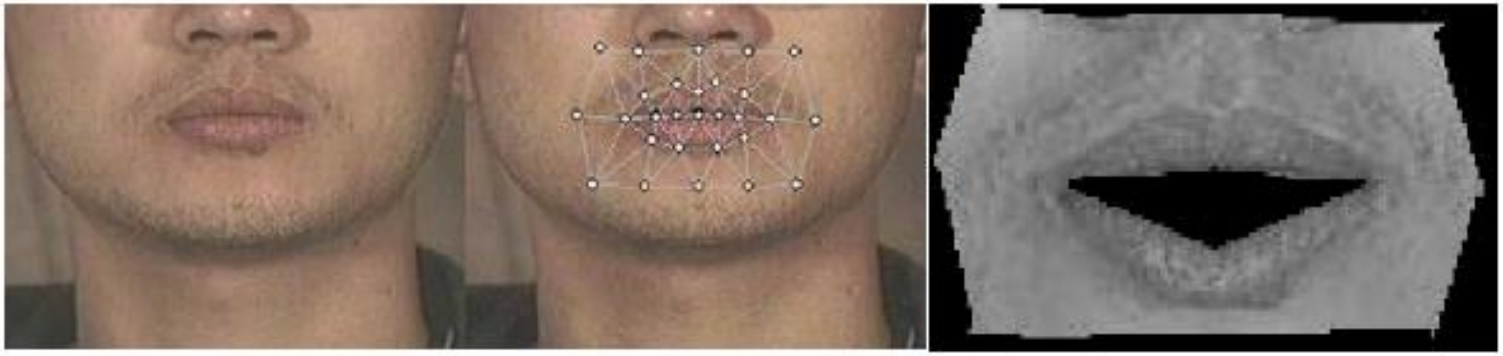
Input



Output

Width of Gaussian kernel affects bluriness

Warping in MP5



1. Warping
   - For each triangle find the affine transform
   - Apply it to the points inside
   - Assign image value to the triangle points
2. Suggestions
   - Barycentric coordinate
   - Reverse mapping

Workflow

1. main.m - wrapper function for overall code
   - 1.1 Audio-Visual Training
     - 1.1.1 read neutral image
     - 1.1.2 load training data
     - 1.1.3 train Neural Network
   - 1.2 Audio-Visual Test Implementation
     - 1.2.1 use Neural Network to find visual features for given 456 frames of test data
   - 1.3 Image Deformation
     - 1.3.1 Iterate through each frame, and for each one apply warping function warping.m.
2. warping.m - function to deform neutral image according to mapping
   - 2.1 interpolate visual features into mesh
   - 2.2 for each triangle:
     - 2.2.1 if triangle has changed, then warp changed triangle using either Affine transformation or Barycentric coordinates
     - 2.2.2 interpolate new image using either nearest neighbor or bilinear interpolation
3. generate_movie.m - function to concatenate frames and create movie
   - 3.1 either use a system call to run given executeable or use Matlab to create a movie from individual frames and overlay audio

Deliverables

1. Code - A self-contained file that does everything listed in the requirements. You can write as many functions (or as few) as you wish, but there must be one overall function that will call everything automatically run without any hassle.
2. Report - Tell us about your general approach to this problem, and describes the algorithms you use. In addition, tell us the approach you used to generate the movie file, as this will probably vary across submisions.
3. Readme - a readme file that tells us how to run your code, and any options that need to be set.
4. Movie - a movie file (avi seems the best choice) that represents the total output of your algorithm