Machine Learning for Signal Processing

Detecting faces in images

Class 7. 19 Sep 2013

Instructor: Bhiksha Raj
Administrivia

- Project teams?
- Project proposals?
A “typical face” that captures the essence of “facehood”.

The principal Eigen face.
A collection of least squares typical faces

• Extension: Many Eigenfaces

• Approximate every face \( f \) as \( f = w_{f,1} V_1 + w_{f,2} V_2 + \ldots + w_{f,k} V_k \)
  
  – \( V_2 \) is used to “correct” errors resulting from using only \( V_1 \)
  
  – \( V_3 \) corrects errors remaining after correction with \( V_2 \)
  
  – And so on..

• \( V = [V_1 \ V_2 \ V_3] \) can be computed through Eigen analysis
Normalizing out variations: HEQ

• Left column: Original image
• Right column: Equalized image
• All images now have similar contrast levels
Eigenfaces after Equalization

• Left panel: Without HEQ
• Right panel: With HEQ
  – Eigen faces are more face like..
    • Need not always be the case
Detecting Faces in Images
Detecting Faces in Images

• Finding face like patterns
  – How do we find if a picture has faces in it
  – Where are the faces?

• A simple solution:
  – Define a “typical face”
  – Find the “typical face” in the image
Finding faces in an image

- Picture is larger than the “typical face”
  - E.g. typical face is 100x100, picture is 600x800

- First convert to greyscale
  - R + G + B
  - Not very useful to work in color
Finding faces in an image

• Goal .. To find out if and where images that look like the “typical” face occur in the picture
Finding faces in an image

• Try to “match” the typical face to each location in the picture
Finding faces in an image

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• Try to “match” the typical face to each location in the picture

• The “typical face” will explain some spots on the image much better than others
  – These are the spots at which we probably have a face!
How to “match”

• What exactly is the “match”
  – What is the match “score”
How to “match”

• What exactly is the “match”
  – What is the match “score”

• The DOT Product
  – Express the typical face as a vector
  – Express the region of the image being evaluated as a vector
    • But first histogram equalize the region
      – Just the section being evaluated, without considering the rest of the image
    – Compute the dot product of the typical face vector and the “region” vector
What do we get

- The right panel shows the dot product at various locations
  - Redder is higher
    - The locations of peaks indicate locations of faces!
What do we get

- The right panel shows the dot product at various locations:
  - Redder is higher
    - The locations of peaks indicate locations of faces!
- Correctly detects all three faces:
  - Likes George’s face most
    - He looks most like the typical face
- Also finds a face where there is none:
  - A false alarm
Scaling and Rotation Problems

• Scaling
  – Not all faces are the same size
  – Some people have bigger faces
  – The size of the face on the image changes with perspective
  – Our “typical face” only represents one of these sizes

• Rotation
  – The head need not always be upright!
    • Our typical face image was upright
Solution

- Create many “typical faces”
  - One for each scaling factor
  - One for each rotation
    - How will we do this?
- Match them all

- Does this work
  - Kind of .. Not well enough at all
  - We need more sophisticated models
Face Detection: A Quick Historical Perspective

- Many more complex methods
  - Use edge detectors and search for face like patterns
  - Find "feature" detectors (noses, ears..) and employ them in complex neural networks..

- The Viola Jones method
  - Boosted cascaded classifiers

- But first, what is boosting
And even before that – what is classification?

• Given “features” describing an entity, determine the category it belongs to
  – Walks on two legs, has no hair. Is this
    • A Chimpanzee
    • A Human
  – Has long hair, is 5’6” tall, is this
    • A man
    • A woman
  – Matches “eye” pattern with score 0.5, “mouth pattern” with score 0.25, “nose” pattern with score 0.1. Are we looking at
    • A face
    • Not a face?
Classification

• Multi-class classification
  – Many possible categories
    • E.g. Sounds “AH, IY, UW, EY..”
    • E.g. Images “Tree, dog, house, person..”

• Binary classification
  – Only two categories
    • Man vs. Woman
    • Face vs. not a face..

• Face detection: Recast as binary face classification
  – For each little square of the image, determine if the square represents a face or not
Face Detection as Classification

- Faces can be many sizes
- They can happen anywhere in the image
- For each face size
  - For each location
    - Classify a rectangular region of the face size, at that location, as a face or not a face
- This is a series of *binary* classification problems

For each square, run a classifier to find out if it is a face or not
Binary classification

• Classification can be abstracted as follows
  • $H: X \rightarrow (+1,-1)$
  • A function $H$ that takes as input some $X$ and outputs a $+1$ or $-1$
    – $X$ is the set of “features”
    – $+1/-1$ represent the two classes

• Many mechanisms (may types of “$H$”)
  – Any many ways of characterizing “$X$”

• We’ll look at a specific method based on voting with simple rules
  – A “META” method
Introduction to Boosting

• An ensemble method that sequentially combines many simple BINARY classifiers to construct a final complex classifier
  – Simple classifiers are often called “weak” learners
  – The complex classifiers are called “strong” learners

• Each weak learner focuses on instances where the previous classifier failed
  – Give greater weight to instances that have been incorrectly classified by previous learners

• Restrictions for weak learners
  – Better than 50% correct

• Final classifier is weighted sum of weak classifiers
Boosting: A very simple idea

• One can come up with many rules to classify
  – E.g. Chimpanzee vs. Human classifier:
    – If arms == long, entity is chimpanzee
    – If height > 5’6” entity is human
    – If lives in house == entity is human
    – If lives in zoo == entity is chimpanzee

• Each of them is a reasonable rule, but makes many mistakes
  – Each rule has an intrinsic error rate

• *Combine* the predictions of these rules
  – But not equally
  – Rules that are less accurate should be given lesser weight
Boosting and the Chimpanzee Problem

- The total confidence in all classifiers that classify the entity as a chimpanzee is
  \[ \text{Score}_{\text{chimp}} = \sum \alpha_{\text{classifier}} \]
  where \( \alpha_{\text{classifier}} \) is the weight of the classifier.

