

Lecture: Visual Bag of Words

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What we will learn today

- Visual bag of words (BoW)
- Spatial Pyramid Matching
- Naive Bayes

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Bag of Words Models

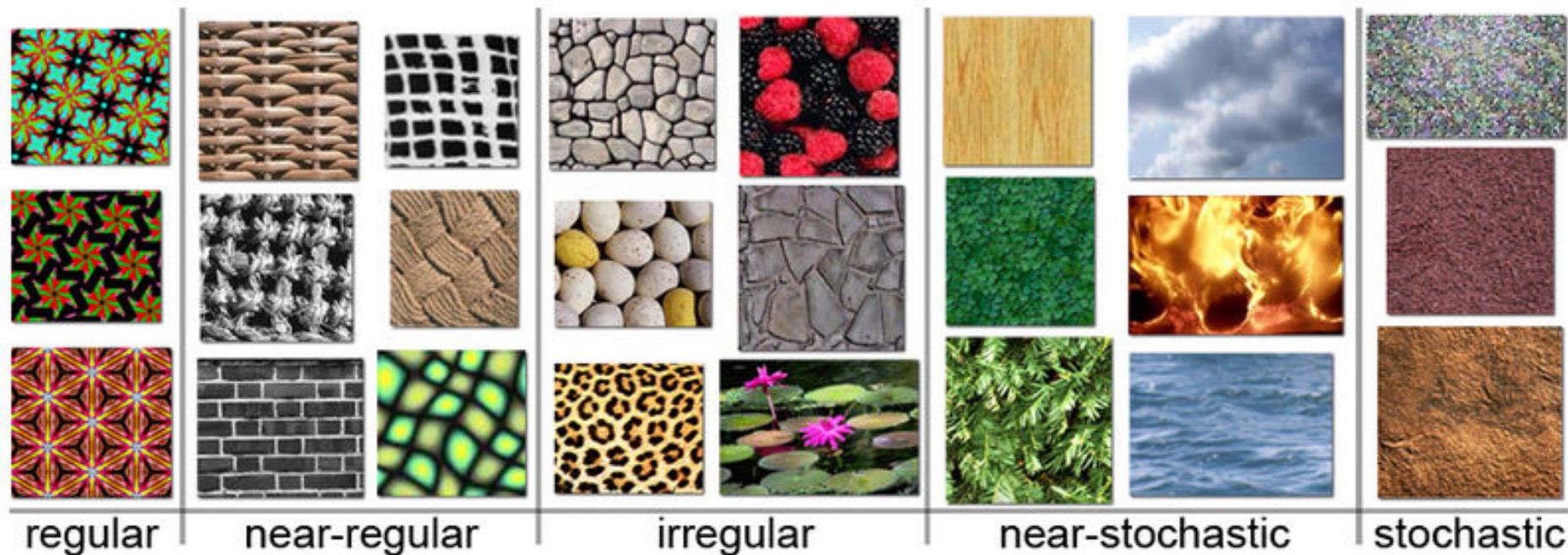
Adapted from slides by Rob Fergus
and Svetlana Lazebnik

Object

Bag of 'words'



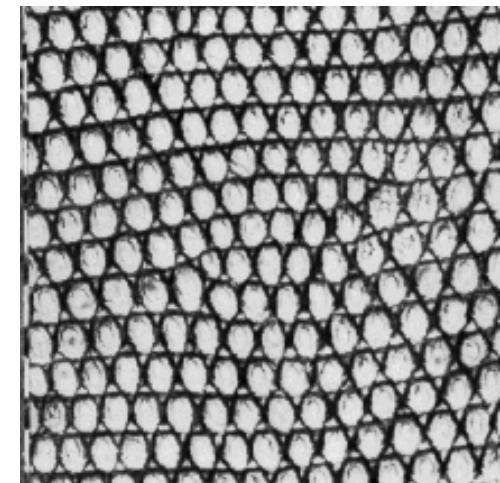
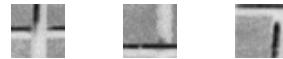
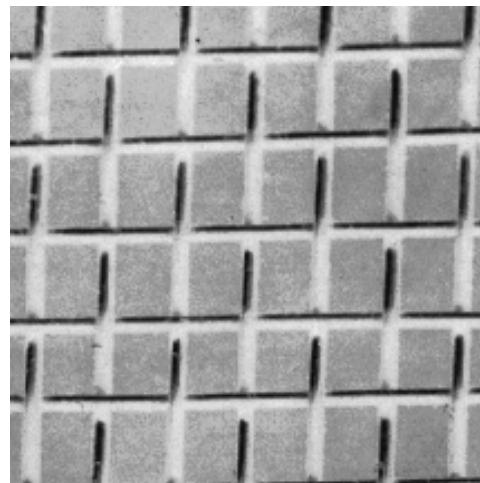
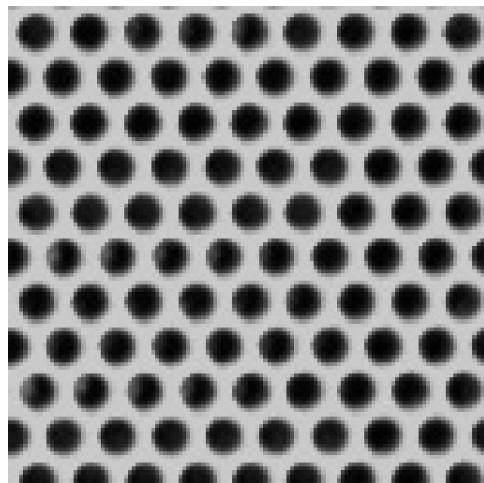
Origin 1: Texture Recognition



Example textures (from Wikipedia)

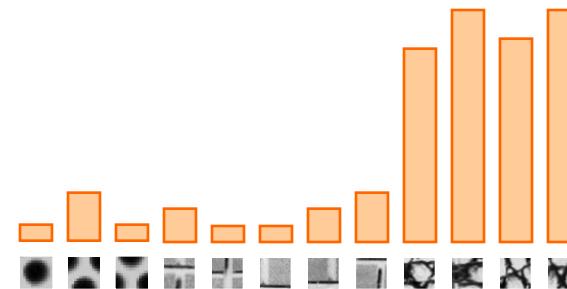
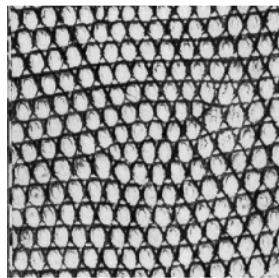
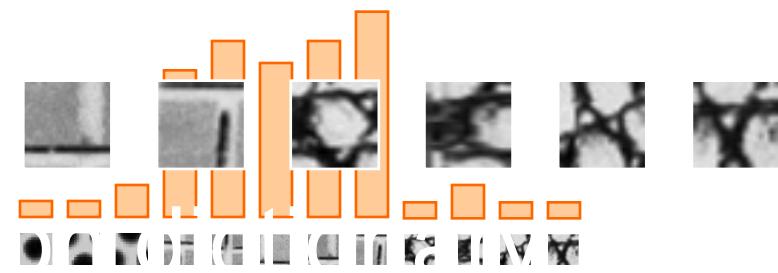
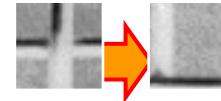
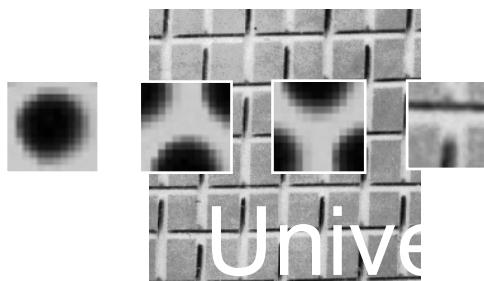
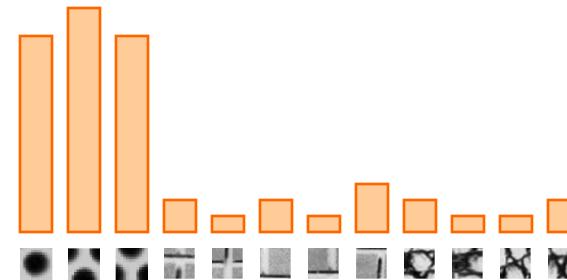
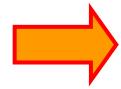
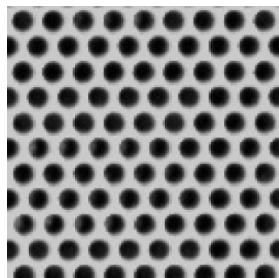
Origin 1: Texture recognition

- Texture is characterized by the repetition of basic elements or ***textons***



Julesz, 1981; Cula & Dana, 2001; Leung & Malik 2001; Mori, Belongie & Malik, 2001; Schmid 2001; Varma & Zisserman, 2002, 2003; Lazebnik, Schmid & Ponce, 2003

Origin 1: Texture recognition



Origin 2: Bag-of-words models

- Orderless document representation: frequencies of words from a dictionary Salton & McGill (1983)

Origin 2: Bag-of-words models

- Orderless document representation: frequencies of words from a dictionary Salton & McGill (1983)

2007-01-23: State of the Union Address

George W. Bush (2001-)

abandon accountable affordable afghanistan africa aided ally anbar armed army **baghdad** bless challenges chamber chaos choices civilians coalition commanders **commitment** confident confront congressman constitution corps debates deduction deficit deliver **democratic** deploy diplomacy disruptions earmarks **economy** einstein **elections** eliminates expand **extremists** failing faithful families **freedom** fuel **funding** god haven ideology immigration impose insurgents iran **iraq** islam julie lebanon love madam marine math medicare moderation neighborhoods nuclear offensive palestinian payroll province pursuing **qaeda** radical **regimes** resolve retreat rieman sacrifices science sectarian senate september **shia** stays strength students succeed sunni **tax** territories **terrorists** threats uphold victory violence violent **war** washington weapons wesley

US Presidential Speeches Tag Cloud

<http://chir.ag/phernalia/preztags/>

Origin 2: Bag-of-words models

- Orderless document representation: frequencies of words from a dictionary

Salton & McGill (1983)



