Bag-of-features for category classification

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INRIA

LEAR

Category recognition

- Image classification: assigning a class label to the image

Car: present
Cow: present
Bike: not present
Horse: not present
...

Category recognition

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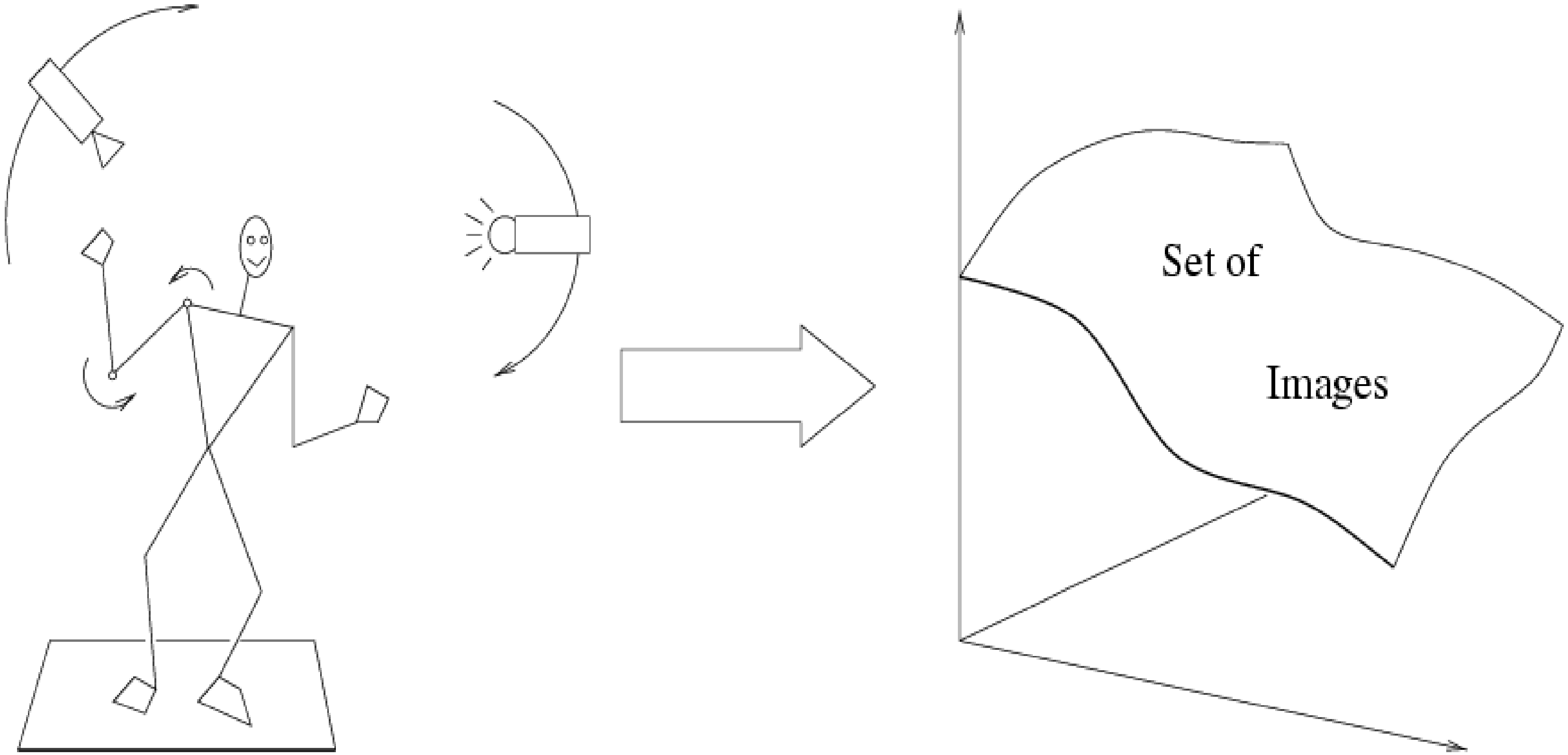
...

- Object localization: define the location and the category

Location

Category

Difficulties: within object variations



Variability: Camera position, Illumination,Internal parameters

⇒ Within-object variations

Difficulties: within-class variations



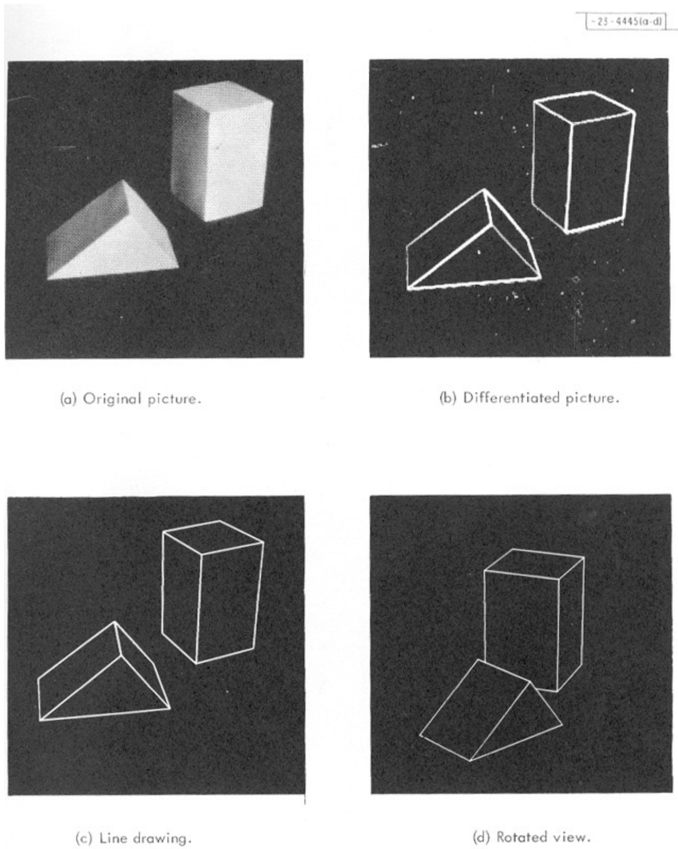



Category recognition

- Robust image description
  - Appropriate descriptors for categories
- Statistical modeling and machine learning for vision
  - Use and validation of appropriate techniques

Why machine learning?

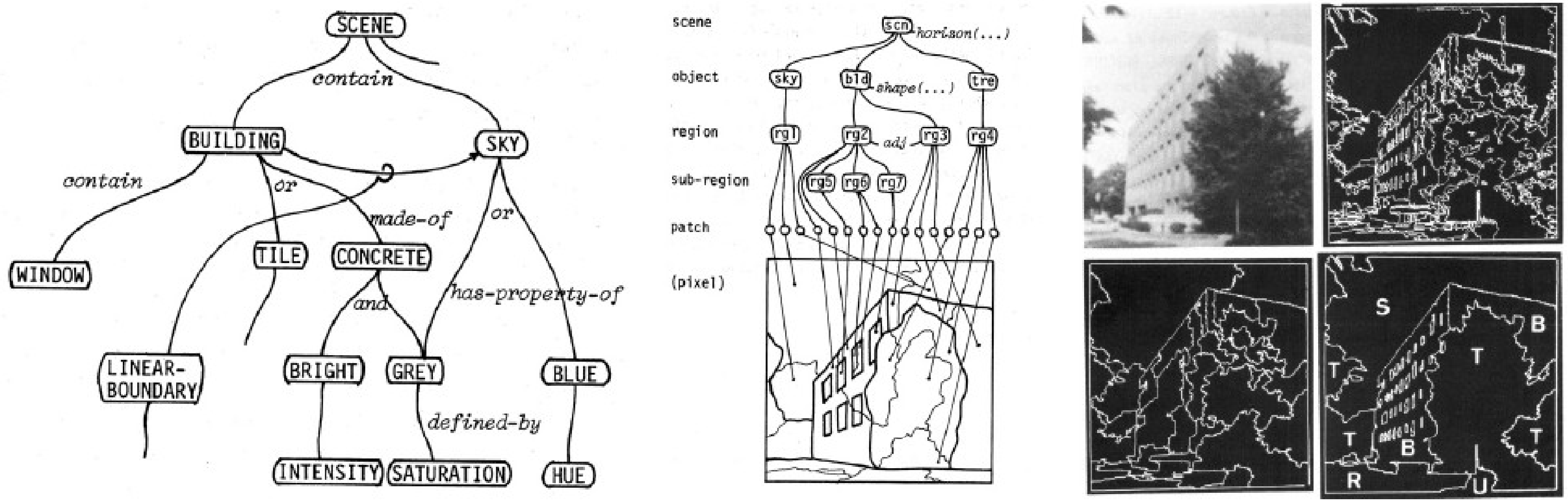
- Early approaches: simple features + handcrafted models
- Can handle only few images, simples tasks



L. G. Roberts, *Machine Perception of Three Dimensional Solids,* Ph.D. thesis, MIT Department of Electrical Engineering, 1963.

Why machine learning?

- Early approaches: manual programming of rules
- Tedious, limited and does not take into accout the data



(a) Bottom-up process (b) Top-down process (c) Result

Figure 3. A system developed in 1978 by Ohta, Kanade and Sakai [33, 32] for knowledge-based interpretation of outdoor natural scenes. The system is able to label an image (c) into semantic classes: S-sky, T-tree, R-road, B-building, U-unknown.

Y. Ohta, T. Kanade, and T. Sakai, "An Analysis System for Scenes Containing objects with Substructures," *International Joint Conference on Pattern Recognition*, 1978.

Why machine learning?

- Today lots of data, complex tasks

Internet images,
personal photo albums

Movies, news, sports

- Instead of trying to encode rules directly, learn them from examples of inputs and desired outputs

Types of learning problems

- Supervised
  - Classification
  - Regression
- Unsupervised
- Semi-supervised
- Active learning
- ….

Supervised learning

- Given training examples of inputs and corresponding outputs, produce the “correct” outputs for new inputs

- Two main scenarios:

  – **Classification:** outputs are discrete variables (category labels). Learn a decision boundary that separates one class from the other.

  – **Regression:** also known as “curve fitting” or “function approximation.” Learn a continuous input-output mapping from examples (possibly noisy).