- The total confidence in all classifiers that classify it as a human is
  \[ \text{Score}_{\text{human}} = \sum \alpha_{\text{classifier}} \]
  where \( \alpha_{\text{classifier}} \) is the weight of the classifier.

- If \( \text{Score}_{\text{chimp}} > \text{Score}_{\text{human}} \) then the our belief that we have a chimpanzee is greater than the belief that we have a human.
Boosting as defined by Freund

• A gambler wants to write a program to predict winning horses. His program must encode the expertise of his brilliant winner friend

• The friend has no single, encodable algorithm. Instead he has many rules of thumb
  – He uses a different rule of thumb for each set of races
    • E.g. “in this set, go with races that have black horses with stars on their foreheads”
  – But cannot really enumerate what rules of thumbs go with what sets of races: he simply “knows” when he encounters a set
    • A common problem that faces us in many situations

• Problem:
  – How best to combine all of the friend’s rules of thumb
  – What is the best set of races to present to the friend, to extract the various rules of thumb
Boosting

• The basic idea: Can a “weak” learning algorithm that performs just slightly better than random guessing be *boosted* into an arbitrarily accurate “strong” learner
  – Each of the gambler’s rules may be just better than random guessing

• This is a “meta” algorithm, that poses no constraints on the form of the weak learners themselves
  – The gambler’s rules of thumb can be anything
Boosting: A Voting Perspective

• Boosting can be considered a form of voting
  – Let a number of different classifiers classify the data
  – Go with the majority
  – Intuition says that as the number of classifiers increases, the dependability of the majority vote increases

• The corresponding algorithms were called Boosting by majority
  – A (weighted) majority vote taken over all the classifiers
  – How do we compute weights for the classifiers?
  – How do we actually train the classifiers
ADA Boost: Adaptive algorithm for learning the weights

• ADA Boost: Not named of ADA Lovelace
• An *adaptive* algorithm that learns the weights of each classifier sequentially
  – Learning adapts to the current accuracy

• Iteratively:
  – Train a simple classifier from training data
    • It will make errors even on training data
    • Train a new classifier that focuses on the training data points that have been misclassified
Boosting: An Example

- Red dots represent training data from Red class
- Blue dots represent training data from Blue class
Boosting: An Example

• Very simple weak learner
  – A line that is parallel to one of the two axes
• First weak learner makes many mistakes
  – Errors coloured black
• Second weak learner focuses on errors made by first learner
**Boosting: An Example**

- **Second strong learner:** weighted combination of first and second weak learners
  - Decision boundary shown by black lines
• The second strong learner also makes mistakes
  – Errors colored black
Boosting: An Example

- Third weak learner concentrates on errors made by second strong learner
Boosting: An Example

- Third weak learner concentrates on errors made by combination of previous weak learners
- Continue adding weak learners until....
• Voila! Final **strong learner:** very few errors on the training data
• The final strong learner has learnt a complicated decision boundary
Boosting: An Example

• The final **strong** learner has learnt a complicated decision boundary

• Decision boundaries in areas with low density of training points assumed inconsequential
Overall Learning Pattern

- Strong learner increasingly accurate with increasing number of weak learners

- Residual errors increasingly difficult to correct
  - Additional weak learners less and less effective
ADABoost

• Cannot just add new classifiers that work well only the previously misclassified data

• Problem: The new classifier will make errors on the points that the earlier classifiers got right
  – Not good
  – On test data we have no way of knowing which points were correctly classified by the first classifier

• Solution: Weight the data to train the second classifier
  – Use all the data but assign them weights
    • Data that are already correctly classified have less weight
    • Data that are currently incorrectly classified have more weight
The red and blue points (correctly classified) will have a weight \( \alpha < 1 \)

Black points (incorrectly classified) will have a weight \( \beta (= 1/\alpha) > 1 \)

To compute the optimal second classifier, we minimize the total weighted error

- Each data point contributes \( \alpha \) or \( \beta \) to the total count of correctly and incorrectly classified points
  - E.g. if one of the red points is misclassified by the new classifier, the total error of the new classifier goes up by \( \alpha \)
ADA Boost

- Each new classifier modifies the weights of the data points based on the accuracy of the current classifier.
- The final classifier too is a weighted combination of all component classifiers.
Formalizing the Boosting Concept

• Given a set of instances \((x_1, y_1), (x_2, y_2), \ldots, (x_N, y_N)\)
  – \(x_i\) is the set of attributes of the \(i\)th instance
  – \(y_i\) is the class for the \(i\)th instance
    • \(y_i\) can be 1 or -1 (binary classification only)