US Presidential Speeches Tag Cloud
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2007-01-23: State of the Union Address

George W. Bush (2001-)

1962-10-22: Soviet Missiles in Cuba

John F. Kennedy (1961-63)

1941-12-08: Request for a Declaration of War

Franklin D. Roosevelt (1933-45)

abandon
choices c
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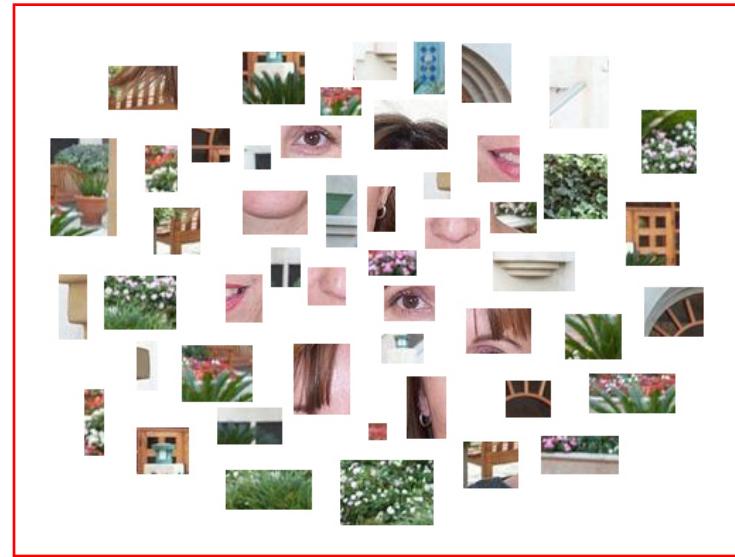
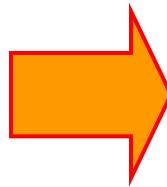
abandoning acknowledge aggression aggressors airplanes armaments **armed army** assault assembly authorizations bombing britain british cheerfully claiming constitution curtail december defeats defending delays **democratic dictators** disclose economic empire endanger **facts** false forgotten fortunes france **freedom** fulfilled fullness fundamental gangsters german **germany** god guam harbor hawaii **hemisphere** hint hitler hostilities immune improving indies innumerable

invasion islands isolate **japanese** labor metals midst midway **navy** nazis obligation offensive officially **pacific** partisanship patriotism pearl peril perpetrated perpetual philippine preservation privilege reject repaired resisting retain revealing rumors seas soldiers **speaks** speedy stamina **strength** sunday sunk supremacy tanks taxes

treachery true tyranny undertaken victory war wartime washington

US Presidential Speeches Tag Cloud
<http://chir.ag/phernalia/preztags/>

Bags of features for object recognition



face, flowers, building

- Works pretty well for image-level classification and for recognizing object *instances*

Bags of features for object recognition



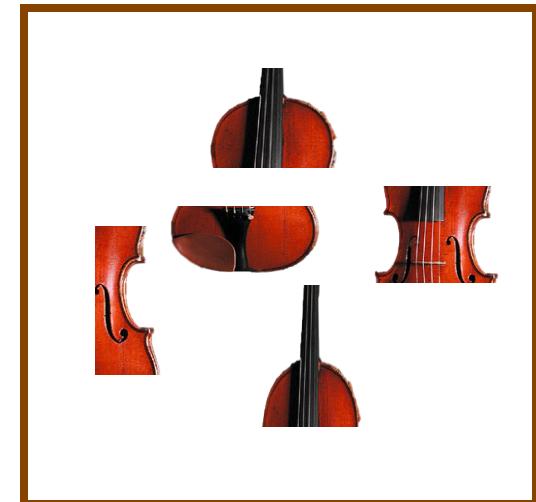
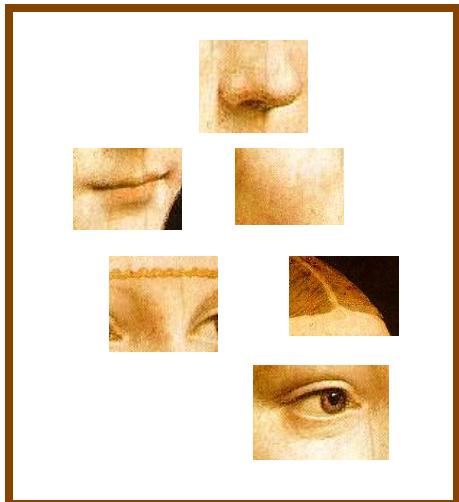
class	bag of features	bag of features	Parts-and-shape model
	Zhang et al. (2005)	Willamowski et al. (2004)	Fergus et al. (2003)
airplanes	98.8	97.1	90.2
cars (rear)	98.3	98.6	90.3
cars (side)	95.0	87.3	88.5
faces	100	99.3	96.4
motorbikes	98.5	98.0	92.5
spotted cats	97.0	—	90.0

Bag of features

- First, take a bunch of images, extract features, and build up a “dictionary” or “visual vocabulary” – a list of common features
- Given a new image, extract features and build a histogram – for each feature, find the closest visual word in the dictionary

Bag of features: outline

1. Extract features



Bag of features: outline

1. Extract features
2. Learn “visual vocabulary”

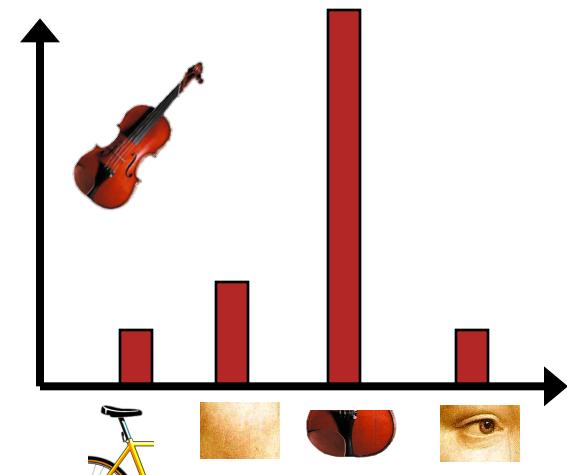
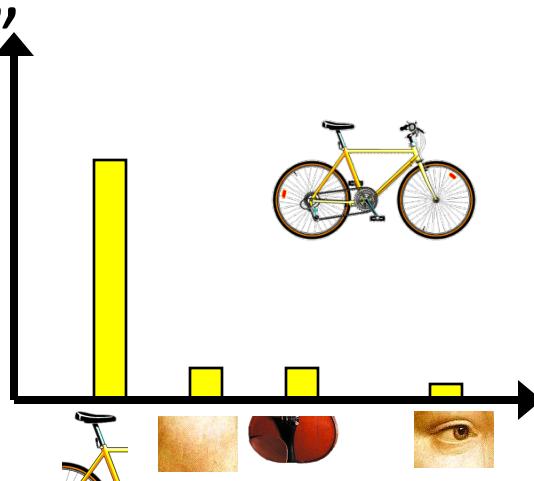
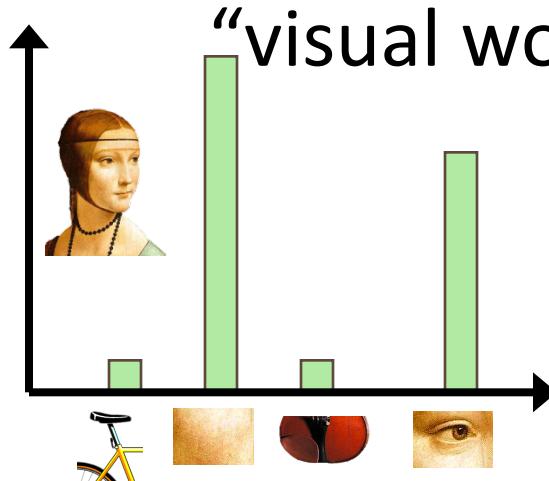


Bag of features: outline

1. Extract features
2. Learn “visual vocabulary”
3. Quantize features using visual vocabulary

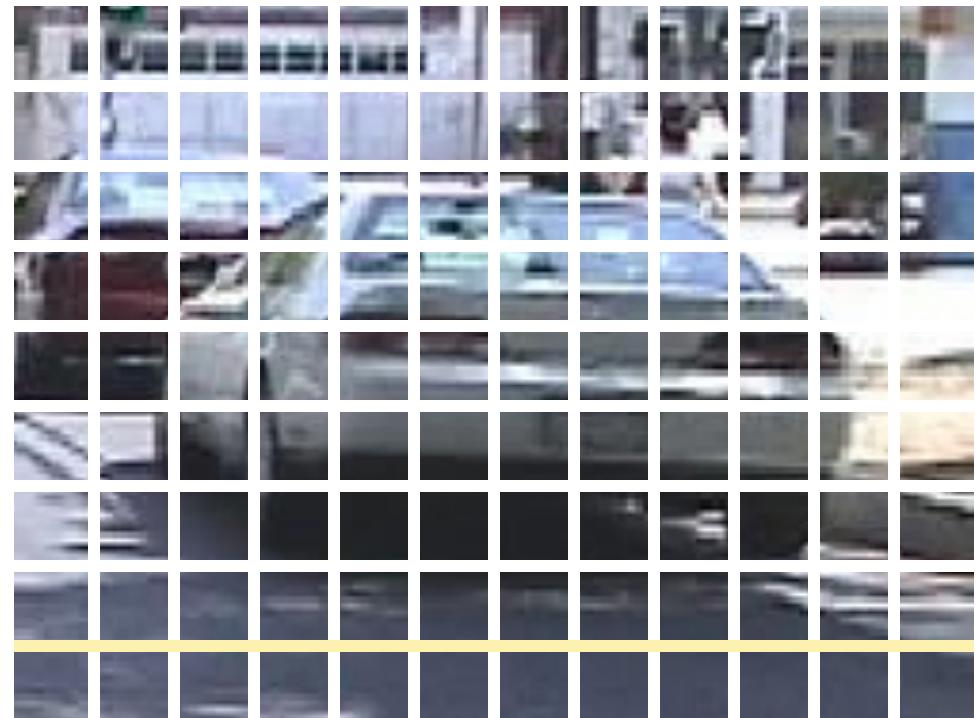
Bag of features: outline

1. Extract features
2. Learn “visual vocabulary”
3. Quantize features using visual vocabulary
4. Represent images by frequencies of “visual words”