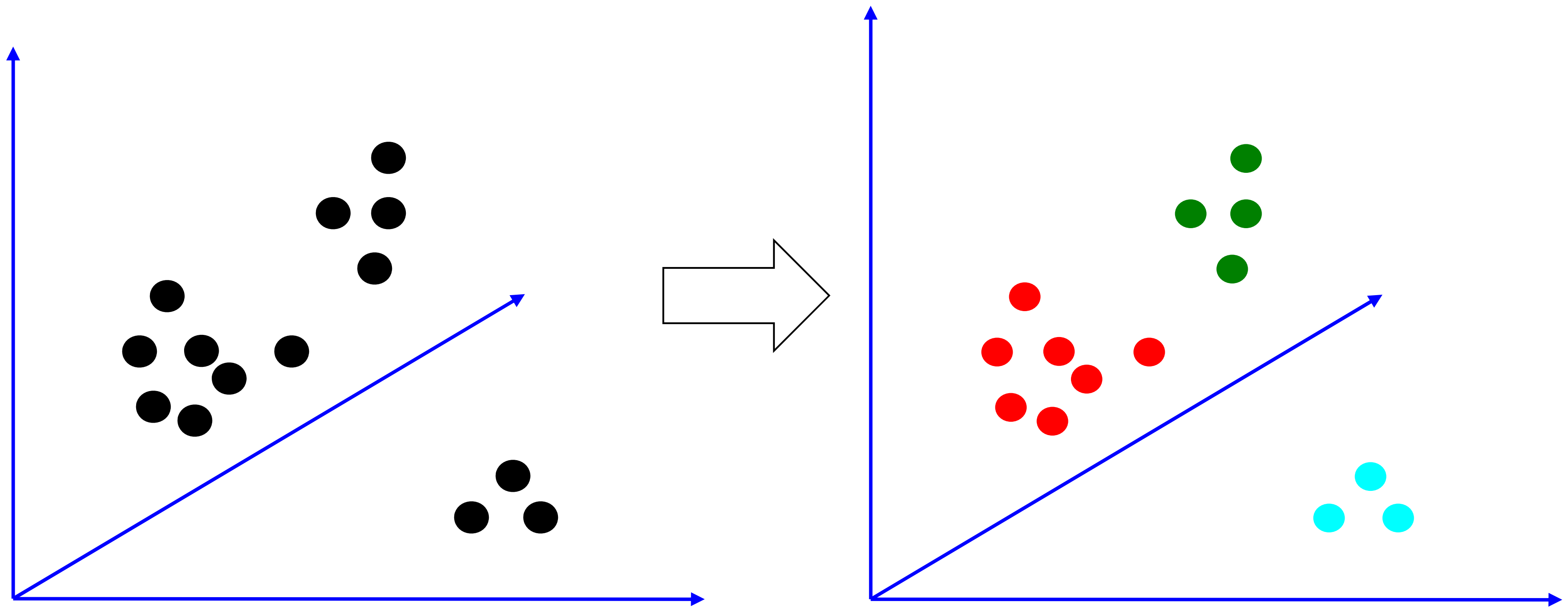
Unsupervised Learning

- Given only *unlabeled* data as input, learn some sort of structure.

- The objective is often more vague or subjective than in supervised learning. This is more an exploratory/descriptive data analysis.

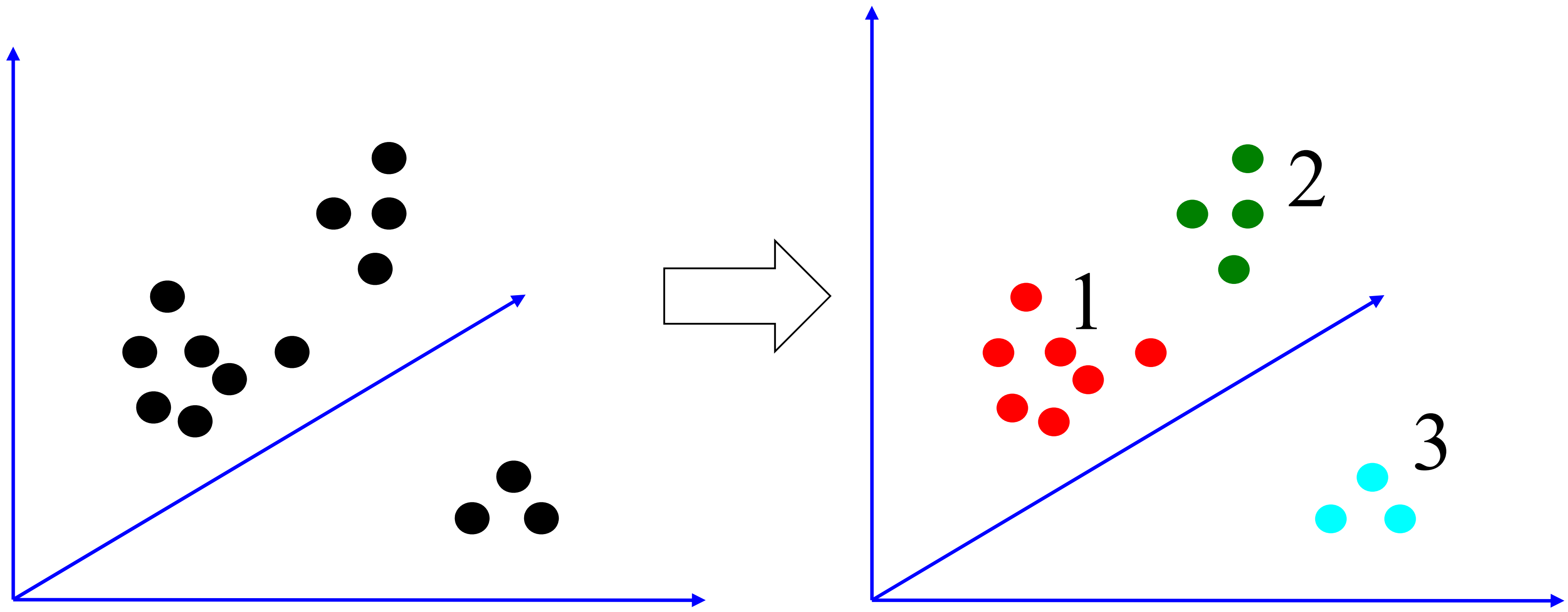
Unsupervised Learning

- **Clustering**
  - Discover groups of “similar” data points



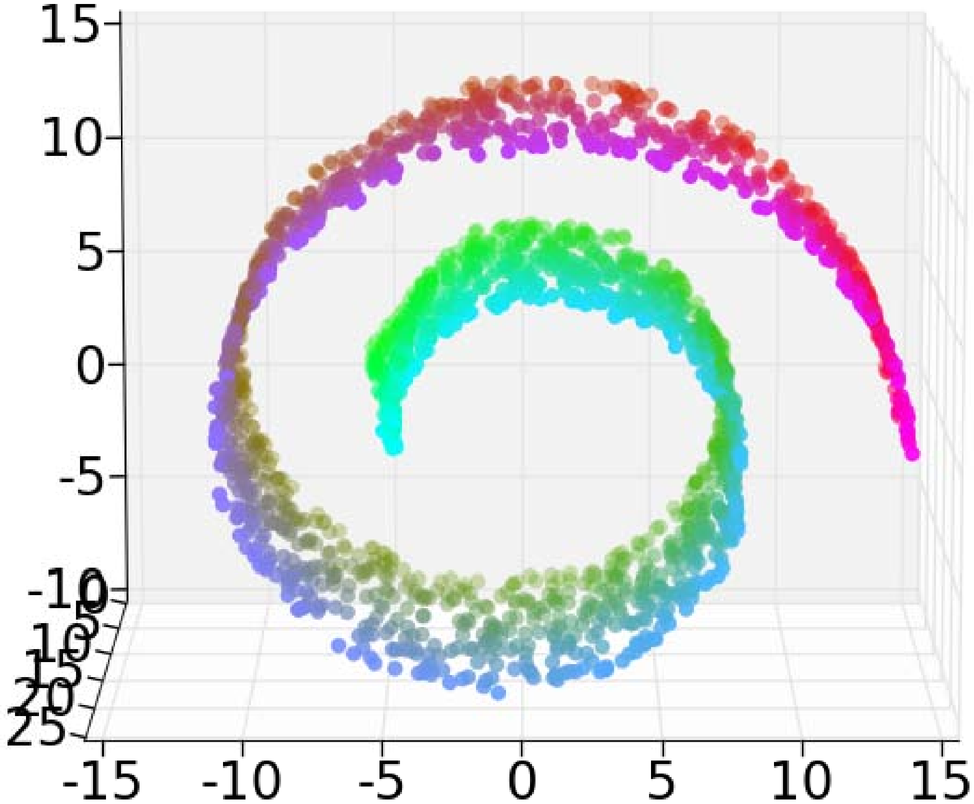
Unsupervised Learning

- **Quantization**
  - Map a continuous input to a discrete (more compact) output



Unsupervised Learning

- **Dimensionality reduction, manifold learning**
  - Discover a lower-dimensional surface on which the data lives

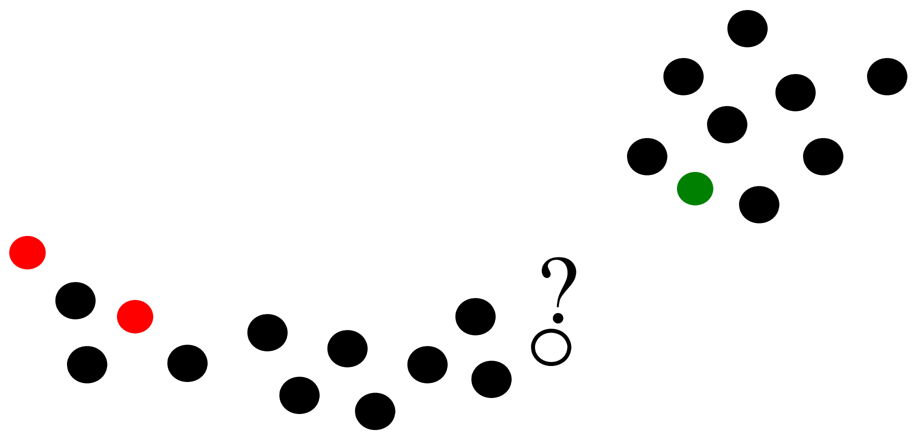


Other types of learning

- **Semi-supervised learning:** lots of data is available, but only small portion is labeled (e.g. since labeling is expensive)

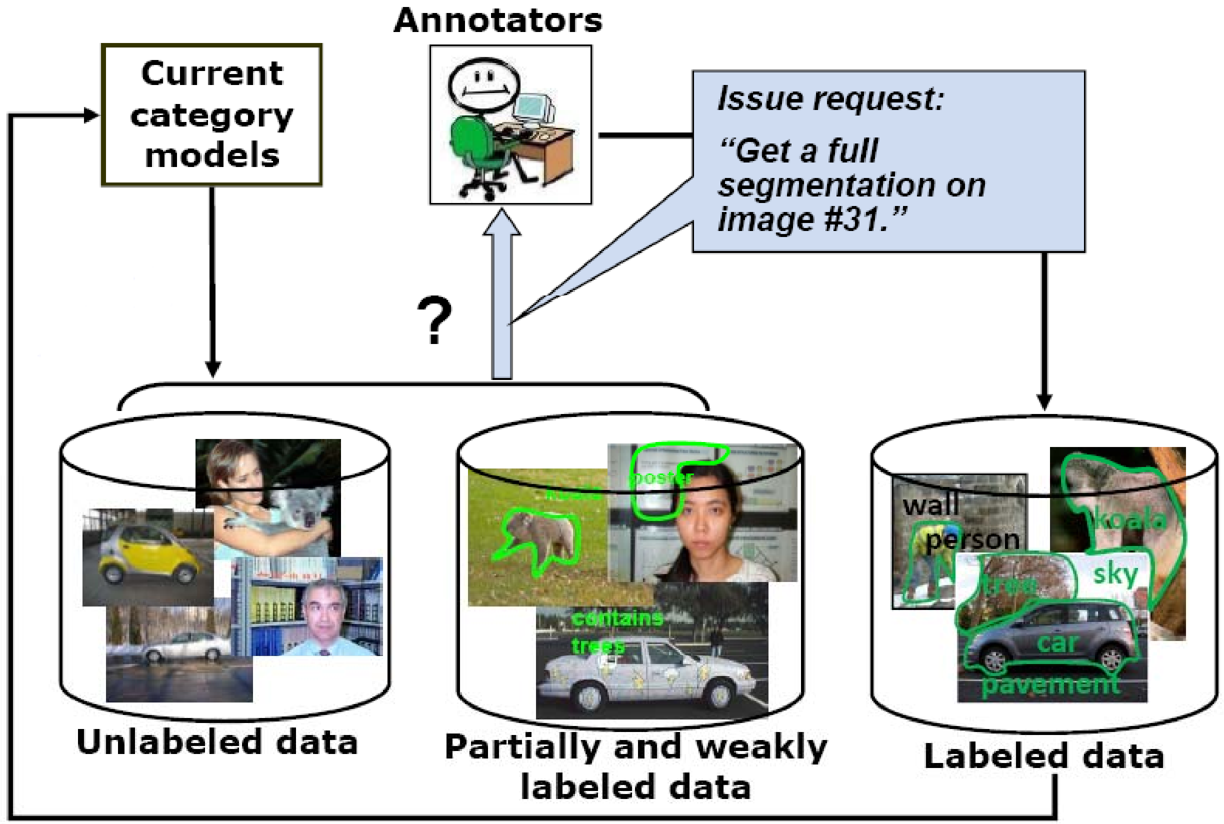
Other types of learning

- **Semi-supervised learning:** lots of data is available, but only small portion is labeled (e.g. since labeling is expensive)
  - Why is learning from labeled and unlabeled data better than learning from labeled data alone?