• Given a set of classifiers \(h_1, h_2, \ldots, h_T\)
  – \(h_i\) classifies an instance with attributes \(x\) as \(h_i(x)\)
  – \(h_i(x)\) is either -1 or +1 (for a binary classifier)
    – \(y \cdot h(x)\) is 1 for all correctly classified points and -1 for incorrectly classified points

• Devise a function \(f(h_1(x), h_2(x), \ldots, h_T(x))\) such that classification based on \(f()\) is superior to classification by any \(h_i(x)\)
  – The function is succinctly represented as \(f(x)\)
The Boosting Concept

• A simple combiner function: Voting
  – \( f(x) = \sum_i h_i(x) \)
  – Classifier \( H(x) = \text{sign}(f(x)) = \text{sign}(\sum_i h_i(x)) \)
  – Simple majority classifier
    • A simple voting scheme

• A better combiner function: Boosting
  – \( f(x) = \sum_i \alpha_i h_i(x) \)
    • Can be any real number
  – Classifier \( H(x) = \text{sign}(f(x)) = \text{sign}(\sum_i \alpha_i h_i(x)) \)
  – A weighted majority classifier
    • The weight \( \alpha_i \) for any \( h_i(x) \) is a measure of our trust in \( h_i(x) \)
Adaptive Boosting

• As before:
  – $y$ is either $-1$ or $+1$
  – $H(x)$ is $+1$ or $-1$
  – If the instance is correctly classified, both $y$ and $H(x)$ will have the same sign
    • The product $y.H(x)$ is 1
    • For incorrectly classified instances the product is $-1$

• Define the error for $x : \frac{1}{2}(1 - yH(x))$
  – For a correctly classified instance, this is 0
  – For an incorrectly classified instance, this is 1
The ADABoost Algorithm

• Given: a set \((x_1, y_1), \ldots, (x_N, y_N)\) of training instances
  – \(x_i\) is the set of attributes for the \(i^{\text{th}}\) instance
  – \(y_i\) is the class for the \(i^{\text{th}}\) instance and can be either +1 or -1
The ADABOost Algorithm

• Initialize $D_1(x_i) = 1/N$

• For $t = 1, ..., T$
  – Train a weak classifier $h_t$ using distribution $D_t$
  – Compute total error on training data
    • $\varepsilon_t = \sum_i \{\frac{1}{2} (1 - y_i h_t(x_i))\}$
  – Set $\alpha_t = \frac{1}{2} \ln \left(\frac{(1 - \varepsilon_t)}{\varepsilon_t}\right)$
  – For $i = 1... N$
    • set $D_{t+1}(x_i) = D_t(x_i) \exp(-\alpha_t y_i h_t(x_i))$
  – Normalize $D_{t+1}$ to make it a distribution

• The final classifier is
  – $H(x) = \text{sign}(\sum_t \alpha_t h_t(x))$
First, some example data

- Face detection with multiple Eigen faces
- Step 0: Derived top 2 Eigen faces from Eigen face training data
- Step 1: On a (different) set of examples, express each image as a linear combination of Eigen faces
  - Examples include both faces and non faces
  - Even the non-face images will are explained in terms of the Eigen faces

\[
\begin{align*}
\text{Image} &= a \times E1 + b \times E2 \rightarrow a = \text{Image}.E1 \\
= 0.3 \ E1 - 0.6 \ E2 \\
= 0.5 \ E1 - 0.5 \ E2 \\
= 0.7 \ E1 - 0.1 \ E2 \\
= 0.6 \ E1 - 0.4 \ E2 \\
= 0.2 \ E1 + 0.4 \ E2 \\
= -0.8 \ E1 - 0.1 \ E2 \\
= 0.4 \ E1 - 0.9 \ E2 \\
= 0.6 \ E1 - 0.4 \ E2 \\
= 0.2 \ E1 + 0.5 \ E2 \\
\end{align*}
\]
Training Data

= 0.3 E1 - 0.6 E2
= 0.5 E1 - 0.5 E2
= 0.7 E1 - 0.1 E2
= 0.6 E1 - 0.4 E2

Face = +1
Non-face = -1

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- The final classifier is
  - $H(x) = \text{sign}(\sum_t \alpha_t h_t(x))$
Training Data

\[= 0.3 \, E1 - 0.6 \, E2\]
\[= 0.5 \, E1 - 0.5 \, E2\]
\[= 0.7 \, E1 - 0.1 \, E2\]
\[= 0.6 \, E1 - 0.4 \, E2\]

\[= 0.2 \, E1 + 0.4 \, E2\]
\[= -0.8 \, E1 - 0.1 \, E2\]
\[= 0.4 \, E1 - 0.9 \, E2\]
\[= 0.2 \, E1 + 0.5 \, E2\]
The ADABOOST Algorithm

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  - For $i = 1 \ldots N$
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- The final classifier is
  - $H(x) = \text{sign}(\sum_t \alpha_t h_t(x))$
The E1 “Stump”

Classifier based on E1:
if ( sign*wt(E1) > thresh) > 0)
    face = true

sign = +1 or -1

Sign = +1, error = 3/8
Sign = -1, error = 5/8

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The E1 “Stump”