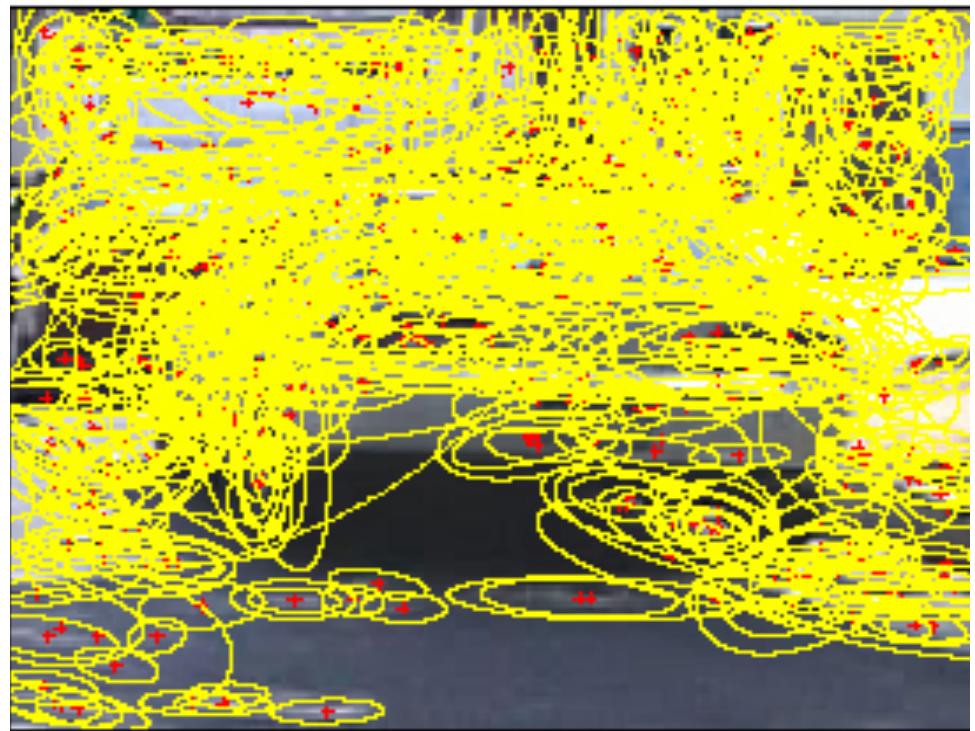
1. Feature extraction

- Regular grid
 - Vogel & Schiele, 2003
 - Fei-Fei & Perona, 2005



1. Feature extraction

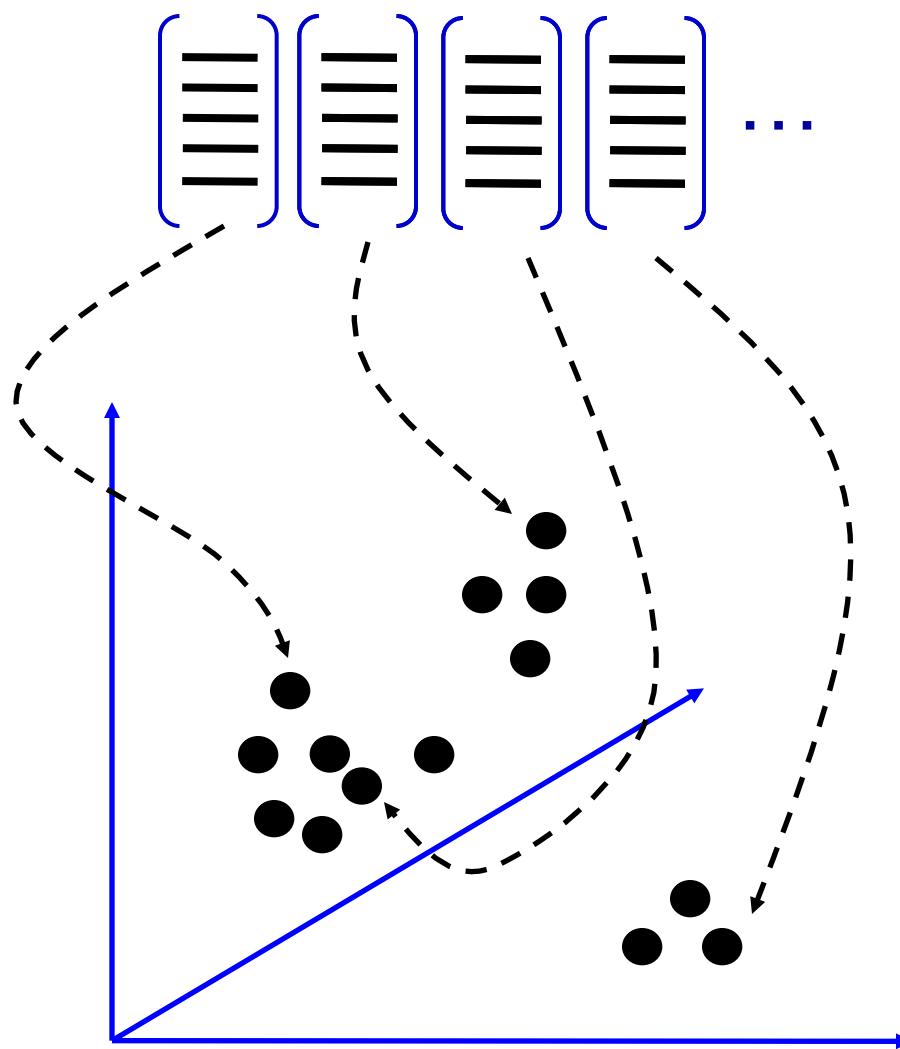
- Regular grid
 - Vogel & Schiele, 2003
 - Fei-Fei & Perona, 2005
- Interest point detector
 - Csurka et al. 2004
 - Fei-Fei & Perona, 2005
 - Sivic et al. 2005



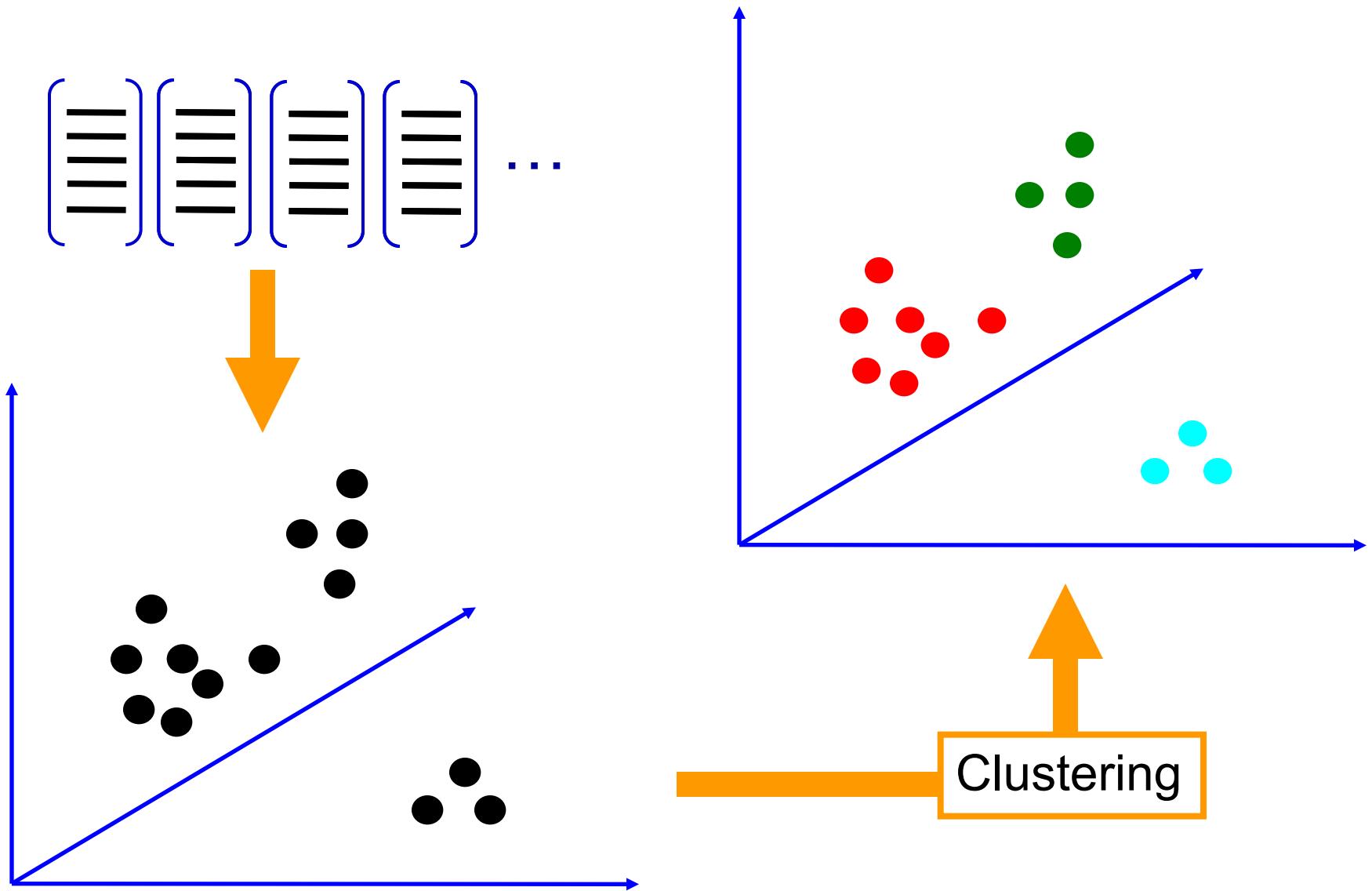
1. Feature extraction

- Regular grid
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 - Fei-Fei & Perona, 2005
- Interest point detector
 - Csurka et al. 2004
 - Fei-Fei & Perona, 2005
 - Sivic et al. 2005
- Other methods
 - Random sampling (Vidal-Naquet & Ullman, 2002)
 - Segmentation-based patches (Barnard et al. 2003)