Other types of learning

- **Active learning:** the learning algorithm can choose its own training examples, or ask a “teacher” for an answer on selected inputs



Category recognition

- Image classification: assigning a class label to the image

Car: present
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...

- Supervised scenario: given a set of training images

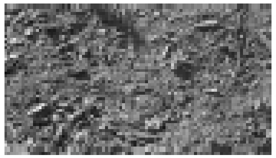
Image classification

- Given

Positive training images containing an object class



Negative training images that don't



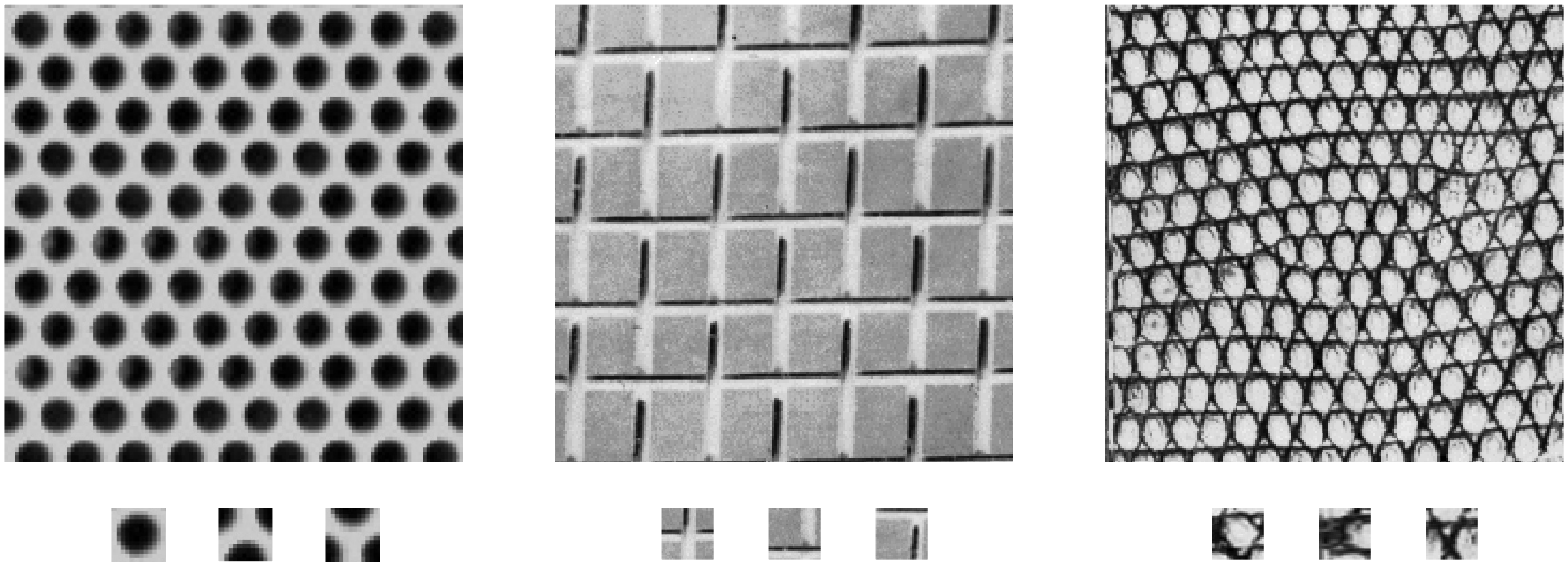
- Classify

A test image as to whether it contains the object class or not

?

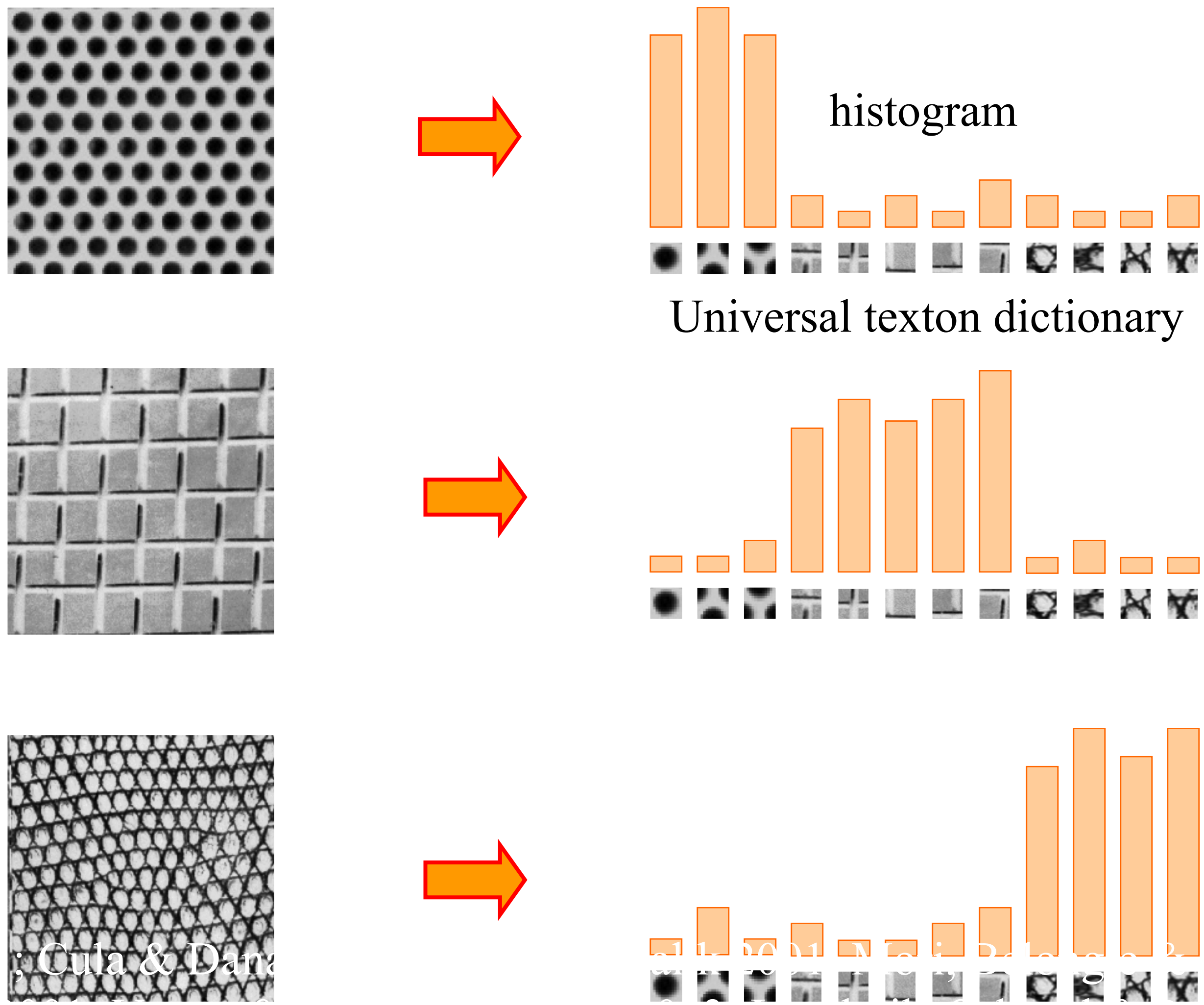
Bag-of-features for image classification

- Origin: texture recognition
  - Texture is characterized by the repetition of basic elements or *textons*



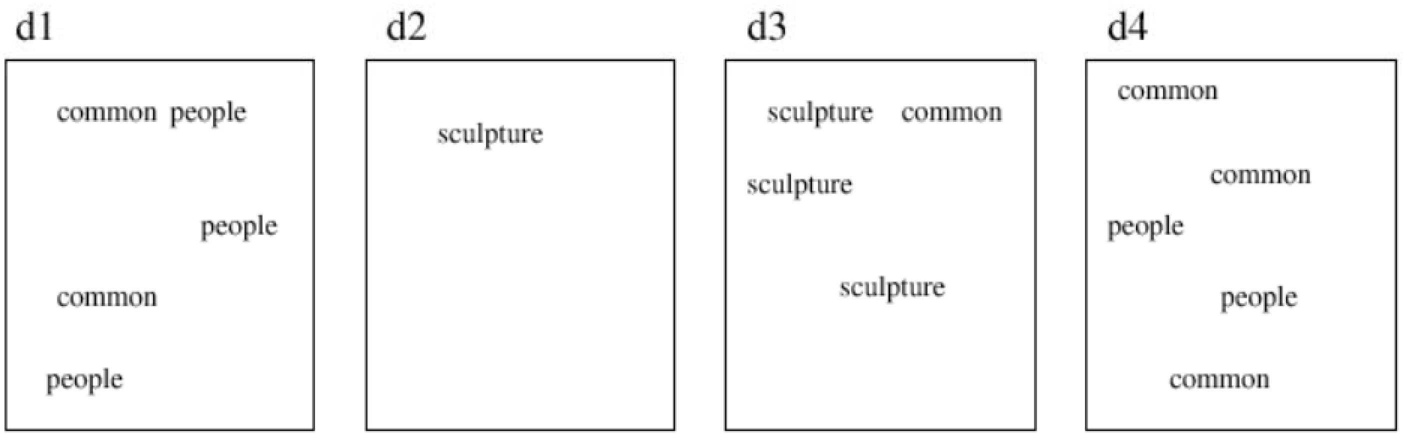
Julesz, 1981; Cula & Dana, 2001; Leung & Malik 2001; Mori, Belongie & Malik, 2001
Schmid 2001; Varma & Zisserman, 2002, 2003; Lazebnik, Schmid & Ponce, 2003

Texture recognition



Bag-of-features – Origin: bag-of-words (text)