Classifier based on E1:
if ( sign*wt(E1) > thresh) > 0) face = true
sign = +1 or -1

threshold

Sign = +1, error = 2/8
Sign = -1, error = 6/8

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Classifier based on E1:
if ( sign*wt(E1) > thresh) > 0
    face = true

sign = +1 or -1

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<td>0.6</td>
<td>-0.4</td>
<td>+1</td>
<td>1/8</td>
</tr>
<tr>
<td>E</td>
<td>0.2</td>
<td>0.4</td>
<td>-1</td>
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</tr>
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<tr>
<td>H</td>
<td>0.2</td>
<td>0.5</td>
<td>-1</td>
<td>1/8</td>
</tr>
</tbody>
</table>
## The E1 “Stump”

Classifier based on E1:
if ( sign*wt(E1) > thresh) > 0) 
face = true

sign = +1 or -1

Sign = +1, error = 1/8
Sign = -1, error = 7/8

### Example

<table>
<thead>
<tr>
<th>ID</th>
<th>E1</th>
<th>E2</th>
<th>Class</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.3</td>
<td>-0.6</td>
<td>+1</td>
<td>1/8</td>
</tr>
<tr>
<td>B</td>
<td>0.5</td>
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<td>0.5</td>
<td>-1</td>
<td>1/8</td>
</tr>
</tbody>
</table>
The E1 “Stump”

Classifier based on E1:
if ( sign*wt(E1) > thresh) > 0)
    face = true

sign = +1 or -1

Sign = +1, error = 2/8
Sign = -1, error = 6/8

<table>
<thead>
<tr>
<th>ID</th>
<th>E1</th>
<th>E2</th>
<th>Class</th>
<th>Weight</th>
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<tbody>
<tr>
<td>A</td>
<td>0.3</td>
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</table>
The Best E1 “Stump”

Classifier based on E1:
if ( sign*wt(E1) > thresh) > 0)
face = true

Sign = +1, error = 1/8
Threshold = 0.45

<table>
<thead>
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<tbody>
<tr>
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</tbody>
</table>
The E2 “Stump”

Classifier based on E2:
if ( sign*wt(E2) > thresh) > 0)  
face = true

sign = +1 or -1

Note order
G A B D C F E H
-0.9 -0.6 -0.5 -0.4 -0.1 -0.1 0.4 0.5
1/8 1/8 1/8 1/8 1/8 1/8 1/8 1/8

threshold

Sign = +1, error = 3/8
Sign = -1, error = 5/8

<table>
<thead>
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<th>Weight</th>
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<tr>
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</table>
The Best E2“Stump”

Classifier based on E2:
if ( sign*wt(E2) > thresh) > 0)  
face = true

sign = -1
Threshold = 0.15

Sign = -1, error = 2/8

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The Best “Stump”

The Best overall classifier based on a single feature is based on E1

If (wt(E1) > 0.45) → Face

Sign = +1, error = 1/8

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<td>-1</td>
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</tbody>
</table>
The AdaBoost Algorithm

- Initialize $D_1(x_i) = 1/N$
- For $t = 1, \ldots, T$
  - Train a weak classifier $h_t$ using distribution $D_t$
  - Compute total error on training data
    - $\varepsilon_t = \text{Sum} \{D_t(x_i) \frac{1}{2}(1 - y_i h_t(x_i))\}$
  - Set $\alpha_t = \frac{1}{2} \ln \left( \frac{\varepsilon_t}{1 - \varepsilon_t} \right)$
  - For $i = 1 \ldots N$
    - set $D_{t+1}(x_i) = D_t(x_i) \exp(-\alpha_t y_i h_t(x_i))$
  - Normalize $D_{t+1}$ to make it a distribution
- The final classifier is
  - $H(x) = \text{sign}(\sum_t \alpha_t h_t(x))$
The Best Error

The Error of the classifier is the sum of the weights of the misclassified instances

\[
\begin{array}{cccccccc}
F & E & H & A & G & B & C & D \\
-0.8 & 0.2 & 0.2 & 0.3 & 0.4 & 0.5 & 0.6 & 0.7 \\
1/8 & 1/8 & 1/8 & 1/8 & 1/8 & 1/8 & 1/8 & 1/8 \\
\end{array}
\]

Sign = +1, error = 1/8

NOTE: THE ERROR IS THE SUM OF THE WEIGHTS OF MISCLASSIFIED INSTANCES
The ADABOOST Algorithm

• Initialize \( D_1(x_i) = 1/N \)
• For \( t = 1, \ldots, T \)
  – Train a weak classifier \( h_t \) using distribution \( D_t \)
  – Compute total error on training data
    • \( \varepsilon_t = \text{Sum} \{ D_t(x_i) \frac{1}{2}(1 - y_i h_t(x_i)) \} \)
    – Set \( \alpha_t = \frac{1}{2} \ln \left( \frac{(1 - \varepsilon_t)}{\varepsilon_t} \right) \)
  – For \( i = 1 \ldots N \)
    • set \( D_{t+1}(x_i) = D_t(x_i) \exp(- \alpha_t y_i h_t(x_i)) \)
    – Normalize \( D_{t+1} \) to make it a distribution
• The final classifier is
  – \( H(x) = \text{sign}(\sum_t \alpha_t h_t(x)) \)
Computing Alpha

\[ \text{Alpha} = 0.5 \ln \left( \frac{1 - 1/8}{1/8} \right) = 0.5 \ln(7) = 0.97 \]