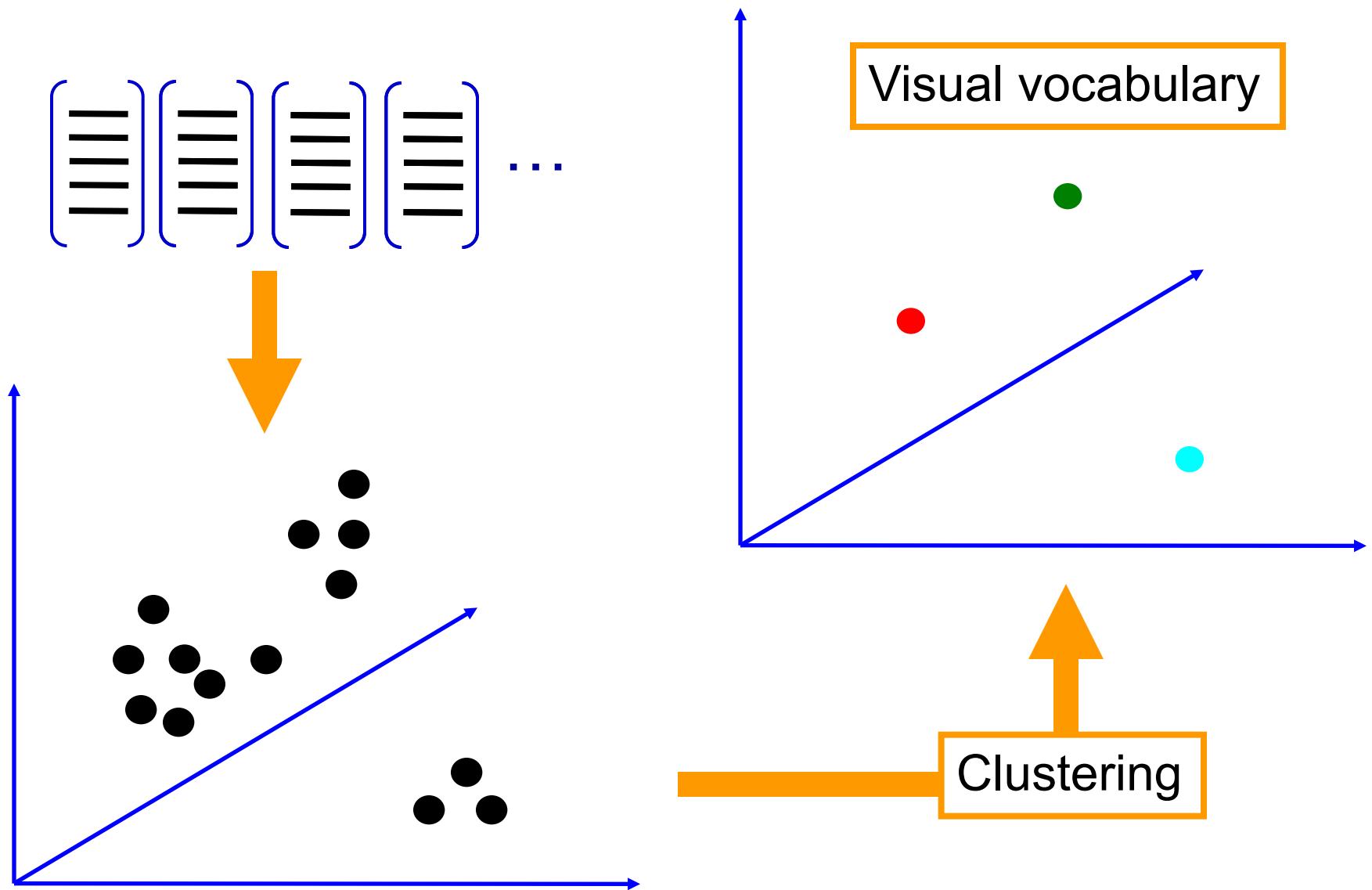
2. Learning the visual vocabulary



2. Learning the visual vocabulary



2. Learning the visual vocabulary



K-means clustering recap

- Want to minimize sum of squared Euclidean distances between points x_i and their nearest cluster centers m_k

$$D(X, M) = \sum_{\text{cluster } k} \sum_{\substack{\text{point } i \text{ in} \\ \text{cluster } k}} (x_i - m_k)^2$$

- Algorithm:
 - Randomly initialize K cluster centers
 - Iterate until convergence:
 - Assign each data point to the nearest center
 - Recompute each cluster center as the mean of all points assigned to it

From clustering to vector quantization

- Clustering is a common method for learning a visual vocabulary or codebook
 - Unsupervised learning process
 - Each cluster center produced by k-means becomes a codevector
 - Codebook can be learned on separate training set
 - Provided the training set is sufficiently representative, the codebook will be “universal”
- The codebook is used for quantizing features
 - A *vector quantizer* takes a feature vector and maps it to the index of the nearest codevector in a codebook
 - Codebook = visual vocabulary
 - Codevector = visual word