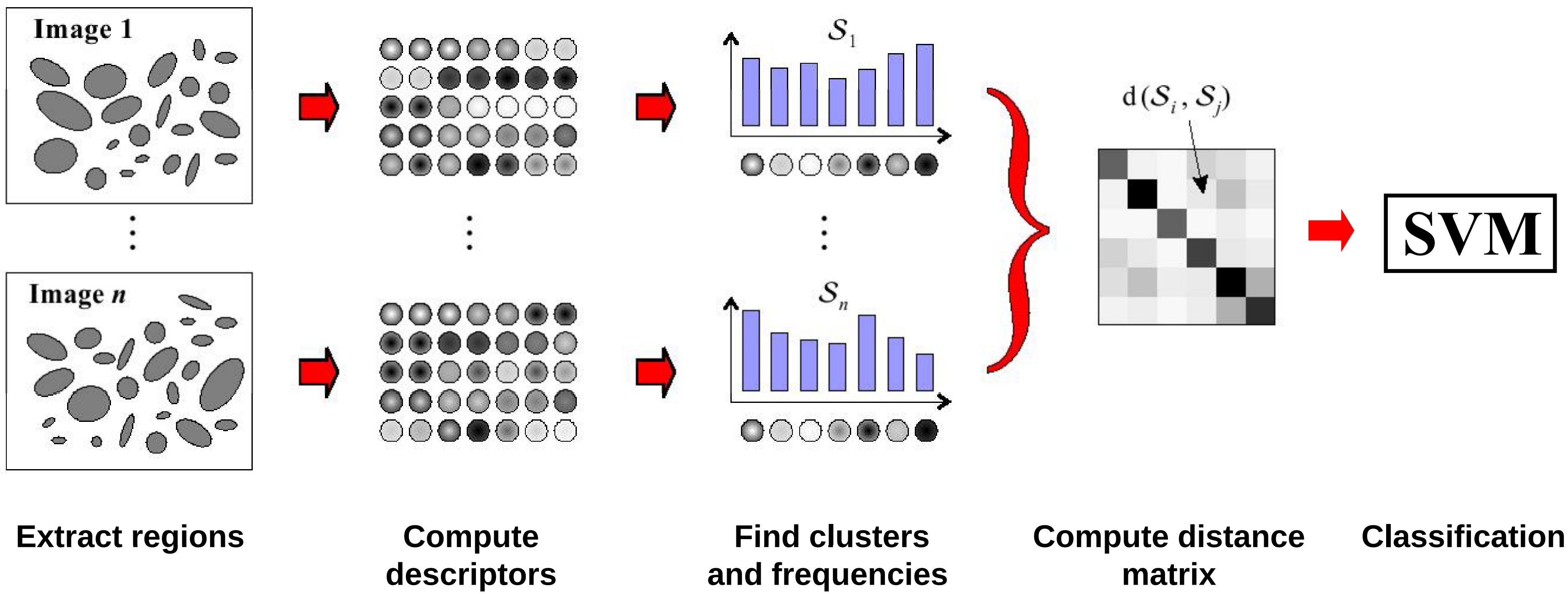
- Orderless document representation: frequencies of words from a dictionary
- Classification to determine document categories



Bag-of-words

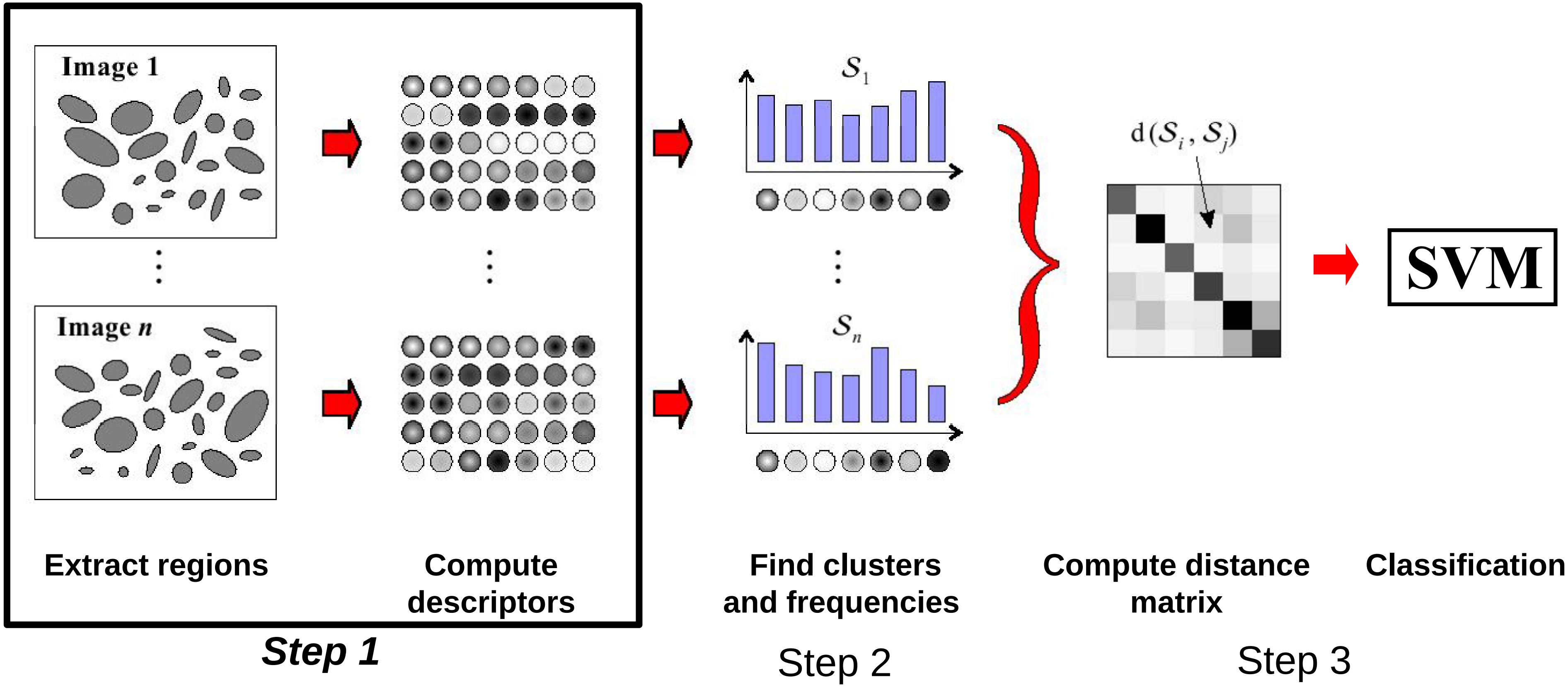
Common	2	0	1	3
People	3	0	0	2
Sculpture	0	1	3	0
…	…	…	…	…

Bag-of-features for image classification



[Nowak,Jurie&Triggs,ECCV’06], [Zhang,Marszalek,Lazebnik&Schmid,IJCV’07]

Bag-of-features for image classification



[Nowak,Jurie&Triggs,ECCV'06], [Zhang,Marszalek,Lazebnik&Schmid,IJCV'07]

Step 1: feature extraction

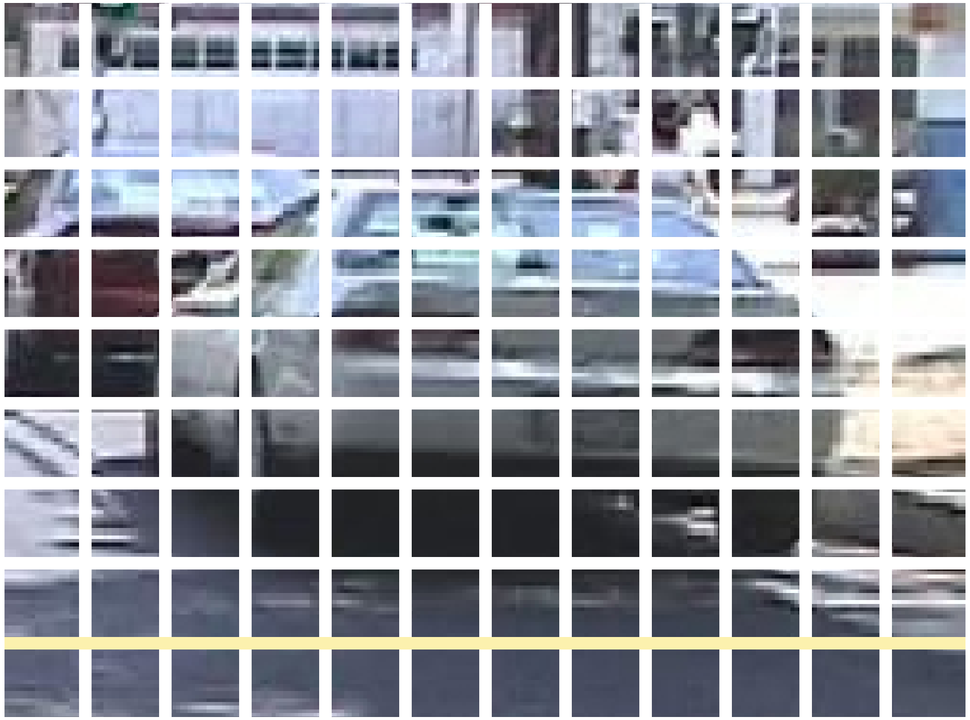
- Scale-invariant image regions + SIFT (see lecture 2)
  – Affine invariant regions give “too” much invariance
  – Rotation invariance for many realistic collections “too” much invariance

- Dense descriptors
  – Improve results in the context of categories (for most categories)
  – Interest points do not necessarily capture “all” features