Sign = +1, error = 1/8
The Boosted Classifier Thus Far

\[
\begin{align*}
\text{F} & \quad 0.8 \\
\text{E} & \quad 0.2 \\
\text{H} & \quad 0.2 \\
\text{A} & \quad 0.3 \\
\text{G} & \quad 0.4 \\
\text{B} & \quad 0.5 \\
\text{C} & \quad 0.6 \\
\text{D} & \quad 0.7 \\
\end{align*}
\]

\[
\begin{align*}
1/8 & \quad 1/8 \\
1/8 & \quad 1/8 \\
1/8 & \quad 1/8 \\
1/8 & \quad 1/8 \\
1/8 & \quad 1/8 \\
1/8 & \quad 1/8 \\
\end{align*}
\]

\[
\text{Sign} = +1, \text{ error} = 1/8
\]

\[
\text{Alpha} = 0.5 \ln((1 - 1/8) / (1/8)) = 0.5 \ln(7) = 0.97
\]

\[
h_1(X) = \text{wt}(E1) > 0.45 \ ? \ +1 \ : \ -1
\]

\[
H(X) = \text{sign}(0.97 \times h_1(X))
\]

It's the same as \( h_1(x) \)
The ADABOOST Algorithm

- Initialize $D_1(x_i) = 1/N$
- For $t = 1, \ldots, T$
  - Train a weak classifier $h_t$ using distribution $D_t$
  - Compute total error on training data
    - $\varepsilon_t = \text{Average} \left\{ \frac{1}{2} (1 - y_i h_t(x_i)) \right\}$
    - Set $\alpha_t = \frac{1}{2} \ln \left( \frac{(1 - \varepsilon_t)}{\varepsilon_t} \right)$
  - For $i = 1 \ldots N$
    - set $D_{t+1}(x_i) = D_t(x_i) \exp(- \alpha_t y_i h_t(x_i))$
  - Normalize $D_{t+1}$ to make it a distribution
- The final classifier is
  - $H(x) = \text{sign}(\sum_t \alpha_t h_t(x))$
The Best Error

\[ D_{t+1}(x_i) = D_t(x_i) \exp(-\alpha_t y_i h_t(x_i)) \]

\[ \exp(\alpha_t) = \exp(0.97) = 2.63 \]

\[ \exp(-\alpha_t) = \exp(-0.97) = 0.38 \]

<table>
<thead>
<tr>
<th>ID</th>
<th>E1</th>
<th>E2</th>
<th>Class</th>
<th>Weight</th>
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</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.3</td>
<td>-0.6</td>
<td>+1</td>
<td>1/8 * 2.63</td>
<td>0.33</td>
</tr>
<tr>
<td>B</td>
<td>0.5</td>
<td>-0.5</td>
<td>+1</td>
<td>1/8 * 0.38</td>
<td>0.05</td>
</tr>
<tr>
<td>C</td>
<td>0.7</td>
<td>-0.1</td>
<td>+1</td>
<td>1/8 * 0.38</td>
<td>0.05</td>
</tr>
<tr>
<td>D</td>
<td>0.6</td>
<td>-0.4</td>
<td>+1</td>
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<tr>
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<td>0.4</td>
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</tr>
</tbody>
</table>

Multiply the correctly classified instances by 0.38
Multiply incorrectly classified instances by 2.63
The ADABoost Algorithm

• Initialize $D_1(x_i) = 1/N$

• For $t = 1, ..., T$
  – Train a weak classifier $h_t$ using distribution $D_t$
  – Compute total error on training data
    • $\varepsilon_t = \text{Average } \{\frac{1}{2} (1 - y_i h_t(x_i))\}$
  – Set $\alpha_t = \frac{1}{2} \ln \left( \frac{(1 - \varepsilon_t)}{\varepsilon_t} \right)$
  – For $i = 1... N$
    • set $D_{t+1}(x_i) = D_t(x_i) \exp(- \alpha_t y_i h_t(x_i))$
    – Normalize $D_{t+1}$ to make it a distribution

• The final classifier is
  – $H(x) = \text{sign}(\sum_t \alpha_t h_t(x))$
The Best Error

\[ D' = D / \text{sum}(D) \]

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<tr>
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<td>-0.6</td>
<td>+1</td>
<td>1/8 * 2.63</td>
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<td>0.48</td>
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<td>1/8 * 0.38</td>
<td>0.05</td>
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Multiply the correctly classified instances by 0.38
Multiply incorrectly classified instances by 2.63
Normalize to sum to 1.0
The Best Error

Multiply the correctly classified instances by 0.38
Multiply incorrectly classified instances by 2.63
Normalize to sum to 1.0

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<td>0.2</td>
<td>0.5</td>
<td>-1</td>
<td>0.074</td>
</tr>
</tbody>
</table>

\[ D' = \frac{D}{\text{sum}(D)} \]
The AdaBoost Algorithm

• Initialize $D_1(x_i) = 1/N$
• For $t = 1, ..., T$
  – Train a weak classifier $h_t$ using distribution $D_t$
  – Compute total error on training data
    • $\varepsilon_t = \text{Average} \{\frac{1}{2} (1 - y_i \cdot h_t(x_i))\}$
    – Set $\alpha_t = \frac{1}{2} \ln \left(\frac{\varepsilon_t}{1 - \varepsilon_t}\right)$
    – For $i = 1... N$
      • set $D_{t+1}(x_i) = D_t(x_i) \exp(-\alpha_t y_i h_t(x_i))$
    – Normalize $D_{t+1}$ to make it a distribution
• The final classifier is
  – $H(x) = \text{sign}\left(\sum_t \alpha_t h_t(x)\right)$
E1 classifier