Example visual vocabulary

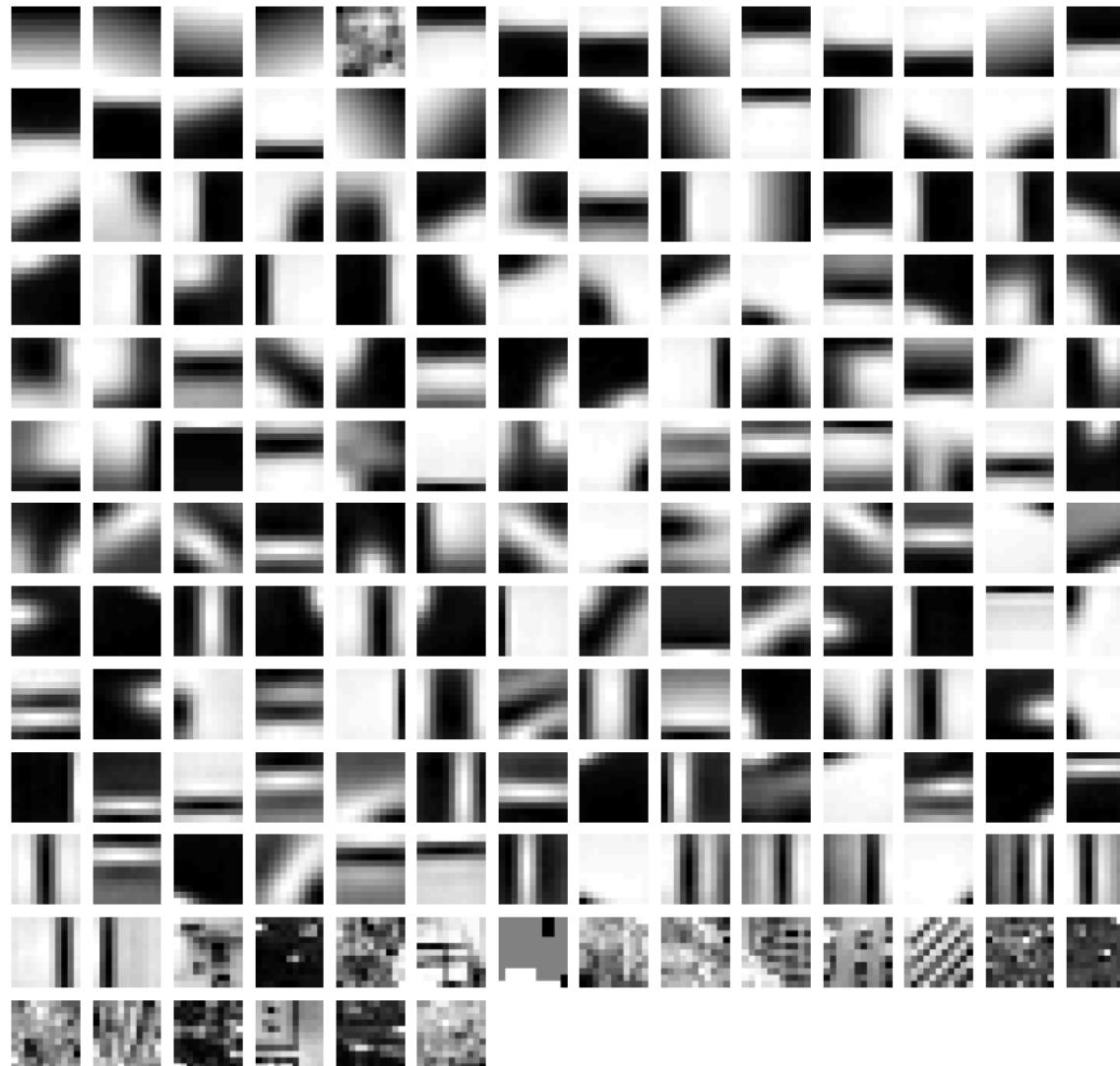
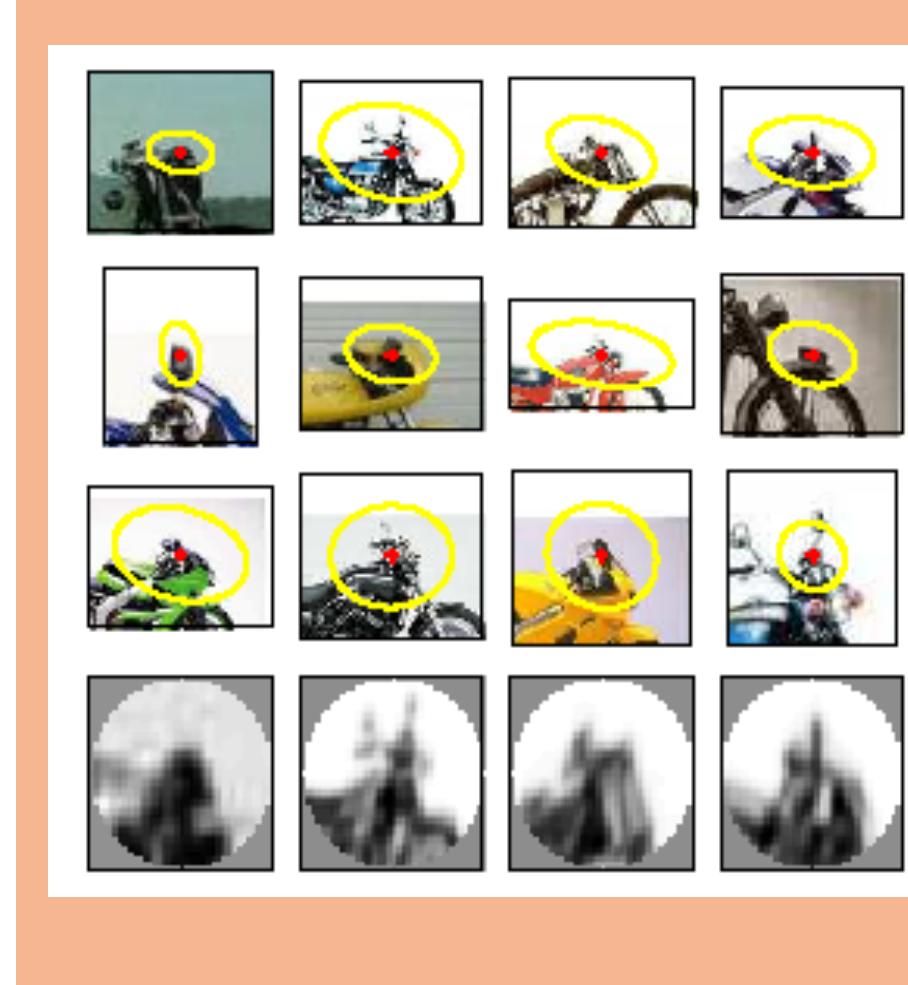
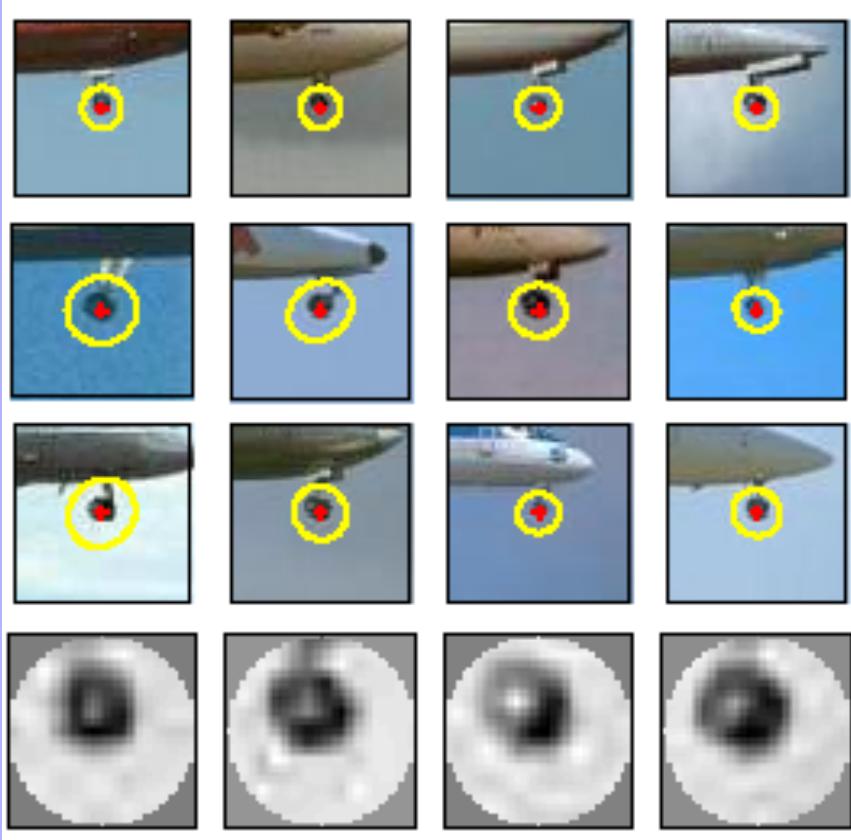
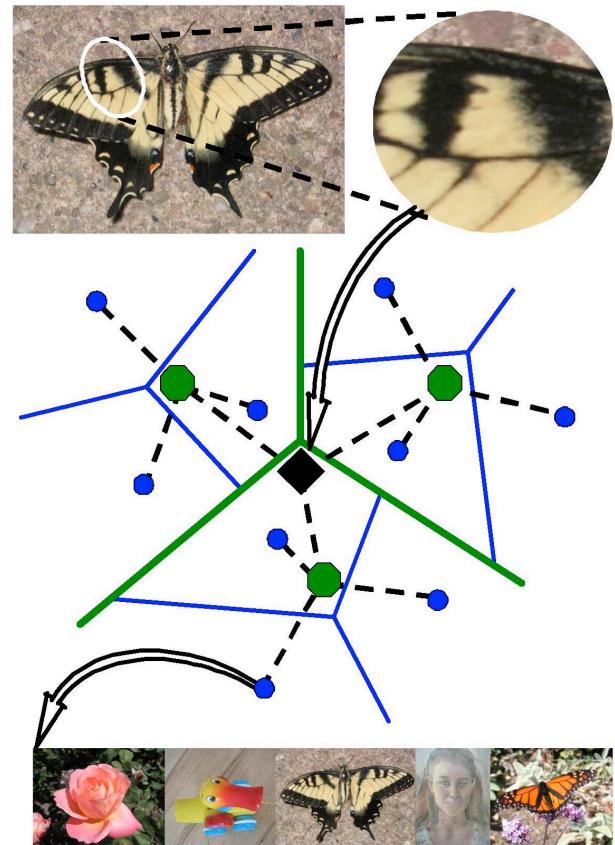


Image patch examples of visual words



Visual vocabularies: Issues

- How to choose vocabulary size?
 - Too small: visual words not representative of all patches
 - Too large: quantization artifacts, overfitting
- Computational efficiency
 - Vocabulary trees
(Nister & Stewenius, 2006)



3. Image representation

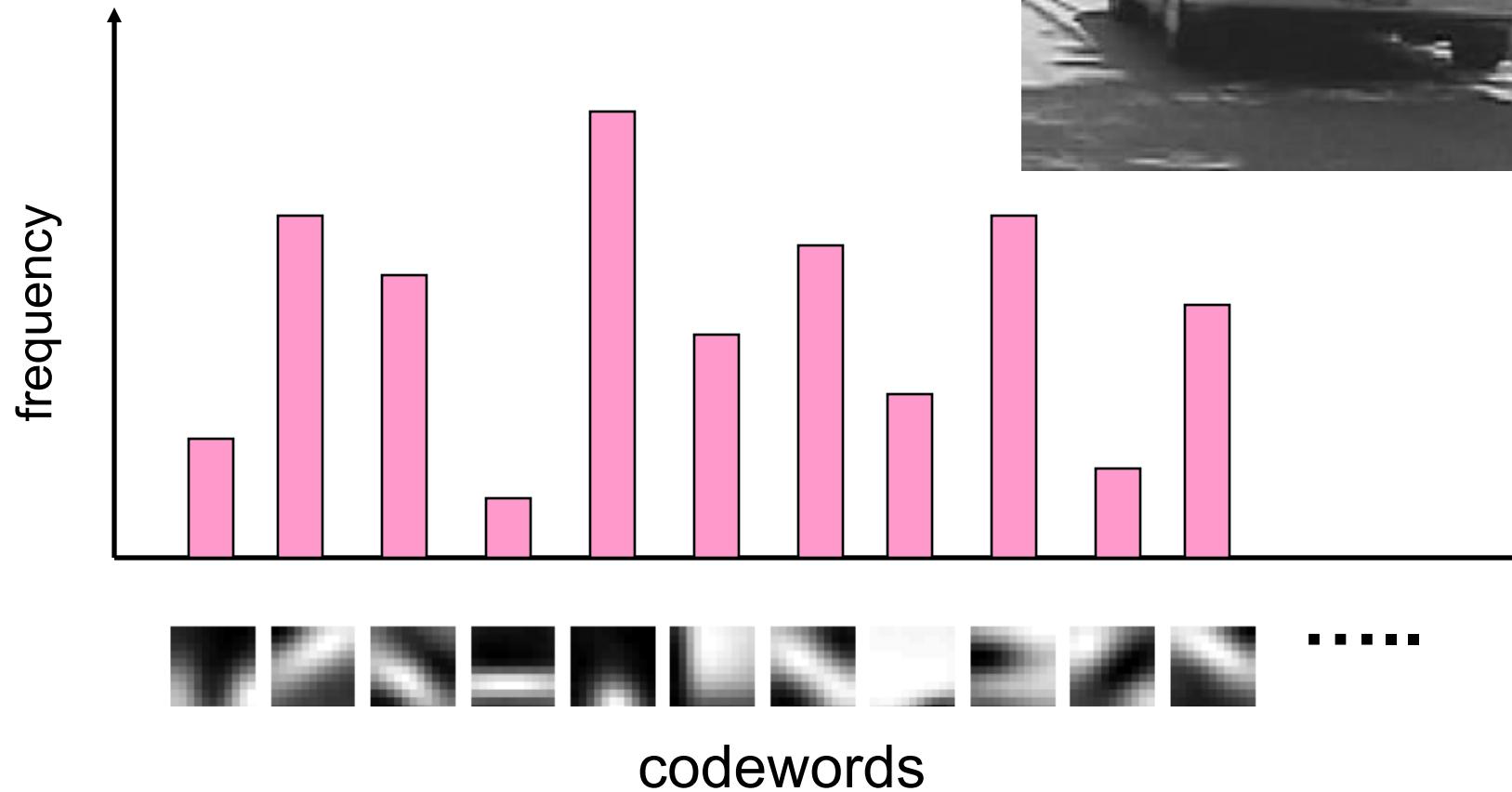
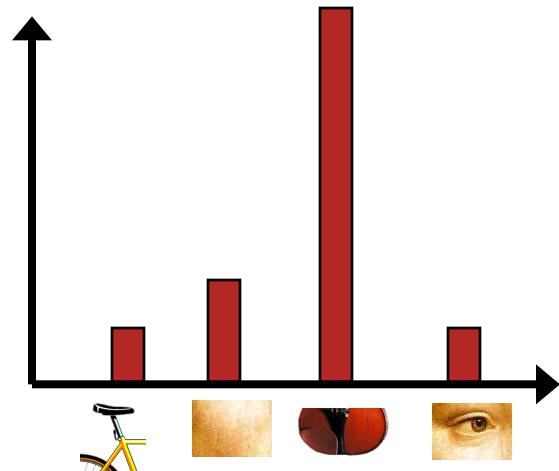
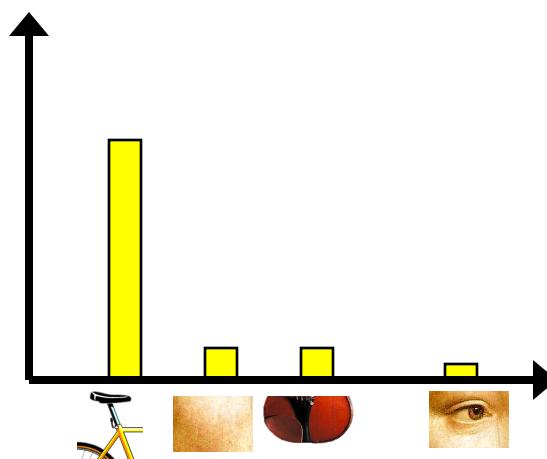
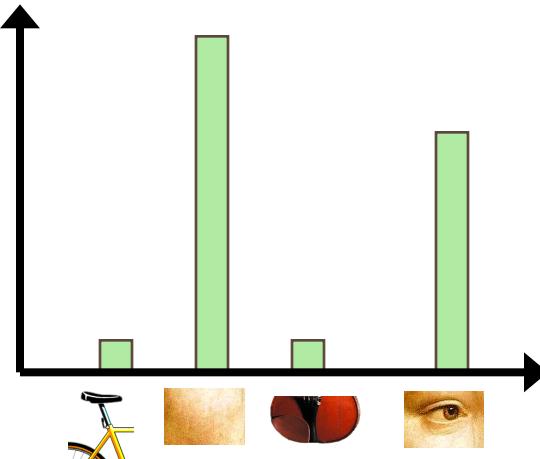