- Color-based descriptors

- Shape-based descriptors

Dense features

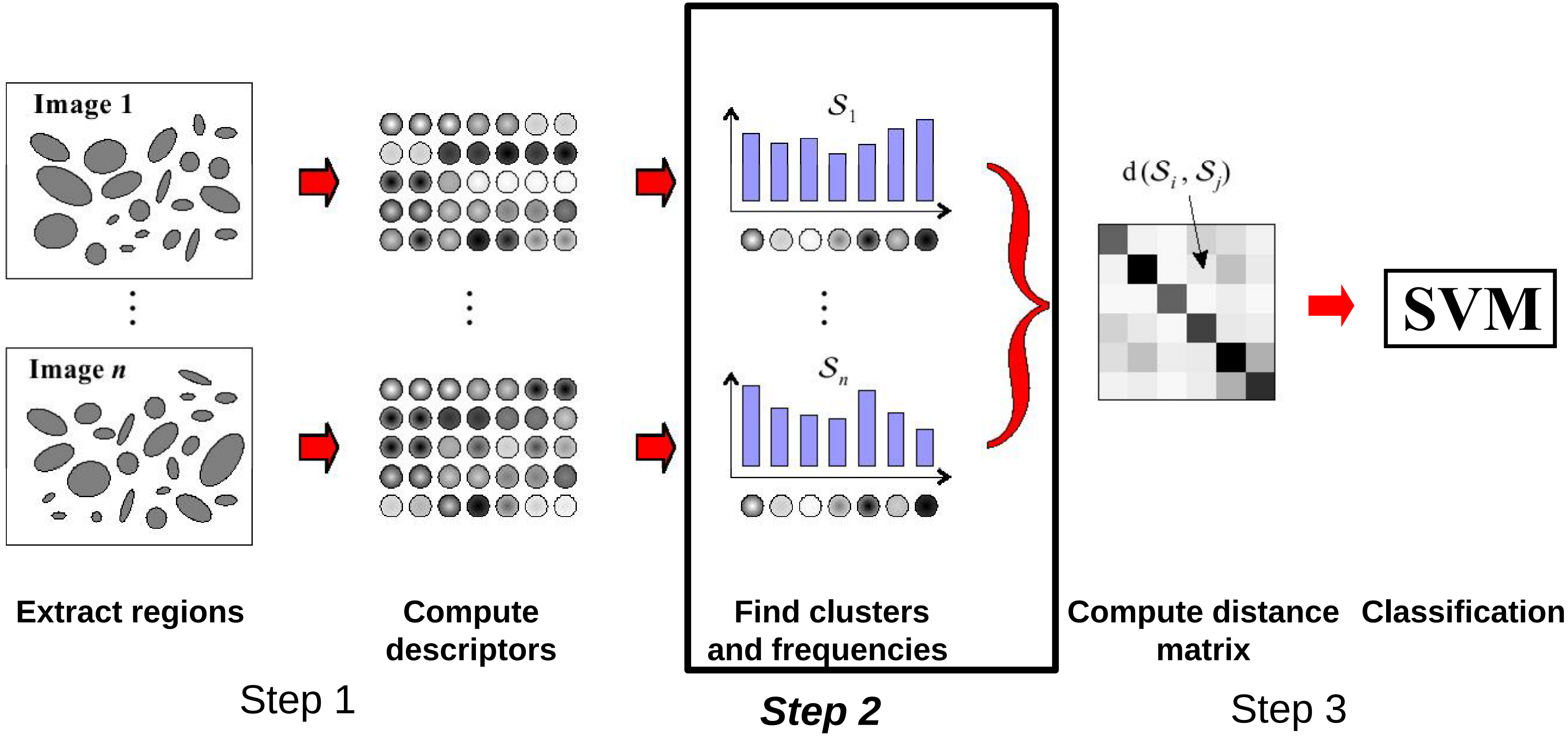


- Multi-scale dense grid: extraction of small overlapping patches at multiple scales

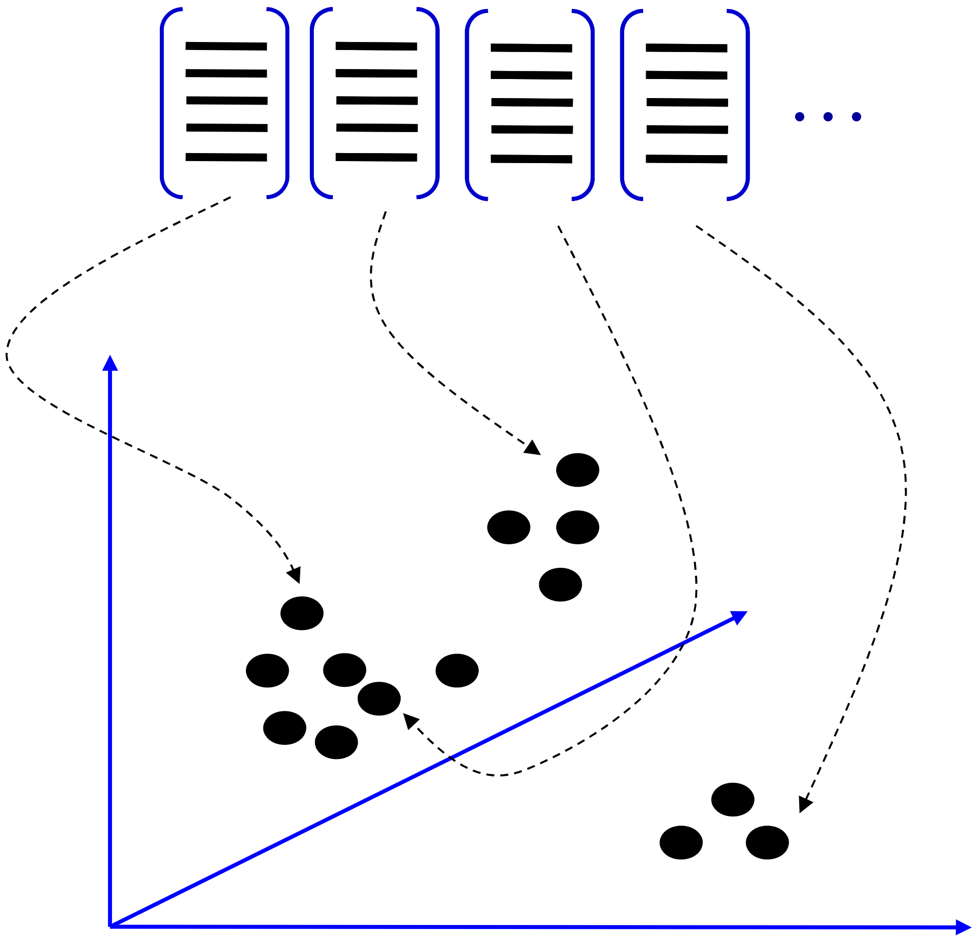
-Computation of the SIFT descriptor for each grid cells

-Exp.: Horizontal/vertical step size 3-6 pixel, scaling factor of 1.2 per level

Bag-of-features for image classification



Step 2: Quantization



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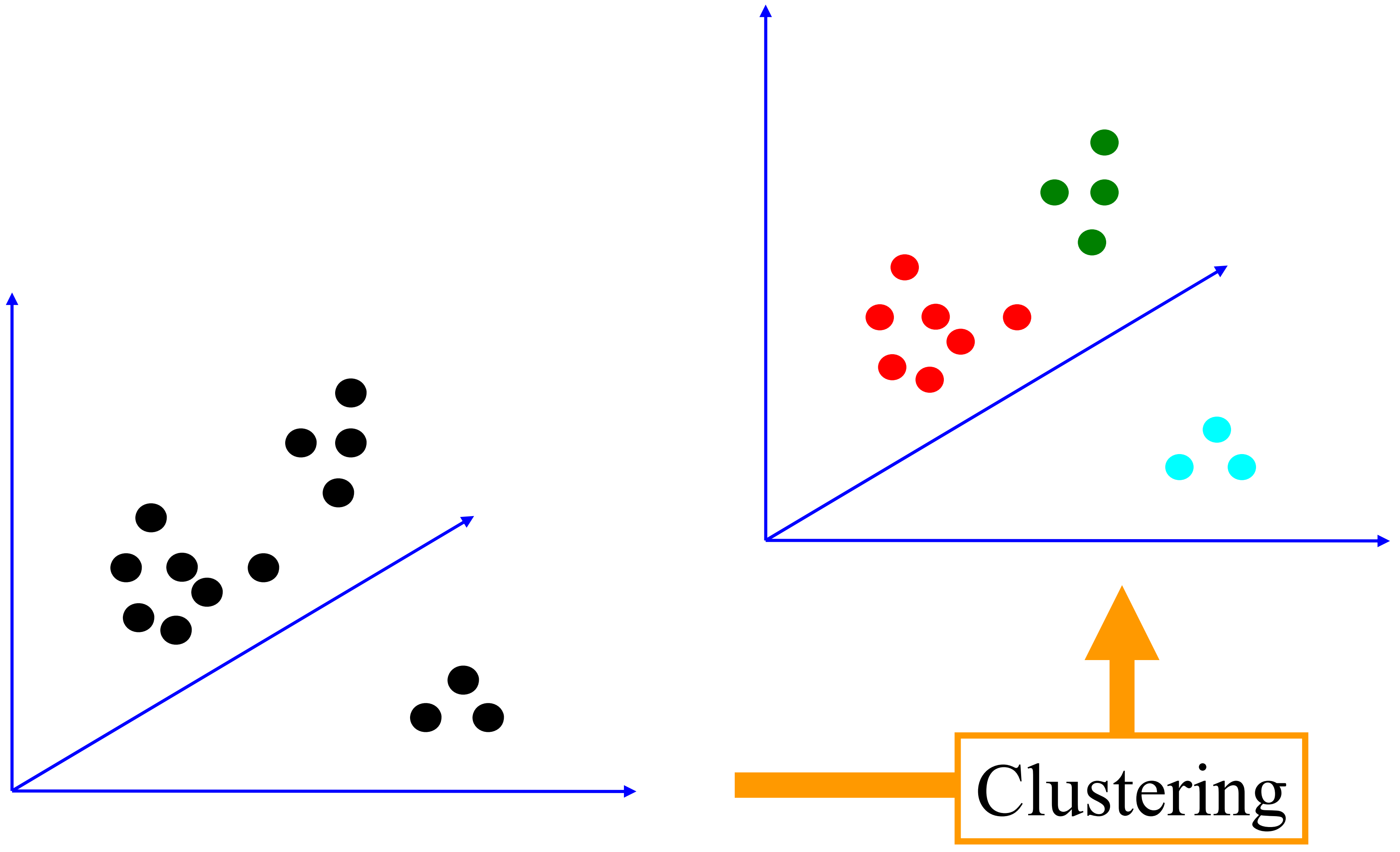
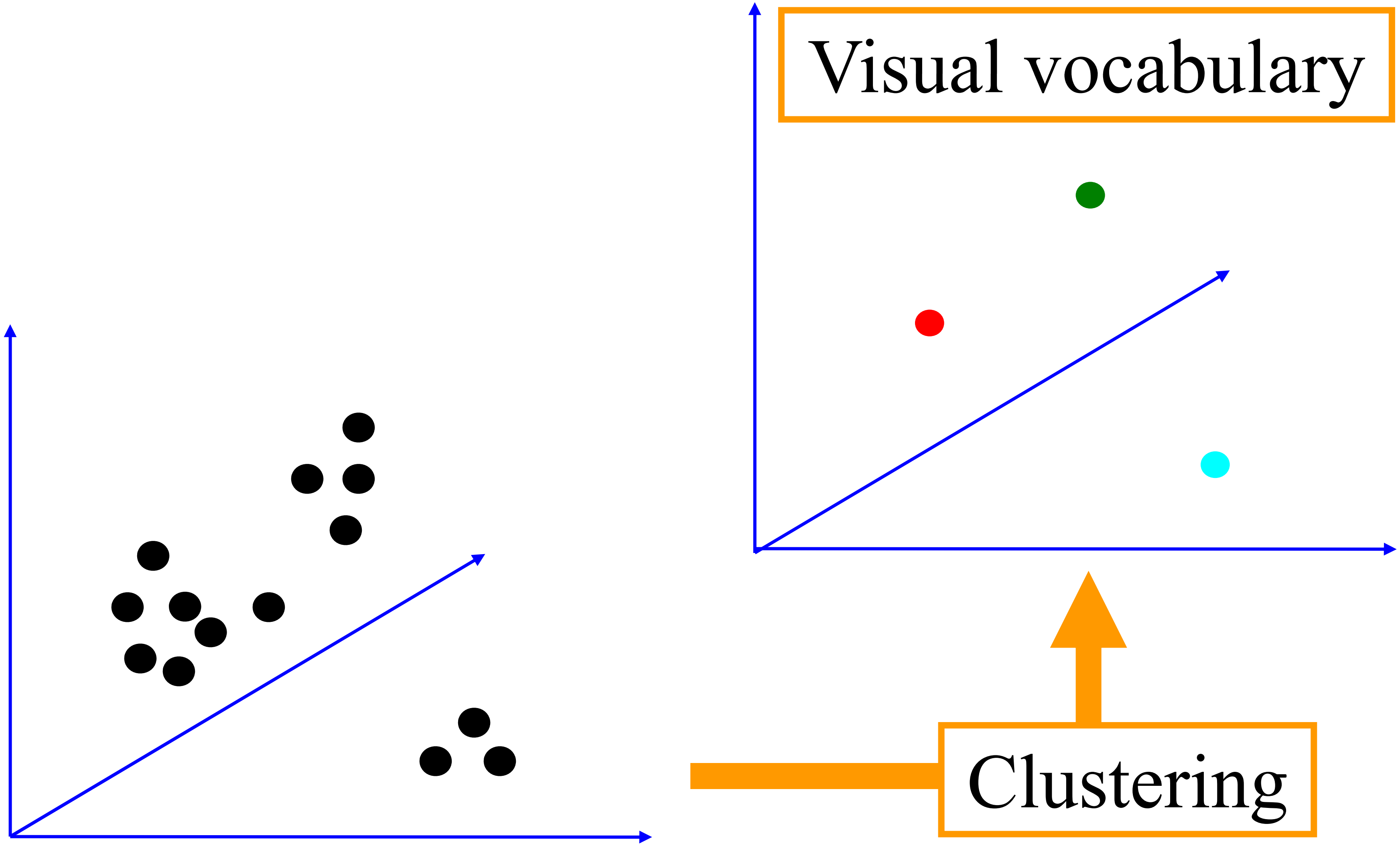
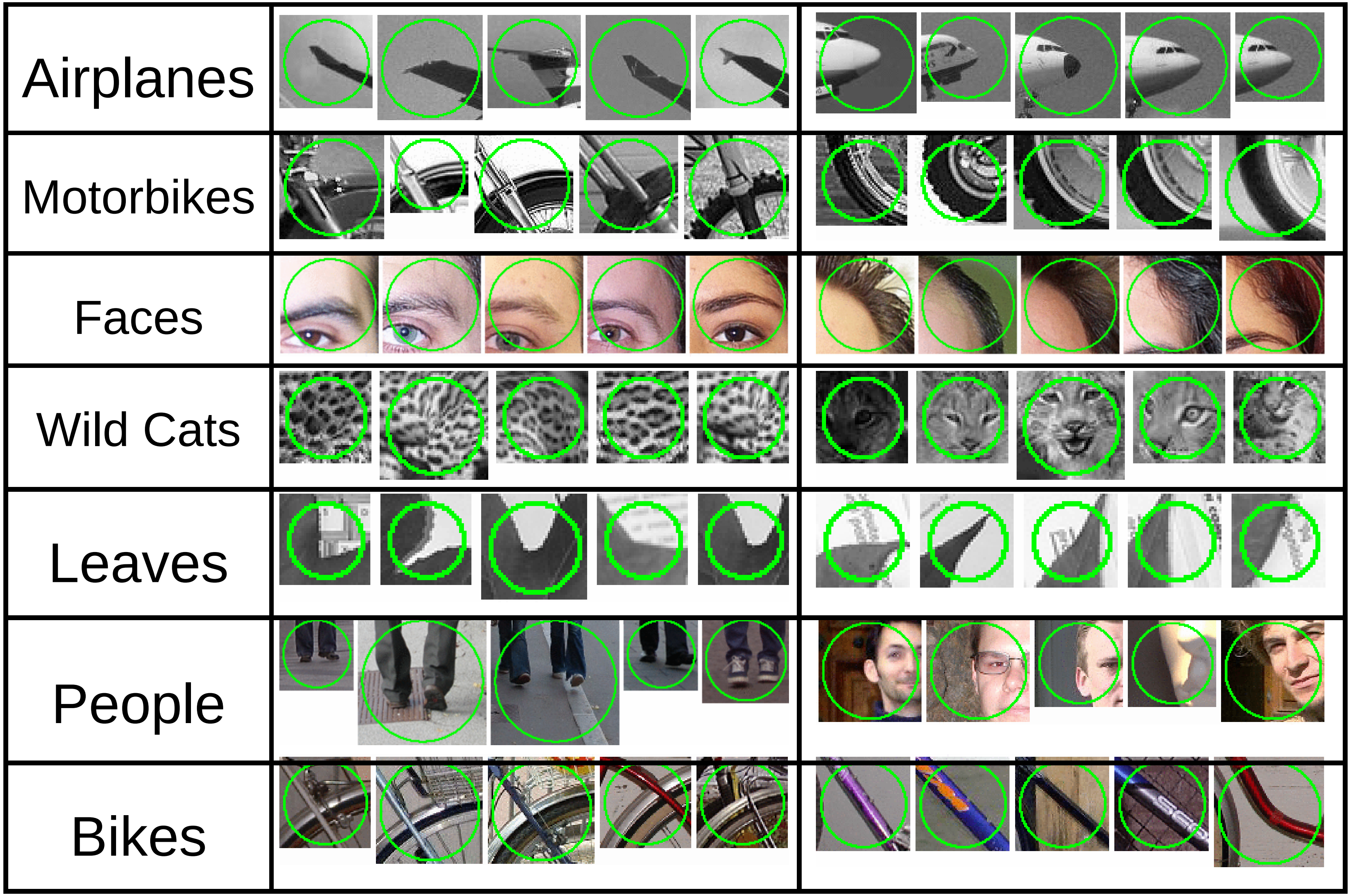