Classifier based on E1:
if ( sign*wt(E1) > thresh) > 0)
face = true

sign = +1 or -1

<table>
<thead>
<tr>
<th>ID</th>
<th>E1</th>
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<tbody>
<tr>
<td>A</td>
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</tr>
<tr>
<td>D</td>
<td>0.6</td>
<td>-0.4</td>
<td>+1</td>
<td>0.074</td>
</tr>
<tr>
<td>E</td>
<td>0.2</td>
<td>0.4</td>
<td>-1</td>
<td>0.074</td>
</tr>
<tr>
<td>F</td>
<td>-0.8</td>
<td>0.1</td>
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</tr>
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<td>0.2</td>
<td>0.5</td>
<td>-1</td>
<td>0.074</td>
</tr>
</tbody>
</table>

Sign = +1, error = 0.222
Sign = -1, error = 0.778
E1 classifier

Classifier based on E1:
if (sign\*wt(E1) > thresh) > 0)
face = true

sign = +1 or -1

Sign = +1, error = 0.148
Sign = -1, error = 0.852

<table>
<thead>
<tr>
<th>ID</th>
<th>E1</th>
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<th>Class</th>
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<td>-1</td>
<td>0.074</td>
</tr>
</tbody>
</table>
The Best E1 classifier

Classifier based on E1:
\[ \text{if ( sign*wt(E1) > thresh) > 0) face = true} \]

\[ \text{sign = +1 or -1} \]

Sign = +1, error = 0.074

<table>
<thead>
<tr>
<th>ID</th>
<th>E1</th>
<th>E2</th>
<th>Class</th>
<th>Weight</th>
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<td>0.5</td>
<td>-1</td>
<td>0.074</td>
</tr>
</tbody>
</table>
The Best E2 classifier

Classifier based on E2:
if ( sign*wt(E2) > thresh) > 0)
face = true

sign = +1 or -1

Sign = -1, error = 0.148

<table>
<thead>
<tr>
<th>ID</th>
<th>E1</th>
<th>E2</th>
<th>Class</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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</tr>
</tbody>
</table>
The Best Classifier

Classifier based on E1: if (wt(E1) > 0.45) face = true

\[ \text{Sign} = +1, \text{ error} = 0.074\]

\[ \text{Alpha} = 0.5 \ln \left( \frac{1 - 0.074}{0.074} \right) = 1.26 \]

<table>
<thead>
<tr>
<th>ID</th>
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<th>E2</th>
<th>Class</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
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</tr>
</tbody>
</table>
The Boosted Classifier Thus Far

\[ h_1(X) = \text{wt}(E_1) > 0.45 ? +1 : -1 \]

\[ h_2(X) = \text{wt}(E_1) > 0.25 ? +1 : -1 \]

\[ H(X) = \text{sign}(0.97 \times h_1(X) + 1.26 \times h_2(X)) \]
Reweighting the Data

<table>
<thead>
<tr>
<th>ID</th>
<th>E1</th>
<th>E2.</th>
<th>Class</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.3</td>
<td>-0.6</td>
<td>+1</td>
<td>0.48*0.28</td>
</tr>
<tr>
<td>B</td>
<td>0.5</td>
<td>-0.5</td>
<td>+1</td>
<td>0.074*0.28</td>
</tr>
<tr>
<td>C</td>
<td>0.7</td>
<td>-0.1</td>
<td>+1</td>
<td>0.074*0.28</td>
</tr>
<tr>
<td>D</td>
<td>0.6</td>
<td>-0.4</td>
<td>+1</td>
<td>0.074*0.28</td>
</tr>
<tr>
<td>E</td>
<td>0.2</td>
<td>0.4</td>
<td>-1</td>
<td>0.074*0.28</td>
</tr>
<tr>
<td>F</td>
<td>-0.8</td>
<td>0.1</td>
<td>-1</td>
<td>0.074*0.28</td>
</tr>
<tr>
<td>G</td>
<td>0.4</td>
<td>-0.9</td>
<td>-1</td>
<td>0.074*3.5</td>
</tr>
<tr>
<td>H</td>
<td>0.2</td>
<td>0.5</td>
<td>-1</td>
<td>0.074*0.28</td>
</tr>
</tbody>
</table>

Sign = +1, error = 0.074

Exp(alpha) = \exp(1.26) = 3.5
Exp(-alpha) = \exp(-1.26) = 0.28

Renormalize
Reweighting the Data

NOTE: THE WEIGHT OF "G" WHICH WAS MISCLASSIFIED BY THE SECOND CLASSIFIER IS NOW SUDDENLY HIGH

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<td>0.6</td>
<td>-0.4</td>
<td>+1</td>
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<td>E</td>
<td>0.2</td>
<td>0.4</td>
<td>-1</td>
<td>0.074*0.28</td>
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<td>F</td>
<td>-0.8</td>
<td>0.1</td>
<td>-1</td>
<td>0.074*0.28</td>
</tr>
<tr>
<td>G</td>
<td>0.4</td>
<td>-0.9</td>
<td>-1</td>
<td>0.074*3.5</td>
</tr>
<tr>
<td>H</td>
<td>0.2</td>
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<td>-1</td>
<td>0.074*0.28</td>
</tr>
</tbody>
</table>

RENORMALIZE
AdaBoost

• In this example both of our first two classifiers were based on E1
  – Additional classifiers may switch to E2