Image classification

- Given the bag-of-features representations of images from different classes, how do we learn a model for distinguishing them?



Uses of BoW representation

- Treat as feature vector for standard classifier
 - e.g k-nearest neighbors, support vector machine
- Cluster BoW vectors over image collection
 - Discover visual themes

Large-scale image matching



11,400 images of game covers
(Caltech games dataset)



- Bag-of-words models have been useful in matching an image to a large database of object *instances*



how do I find this image in the database?

Large-scale image search



Build the database:

- Extract features from the database images
- Learn a vocabulary using k-means (typical k: 100,000)
- Compute *weights* for each word
- Create an inverted file mapping words → images

Weighting the words

- Just as with text, some visual words are more discriminative than others

the, and, or vs. *cow, AT&T, Cher*

- the bigger fraction of the documents a word appears in, the less useful it is for matching
 - e.g., a word that appears in *all* documents is not helping us

TF-IDF weighting

- Instead of computing a regular histogram distance, we'll weight each word by its *inverse document frequency*
- inverse document frequency (IDF) of word j =

$$\log \frac{\text{number of documents}}{\text{number of documents in which } j \text{ appears}}$$

TF-IDF weighting

- To compute the value of bin j in image I :

term frequency of j in I \times inverse document frequency of j

Inverted file

- Each image has ~1,000 features
- We have ~100,000 visual words
 - each histogram is extremely sparse (mostly zeros)
- Inverted file
 - mapping from words to documents

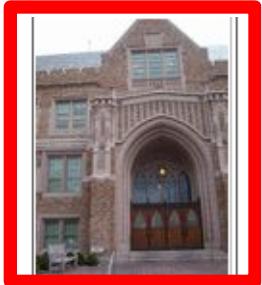
```
"a":      {2}
"banana": {2}
"is":     {0, 1, 2}
"it":     {0, 1, 2}
"what":   {0, 1}
```

Inverted file

- Can quickly use the inverted file to compute similarity between a new image and all the images in the database
 - Only consider database images whose bins overlap the query image

Large-scale image search

query image



top 6 results



- Cons:
 - performance degrades as the database grows

Large-scale image search

- Pros:
 - Works well for CD covers, movie posters
 - Real-time performance possible



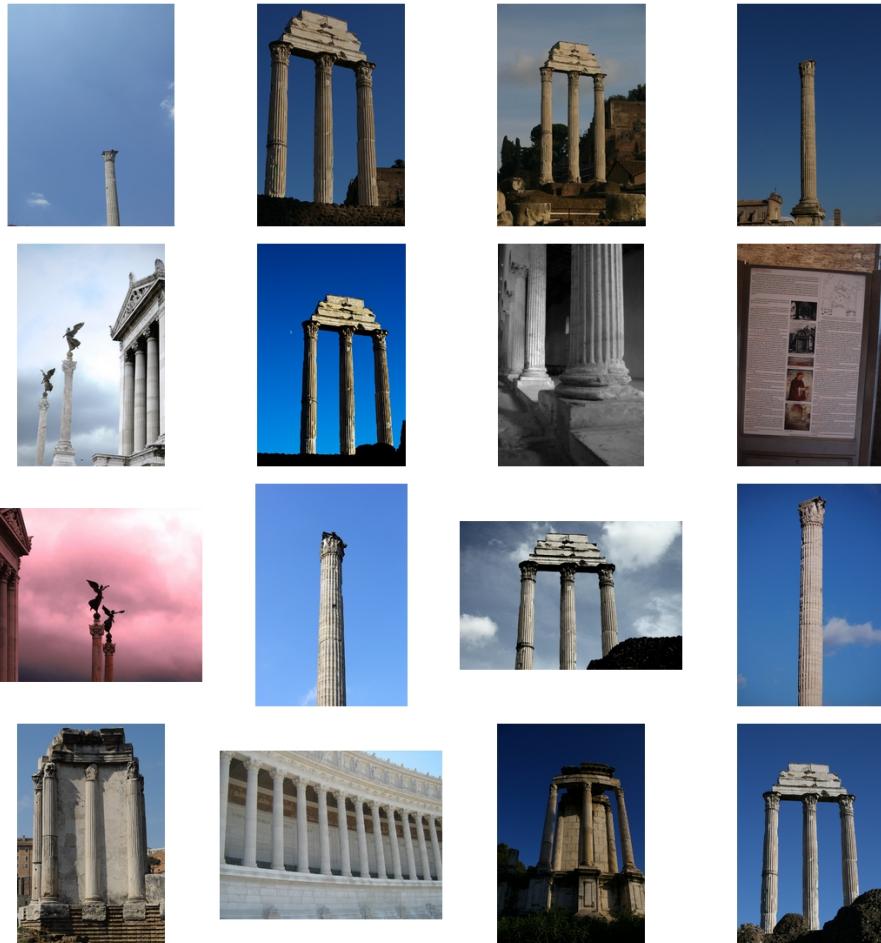
real-time retrieval from a database of 40,000 CD covers

Nister & Stewenius, **Scalable Recognition with a Vocabulary Tree**

Example bag-of-words matches



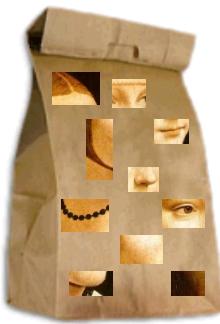
Example bag-of-words matches



Matching Statistics

Dataset	Size	Matches possible	Matches Tried	Matches Found	Time
Dubrovnik	58K	1.6 Billion	2.6M	0.5M	5 hrs
Rome	150K	11.2 Billion	8.8M	2.7M	13 hrs
Venice	250K	31.2 Billion	35.5M	6.2M	27 hrs

What about spatial info?



What we will learn today

- Visual bag of words (BoW)
- Spatial Pyramid Matching
- Naïve Bayes

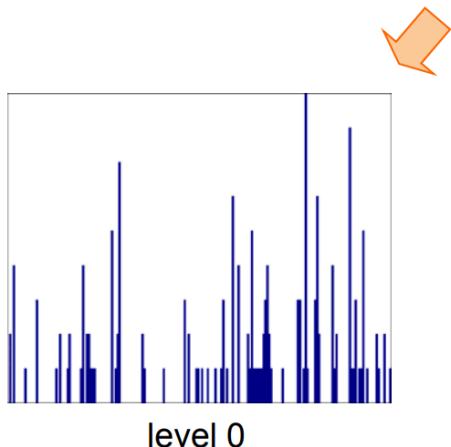
Pyramids

- Very useful for representing images.
- Pyramid is built by using multiple copies of image.
- Each level in the pyramid is $1/4$ of the size of previous level.
- The lowest level is of the highest resolution.
- The highest level is of the lowest resolution.