Step 2: Quantization



Examples for visual words



Step 2: Quantization

- Cluster descriptors
  - K-means
  - Gaussian mixture model
- Assign each visual word to a cluster
  - Hard or soft assignment
- Build frequency histogram

K-means clustering

- Minimizing sum of squared Euclidean distances between points x_i and their nearest cluster centers

- 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

- Local minimum, solution dependent on initialization

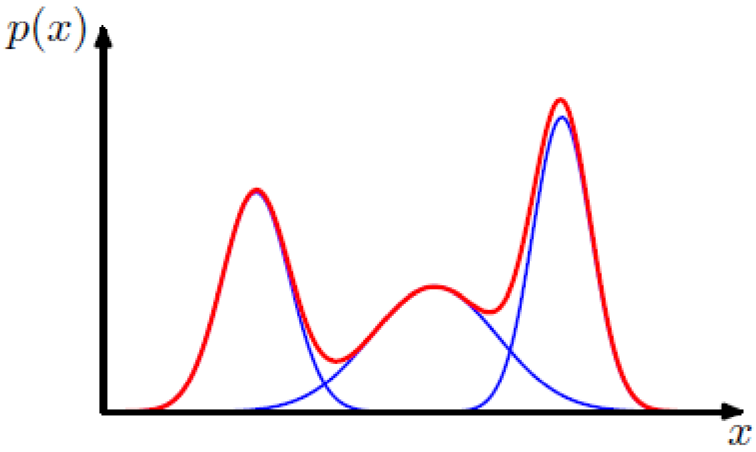
- Initialization important, run several times, select best

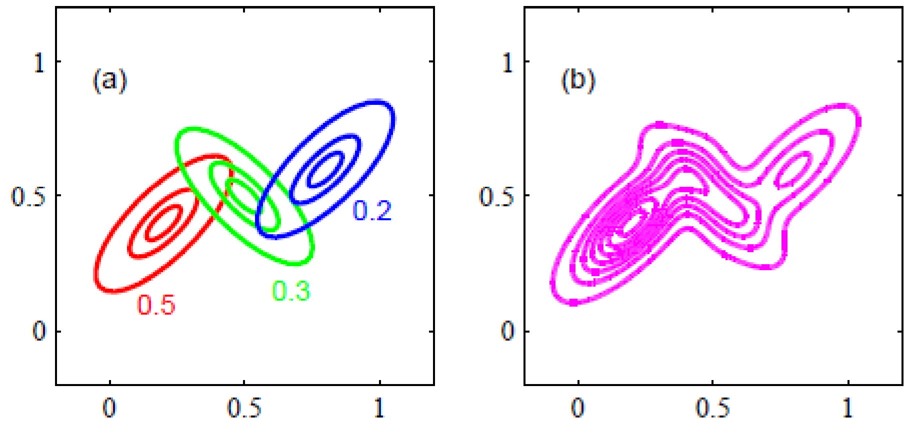
Gaussian mixture model (GMM)

- Mixture of Gaussians: weighted sum of Gaussians

$$p(\mathbf{x}) = \sum_{k=1}^{K} \pi_k \, \mathcal{N}(\mathbf{x}; \boldsymbol{\mu}_k, \Sigma_k)$$

where $\mathcal{N}(\mathbf{x}; \boldsymbol{\mu}, \Sigma) = (2\pi)^{(-d/2)} |\Sigma|^{-1/2} \exp\left(-\frac{1}{2}(\mathbf{x} - \boldsymbol{\mu})^\top \Sigma^{-1} (\mathbf{x} - \boldsymbol{\mu})\right)$