• In general, the reweighting of the data will result in a different feature being picked for each classifier

• This also automatically gives us a feature selection strategy
  – In this data the wt(E1) is the most important feature
AdaBoost

• NOT required to go with the best classifier so far
• For instance, for our second classifier, we might use the best E2 classifier, even though its worse than the E1 classifier
  – So long as its right more than 50% of the time

• We can continue to add classifiers even after we get 100% classification of the training data
  – Because the weights of the data keep changing
  – Adding new classifiers beyond this point is often a good thing to do
The final classifier is

\[ H(x) = \text{sign} \left( \sum_t \alpha_t h_t(x) \right) \]

The output is 1 if the total weight of all weak learners that classify \( x \) as 1 is greater than the total weight of all weak learners that classify it as -1.
Boosting and Face Detection

• Boosting is the basis of one of the most popular methods for face detection: The Viola-Jones algorithm
  – Current methods use other classifiers like SVMs, but adaboost classifiers remain easy to implement and popular
  – OpenCV implements Viola Jones..
The problem of face detection

• 1. Defining Features
  – Should we be searching for noses, eyes, eyebrows etc.?
    • Nice, but expensive
  – Or something simpler

• 2. Selecting Features
  – Of all the possible features we can think of, which ones make sense

• 3. Classification: Combining evidence
  – How does one combine the evidence from the different features?
Features: The Viola Jones Method

- Integral Features!!
  - Like the Checkerboard
- The same principle as we used to decompose images in terms of checkerboards:
  - The image of any object has changes at various scales
  - These can be represented coarsely by a checkerboard pattern
- The checkerboard patterns must however now be localized
  - Stay within the region of the face

\[ \text{Image} \approx w_1 B_1 + w_2 B_2 + w_3 B_3 + \ldots \]
Features

• Checkerboard Patterns to represent facial features
  – The white areas are subtracted from the black ones.
  – Each checkerboard explains a *localized* portion of the image
• Four types of checkerboard patterns (only)
Explaining a portion of the face with a checker.

• How much is the difference in average intensity of the image in the black and white regions
  – Sum(pixel values in white region) – Sum(pixel values in black region)

• This is actually the dot product of the region of the face covered by the rectangle and the checkered pattern itself
  – White = 1, Black = -1
“Integral” features

- Each checkerboard has the following characteristics
  - Length
  - Width
  - Type
    - Specifies the number and arrangement of bands

- The four checkerboards above are the four used by Viola and Jones
Integral images

- Summed area tables

- For each pixel store the sum of ALL pixels to the left of and above it.
Fast Computation of Pixel Sums

To compute the sum of the pixels within “D”:
- \( \text{Pixelsum}(1) = \text{Area}(A) \)
- \( \text{Pixelsum}(2) = \text{Area}(A) + \text{Area}(B) \)
- \( \text{Pixelsum}(3) = \text{Area}(A) + \text{Area}(C) \)
- \( \text{Pixelsum}(4) = \text{Area}(A) + \text{Area}(B) + \text{Area}(C) + \text{Area}(D) \)

\( \text{Area}(D) = \text{Pixelsum}(4) - \text{Pixelsum}(2) - \text{Pixelsum}(3) + \text{Pixelsum}(1) \)
A Fast Way to Compute the Feature

• Store pixel table for every pixel in the image
  – The sum of all pixel values to the left of and above the pixel
• Let A, B, C, D, E, F be the pixel table values at the locations shown
  – Total pixel value of black area = D + A – B – C
  – Total pixel value of white area = F + C – D – E
  – Feature value = (F + C – D – E) – (D + A – B – C)
How many features?

- Each checker board of width $P$ and height $H$ can start at any of $(N-P)(M-H)$ pixels

- $(M-H)*(N-P)$ possible starting locations
  - Each is a unique checker feature
    - E.g. at one location it may measure the forehead, at another the chin
How many features

- Each feature can have many sizes
  - Width from (min) to (max) pixels
  - Height from (min ht) to (max ht) pixels
- At each size, there can be many starting locations
  - Total number of possible checkerboards of one type:
    No. of possible sizes \times No. of possible locations
- There are four types of checkerboards
  - Total no. of possible checkerboards: VERY VERY LARGE!
Learning: No. of features

• Analysis performed on images of 24x24 pixels only
  – Reduces the no. of possible features to about 180000

• Restrict checkerboard size
  – Minimum of 8 pixels wide
  – Minimum of 8 pixels high
    • Other limits, e.g. 4 pixels may be used too
  – Reduces no. of checkerboards to about 50000
No. of features

- Each possible checkerboard gives us one feature
- A total of up to 180000 features derived from a 24x24 image!
- Every 24x24 image is now represented by a set of 180000 numbers
  - This is the set of features we will use for classifying if it is a face or not!