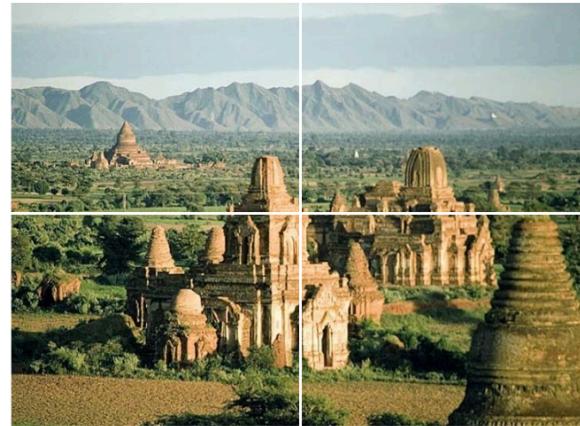
Bag of words + pyramids



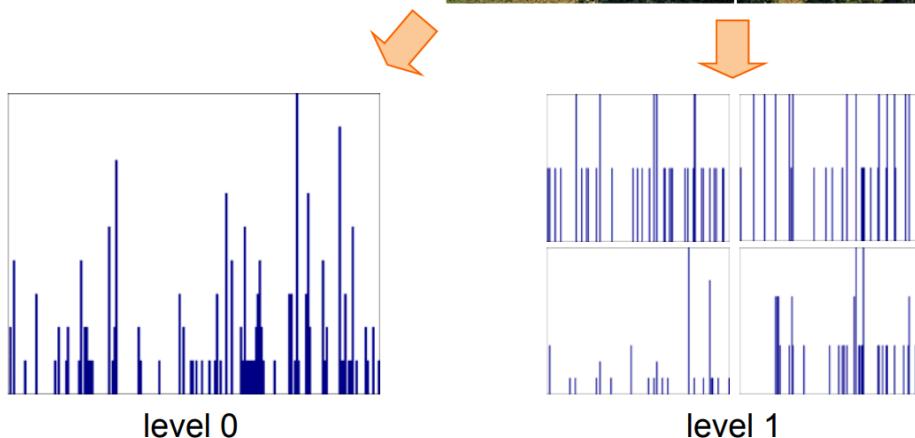
Locally orderless representation at several levels of spatial resolution



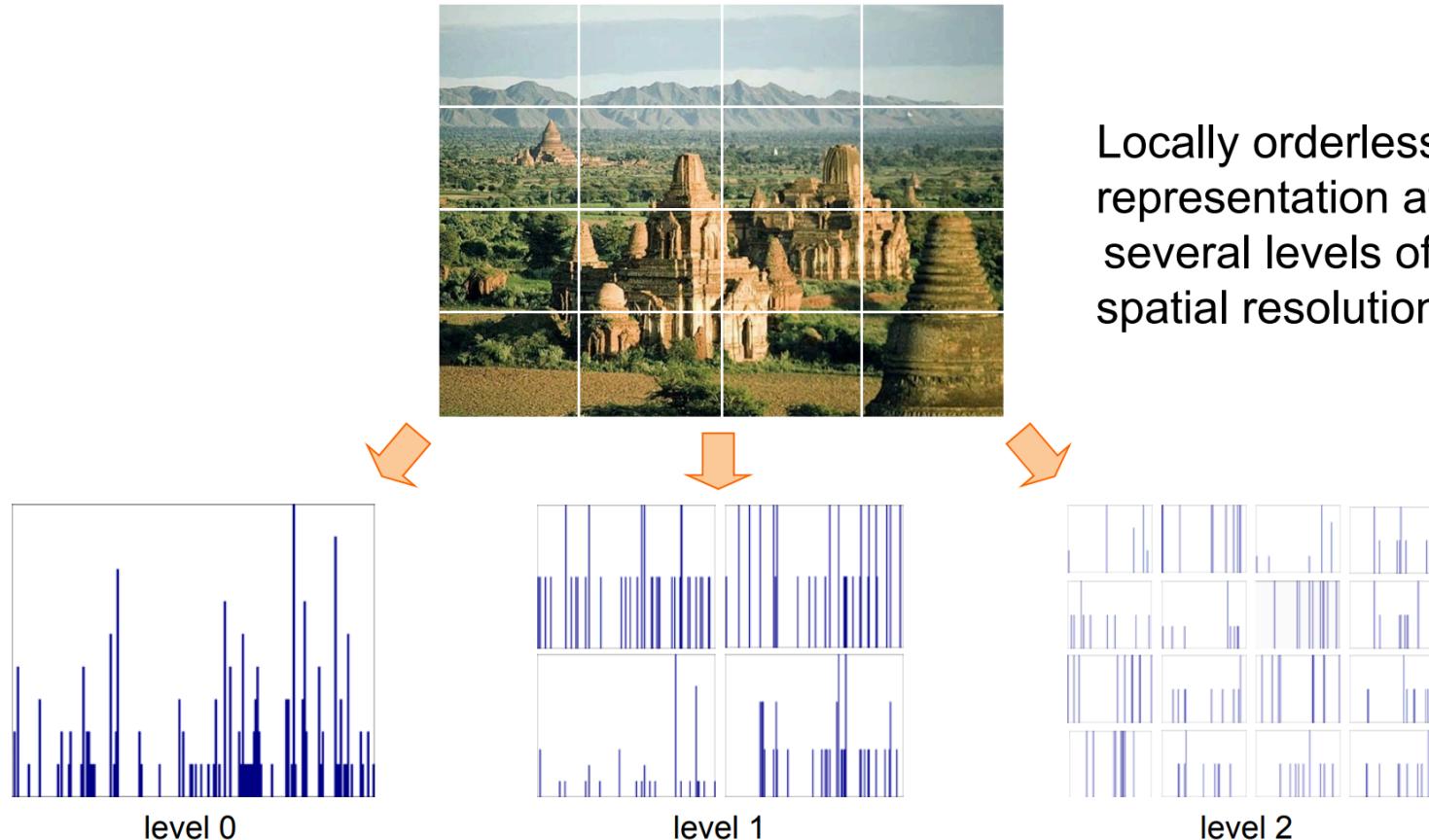
Bag of words + pyramids



Locally orderless representation at several levels of spatial resolution



Bag of words + pyramids



What we will learn today

- Visual bag of words (BoW)
- Spatial Pyramid Matching
- Naïve Bayes

Naïve Bayes

- Classify image using histograms of occurrences on visual words:



- if only present/absence of a word is taken into account: $x_i \in \{0, 1\}$
- Naïve Bayes classifier assumes that visual words are conditionally independent given object class

Csurka Bray, Dance & Fan, 2004

Naïve Bayes - prior

- Model for each object class:

$$P(x | c) = \prod_{i=1}^m P(x_i | c)$$

- Class priors $P(c)$ encode how likely we are to see one class versus others.
- Note that:

$$\prod_{i=1}^m P(c) = 1$$

Csurka Bray, Dance & Fan, 2004

Naïve Bayes - posterior

- With the equations from the previous slides, we can now calculate the probability that an image represented by x belongs to class category c .

$$P(c | x) = \frac{P(c) P(x | c)}{\sum_{c'} P(c') P(x | c')}$$

Bayes Theorem

Naïve Bayes – posterior

- With the equations from the previous slides, we can now calculate the probability that an image represented by x belongs to class category c .

$$P(c | x) = \frac{P(c) P(x | c)}{\sum_{c'} P(c') P(x | c')}$$
$$P(c | x) = \frac{P(c) \prod_{i=1}^m P(x_i | c)}{\sum_{c'} P(c') \prod_{i=1}^m P(x_i | c')}$$

Naïve Bayes - classification

- We can now classify that the image represented by x belongs class that has the highest probability:

$$c^* = \arg \max_c P(c | x)$$

$$c^* = \arg \max_c \log P(c | x)$$

Let's break down the posterior

The probability that x belongs to class c_1 :

$$P(c_1 | x) = \frac{P(c_1) \prod_{i=1}^m P(x_i | c_1)}{\sum_{c'} P(c') \prod_{i=1}^m P(x_i | c')}$$

And the probability that x belongs to class c_2 :

$$P(c_2 | x) = \frac{P(c_2) \prod_{i=1}^m P(x_i | c_2)}{\sum_{c'} P(c') \prod_{i=1}^m P(x_i | c')}$$

Both their denominators are the same

The probability that x belongs to class c_1 :

$$P(c_1 | x) = \frac{P(c_1) \prod_{i=1}^m P(x_i | c_1)}{\sum_{c'} P(c') \prod_{i=1}^m P(x_i | c')}$$

And the probability that x belongs to class c_2 :

$$P(c_2 | x) = \frac{P(c_2) \prod_{i=1}^m P(x_i | c_2)}{\sum_{c'} P(c') \prod_{i=1}^m P(x_i | c')}$$

Both their denominators are the same

- Since we only want the max, we can ignore the denominator:

$$P(c_1 | \mathbf{x}) \propto P(c_1) \prod_{i=1}^m P(x_i | c_1)$$

$$P(c_2 | \mathbf{x}) \propto P(c_2) \prod_{i=1}^m P(x_i | c_2)$$

For the general class c ,

$$P(c \mid \mathbf{x}) \propto P(c) \prod_{i=1}^m P(x_i \mid c)$$

For the general class c ,

$$P(c \mid \mathbf{x}) \propto P(c) \prod_{i=1}^m P(x_i \mid c)$$

We can take the log:

$$\log P(c \mid \mathbf{x}) \propto \log P(c) + \sum_{i=1}^m \log P(x_i \mid c)$$

Naïve Bayes - classification

- So, the following classification becomes:

$$c^* = \arg \max_c P(c | x)$$

$$c^* = \arg \max_c \log P(c | x)$$

$$c^* = \arg \max_c \log P(c) + \sum_{i=1}^m \log P(x_i | c)$$

Scene category dataset

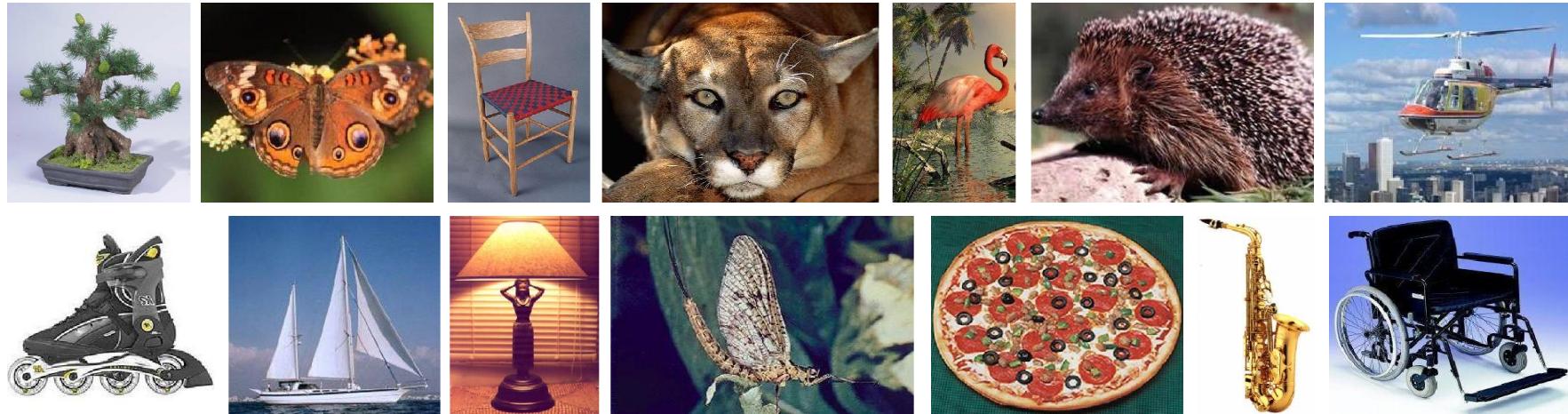


Multi-class classification results
(100 training images per class)