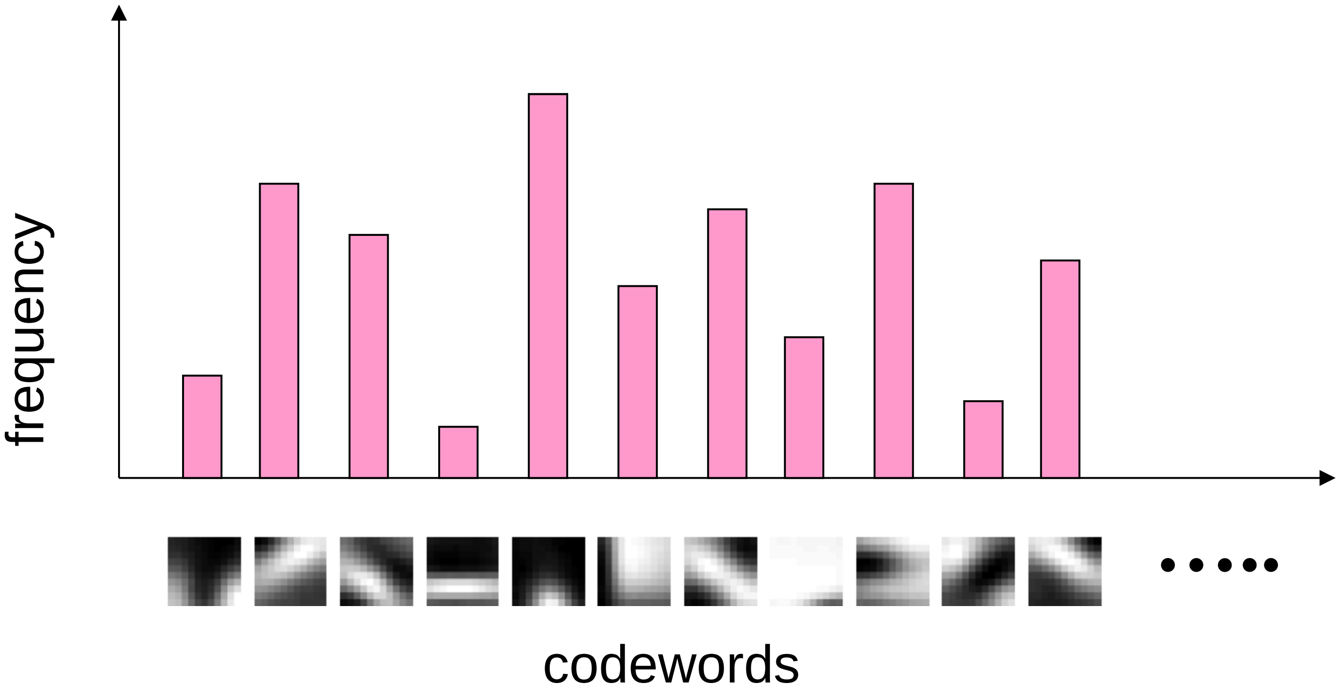




Hard or soft assignment

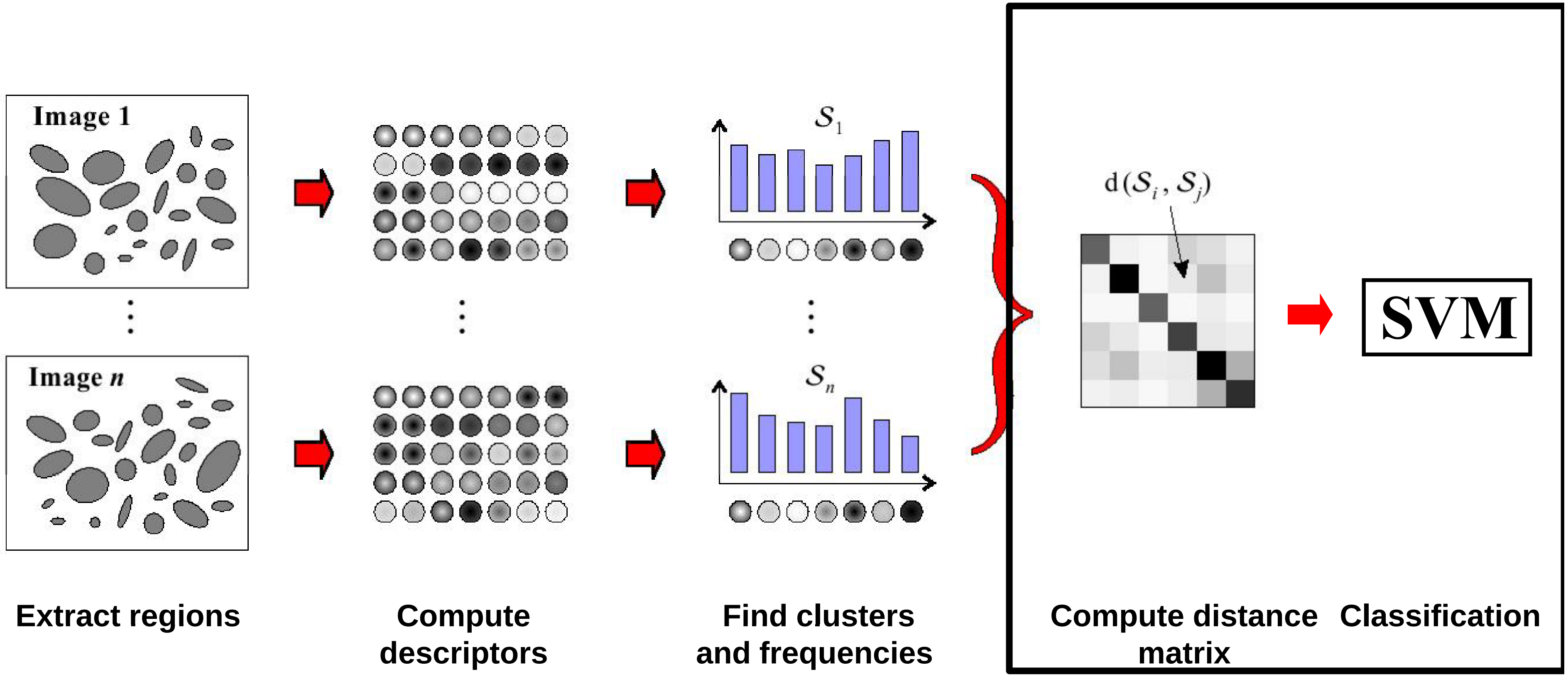
- K-means → hard assignment
  - Assign to the closest cluster center
  - Count number of descriptors assigned to a center
- Gaussian mixture model → soft assignment
  - Estimate distance to all centers
  - Sum over number of descriptors
- Represent image by a frequency histogram

Image representation



- Each image is represented by a vector, typically 1000-4000 dimension
- fine grained – represent model instances
- coarse grained – represent object categories

Bag-of-features for image classification

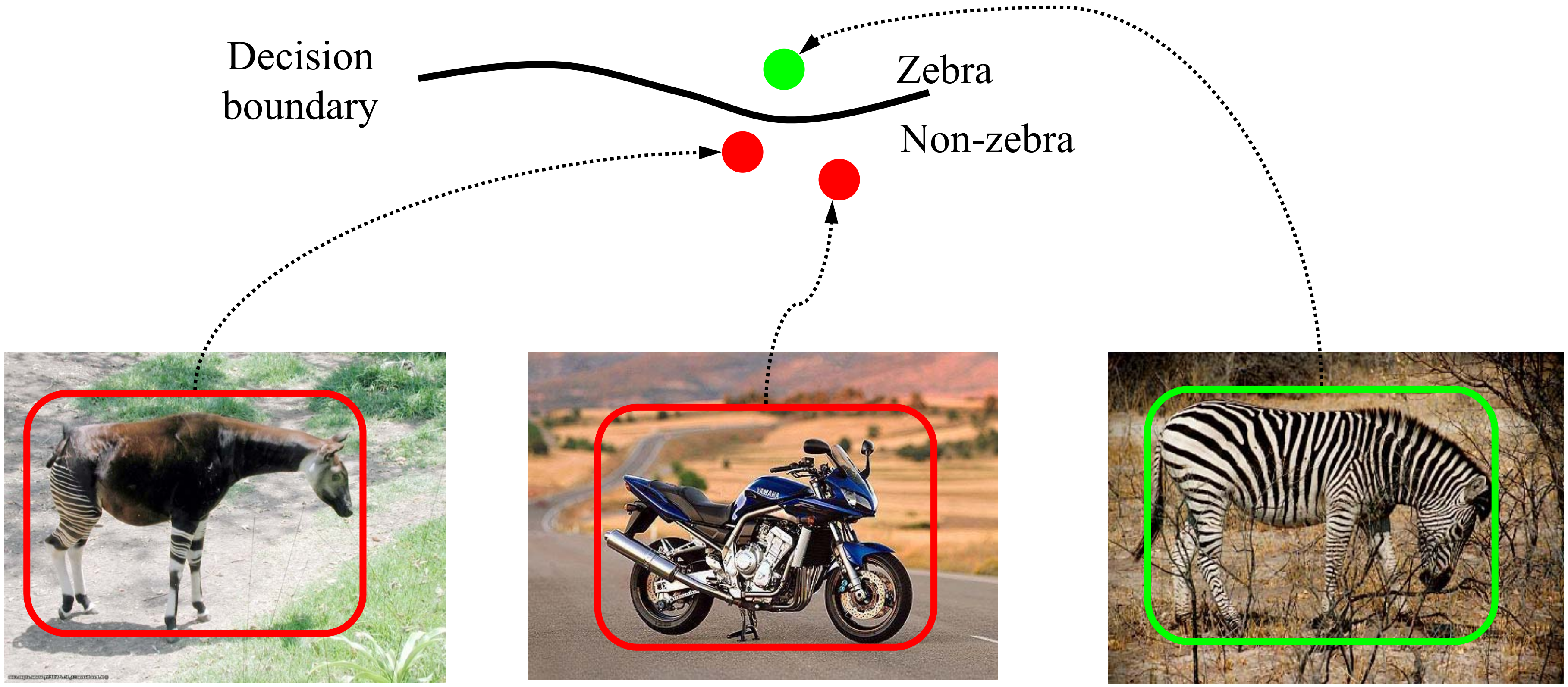


Extract regions **Compute descriptors** **Find clusters and frequencies** **Compute distance matrix** **Classification**

Step 1 Step 2 ***Step 3***

Step 3: Classification

- Learn a decision rule (classifier) assigning bag-of-features representations of images to different classes