<table>
<thead>
<tr>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
<th>.....</th>
<th>F180000</th>
</tr>
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<tbody>
<tr>
<td>7</td>
<td>9</td>
<td>2</td>
<td>-1</td>
<td>.....</td>
<td>12</td>
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<tr>
<td>-11</td>
<td>3</td>
<td>19</td>
<td>17</td>
<td>.....</td>
<td>2</td>
</tr>
</tbody>
</table>
The Classifier

• The Viola-Jones algorithm uses a simple Boosting based classifier

• Each “weak learner” is a simple threshold

• At each stage find the best feature to classify the data with
  – I.e the feature that gives us the best classification of all the training data
    • Training data includes many examples of faces and non-face images
  – The classification rule is of the kind
    • If feature > threshold, face (or if feature < threshold, face)
    • The optimal value of “threshold” must also be determined.
The Weak Learner

• Training (for each weak learner):
  – For each feature f (of all 180000 features)
    • Find a threshold \( \theta(f) \) and polarity \( p(f) \) (\( p(f) = -1 \) or \( p(f) = 1 \)) such that \( (f > p(f) \theta(f)) \) performs the best classification of faces
      – Lowest overall error in classifying all training data
        » Error counted over weighted samples
    • Let the optimal overall error for f be error(f)
  – Find the feature \( f' \) such that error(f') is lowest
  – The weak learner is the test \( (f' > p(f') \theta(f')) \Rightarrow \text{face} \)

• Note that the procedure for learning weak learners also identifies the most useful features for face recognition
The Viola Jones Classifier

• A boosted threshold-based classifier
• First weak learner: Find the best feature, and its optimal threshold
  – Second weak learner: Find the best feature, for the weighted training data, and its threshold (weighting from one weak learner)
  • Third weak learner: Find the best feature for the weighted data and its optimal threshold (weighting from two weak learners)
    – Fourth weak learner: Find the best feature for the weighted data and its optimal threshold (weighting from three weak learners)
  » ..
To Train

• Collect a large number of histogram equalized facial images
  – Resize all of them to 24x24
  – These are our “face” training set

• Collect a much much much much larger set of 24x24 non-face images of all kinds
  – Each of them is histogram equalized
  – These are our “non-face” training set

• Train a boosted classifier
The Viola Jones Classifier

• During tests:
  – Given any new 24x24 image
    • \( R = \sum_{f} \alpha_f \cdot (f > p \cdot \theta(f)) \)
    • Only a small number of features (\( f < 100 \)) typically used

• Problems:
  – Only classifies 24 x 24 images entirely as faces or non-faces
    • Pictures are typically much larger
    • They may contain many faces
    • Faces in pictures can be much larger or smaller
  – Not accurate enough
Multiple faces in the picture

• Scan the image
  – Classify each 24x24 rectangle from the photo
  – All rectangles that get classified as having a face indicate the location of a face
• For an NxM picture, we will perform (N-24)*(M-24) classifications
• If overlapping 24x24 rectangles are found to have faces, merge them
Multiple faces in the picture

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  - Classify each 24x24 rectangle from the photo
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Multiple faces in the picture

• Scan the image
  – Classify each 24x24 rectangle from the photo
  – All rectangles that get classified as having a face indicate the location of a face
• For an NxM picture, we will perform \((N-24)*(M-24)\) classifications
• If overlapping 24x24 rectangles are found to have faces, merge them
We already have a classifier
- That uses weak learners

*Scale each classifier*
- Every weak learner
- Scale its size up by factor $\alpha$. Scale the threshold up to $\alpha \theta$.
- Do this for many scaling factors
Overall solution

• Scan the picture with classifiers of size 24x24
• Scale the classifier to 26x26 and scan
• Scale to 28x28 and scan etc.

• Faces of different sizes will be found at different scales
False Rejection vs. False detection

- False Rejection: There’s a face in the image, but the classifier misses it
  - Rejects the hypothesis that there’s a face
- False detection: Recognizes a face when there is none.

- Classifier:
  - Standard boosted classifier: \( H(x) = \text{sign}(\sum_t \alpha_t h_t(x)) \)
  - Modified classifier \( H(x) = \text{sign}(\sum_t \alpha_t h_t(x) + Y) \)
    - \( \sum_t \alpha_t h_t(x) \) is a measure of certainty
      - The higher it is, the more certain we are that we found a face
    - If \( Y \) is large, then we assume the presence of a face even when we are not sure
      - By increasing \( Y \), we can reduce false rejection, while increasing false detection
• Ideally false rejection will be 0%, false detection will also be 0%

• As Y increases, we reject faces less and less
  – But accept increasing amounts of garbage as faces

• Can set Y so that we rarely miss a face
Problem: Not accurate enough, too slow

- If we set Y high enough, we will never miss a face
  - But will classify a lot of junk as faces
- Solution: Classify the output of the first classifier with a second classifier
  - And so on.
Problem: Not accurate enough, too slow

- If we set Y high enough, we will never miss a face
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Useful Features Learned by Boosting
A Cascade of Classifiers

All Sub-windows

1 2 3

T T T

Further Processing

Reject Sub-window
Detection in Real Images

• Basic classifier operates on 24 x 24 subwindows

• Scaling:
  – Scale the detector (rather than the images)
  – Features can easily be evaluated at any scale
  – Scale by factors of 1.25

• Location:
  – Move detector around the image (e.g., 1 pixel increments)

• Final Detections
  – A real face may result in multiple nearby detections
  – Postprocess detected subwindows to combine overlapping detections into a single detection
Training

• In paper, 24x24 images of faces and non faces (positive and negative examples).
Sample results using the Viola-Jones Detector

- Notice detection at multiple scales
More Detection Examples
Practical implementation

• Details discussed in Viola-Jones paper

• Training time = weeks (with 5k faces and 9.5k non-faces)

• Final detector has 38 layers in the cascade, 6060 features

• 700 Mhz processor:
  – Can process a 384 x 288 image in 0.067 seconds (in 2003 when paper was written)