Level	Weak features (vocabulary size: 16)		Strong features (vocabulary size: 200)	
	Single-level	Pyramid	Single-level	Pyramid
0 (1×1)	45.3 ± 0.5		72.2 ± 0.6	
1 (2×2)	53.6 ± 0.3	56.2 ± 0.6	77.9 ± 0.6	79.0 ± 0.5
2 (4×4)	61.7 ± 0.6	64.7 ± 0.7	79.4 ± 0.3	81.1 ± 0.3
3 (8×8)	63.3 ± 0.8	66.8 ± 0.6	77.2 ± 0.4	80.7 ± 0.3

Caltech101 dataset

http://www.vision.caltech.edu/Image_Datasets/Caltech101/Caltech101.html

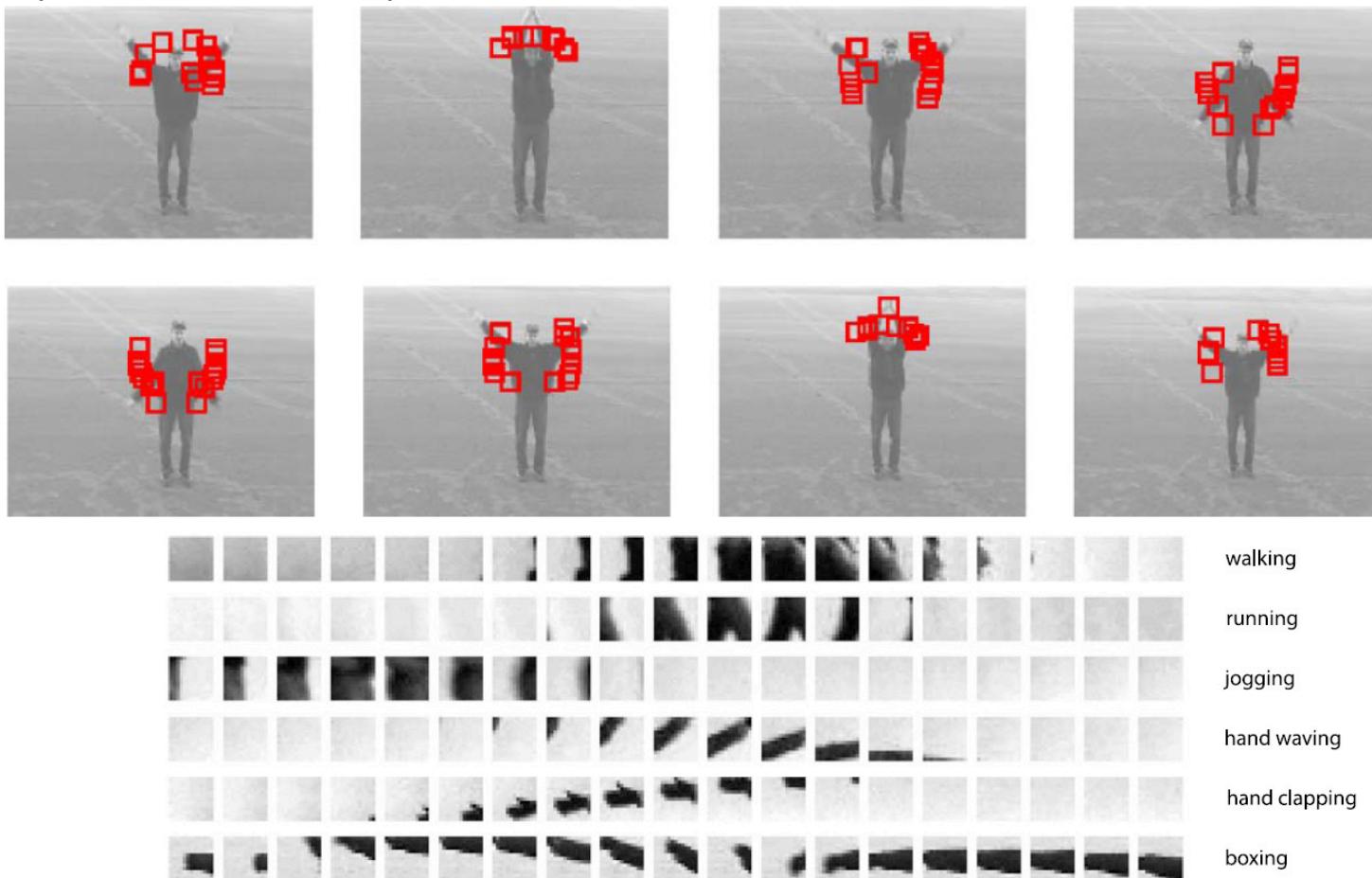


Multi-class classification results (30 training images per class)

	Weak features (16)		Strong features (200)	
Level	Single-level	Pyramid	Single-level	Pyramid
0	15.5 ± 0.9		41.2 ± 1.2	
1	31.4 ± 1.2	32.8 ± 1.3	55.9 ± 0.9	57.0 ± 0.8
2	47.2 ± 1.1	49.3 ± 1.4	63.6 ± 0.9	64.6 ± 0.8
3	52.2 ± 0.8	54.0 ± 1.1	60.3 ± 0.9	64.6 ± 0.7

Bags of features for action recognition

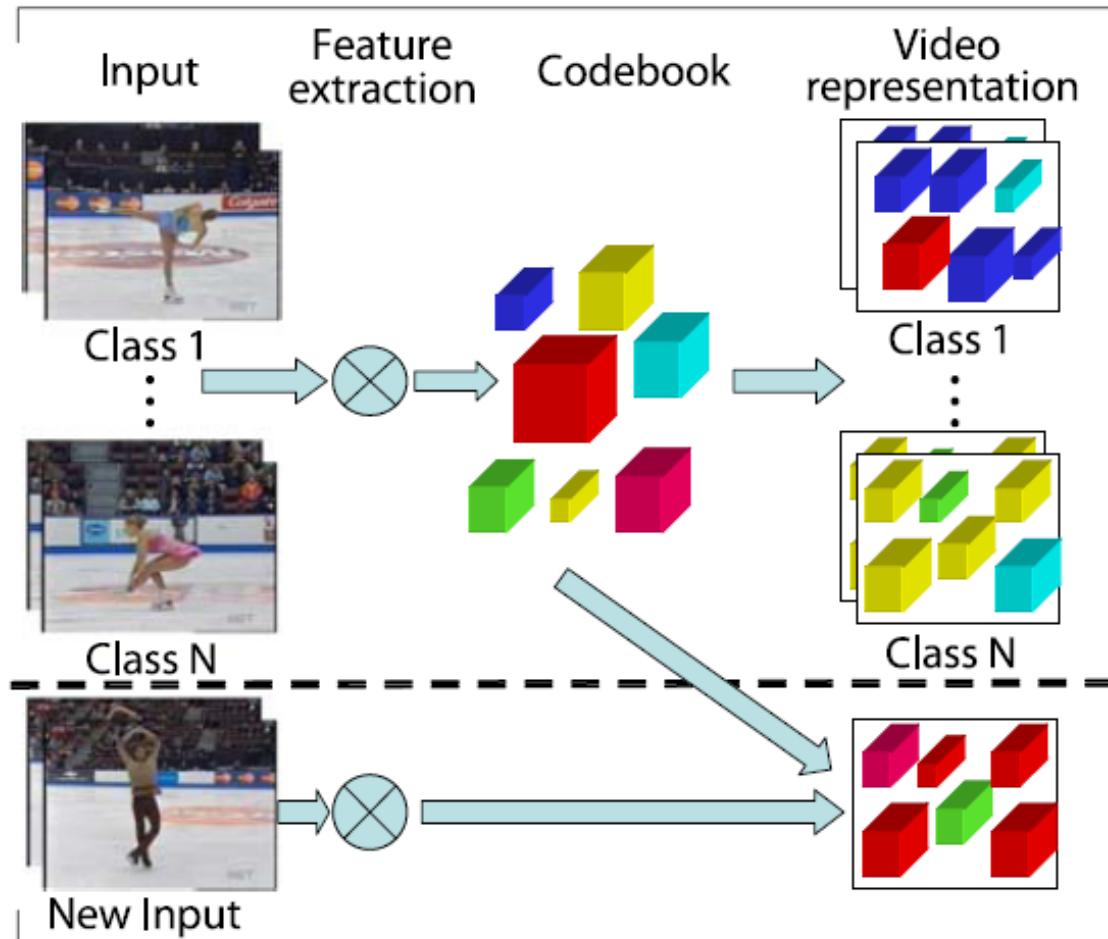
Space-time interest points



Juan Carlos Niebles, Hongcheng Wang and Li Fei-Fei, [Unsupervised Learning of Human Action Categories Using Spatial-Temporal Words](#), IJCV 2008.

Bags of features for action recognition

Feature extraction and description



Juan Carlos Niebles, Hongcheng Wang and Li Fei-Fei, [Unsupervised Learning of Human Action Categories Using Spatial-Temporal Words](#), IJCV 2008.

What we have learned today

- Visual bag of words (BoW)
- Spatial Pyramid Matching
- Naïve Bayes