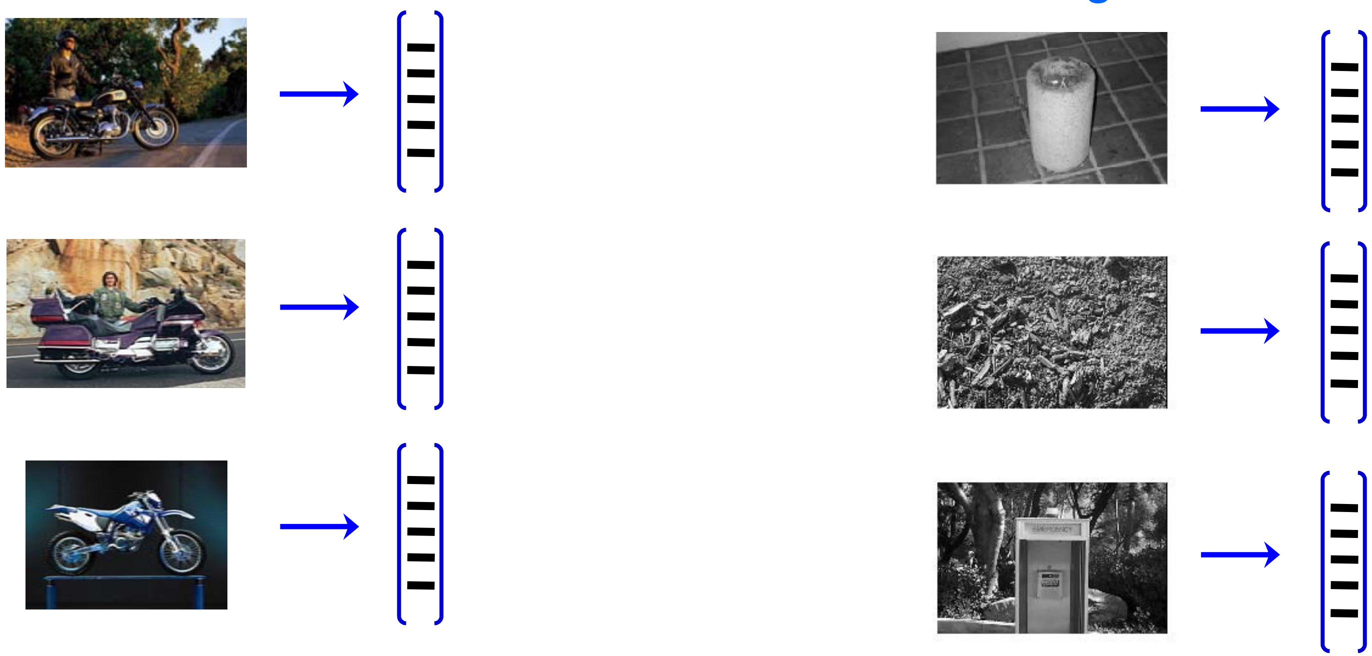


Training data

Vectors are histograms, one from each training image

positive

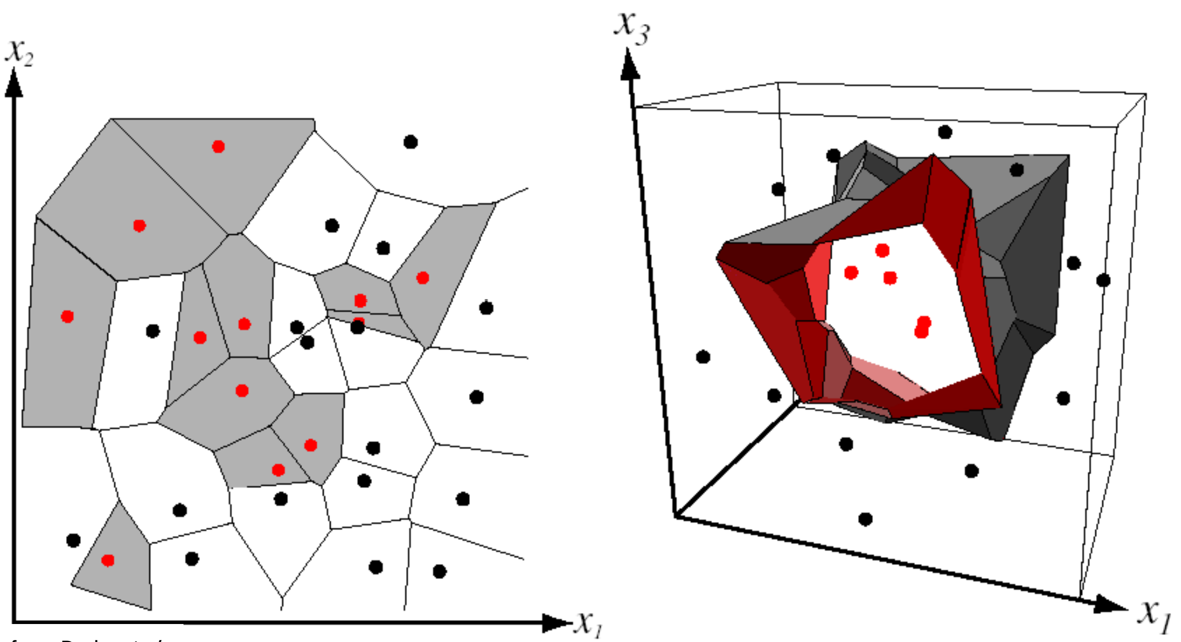
negative



Train classifier,e.g.SVM

Nearest Neighbor Classifier

- Assign label of nearest training data point to each test data point

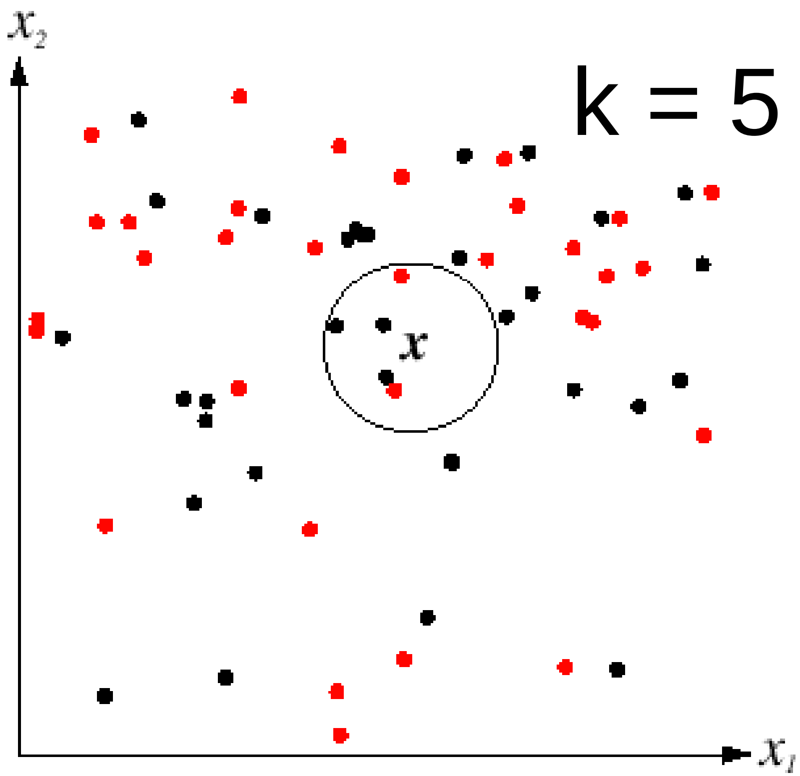


from Duda *et al.*

Voronoi partitioning of feature space
for 2-category 2-D and 3-D data

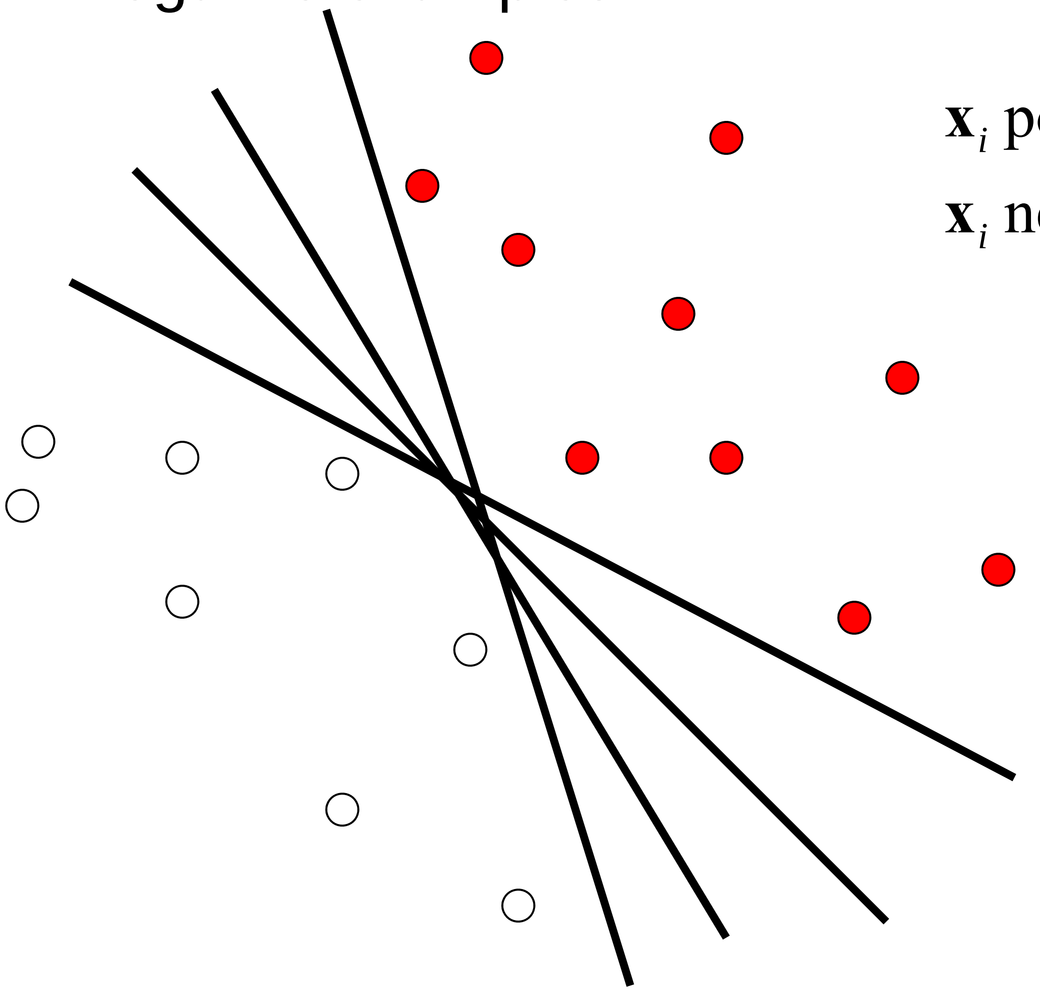
k-Nearest Neighbors

- For a new point, find the k closest points from training data
- Labels of the k points “vote” to classify
- Works well provided there is lots of data and the distance function is good



Linear classifiers

- Find linear function (*hyperplane*) to separate positive and negative examples

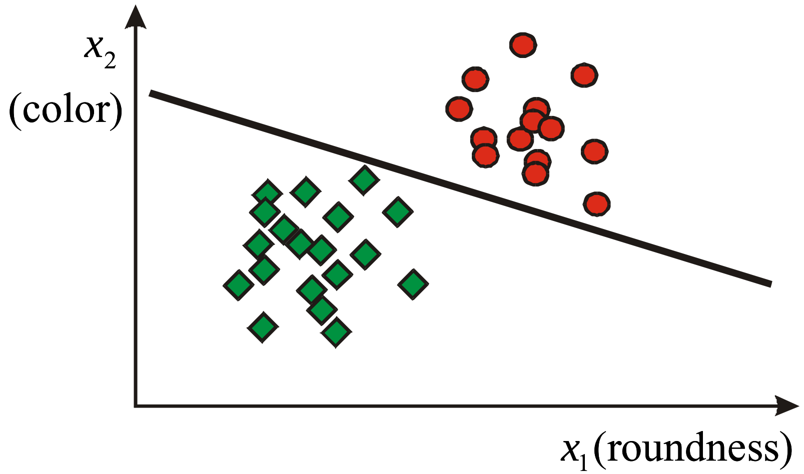


$$\mathbf{x}_i \text{ positive}: \quad \mathbf{x}_i \cdot \mathbf{w} + b \geq 0$$
$$\mathbf{x}_i \text{ negative}: \quad \mathbf{x}_i \cdot \mathbf{w} + b < 0$$

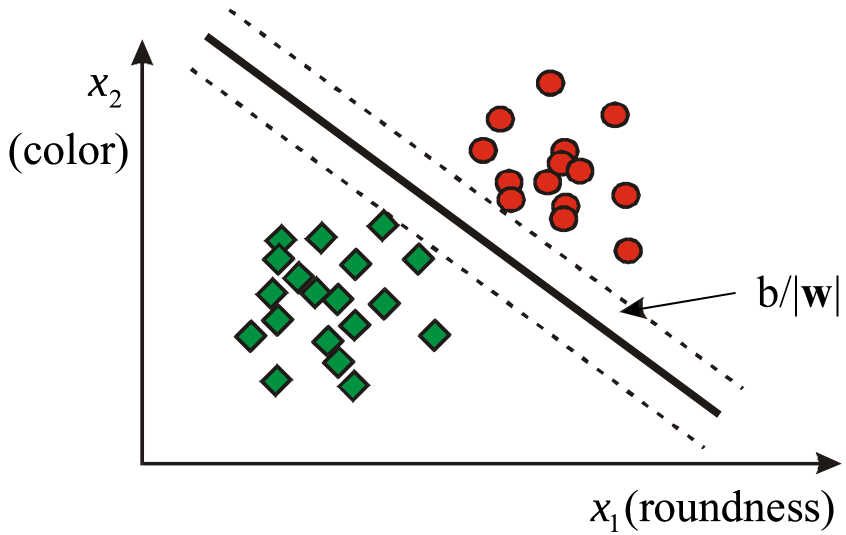
Which hyperplane
is best?

Linear classifiers - margin

- Generalization is not good in this case:

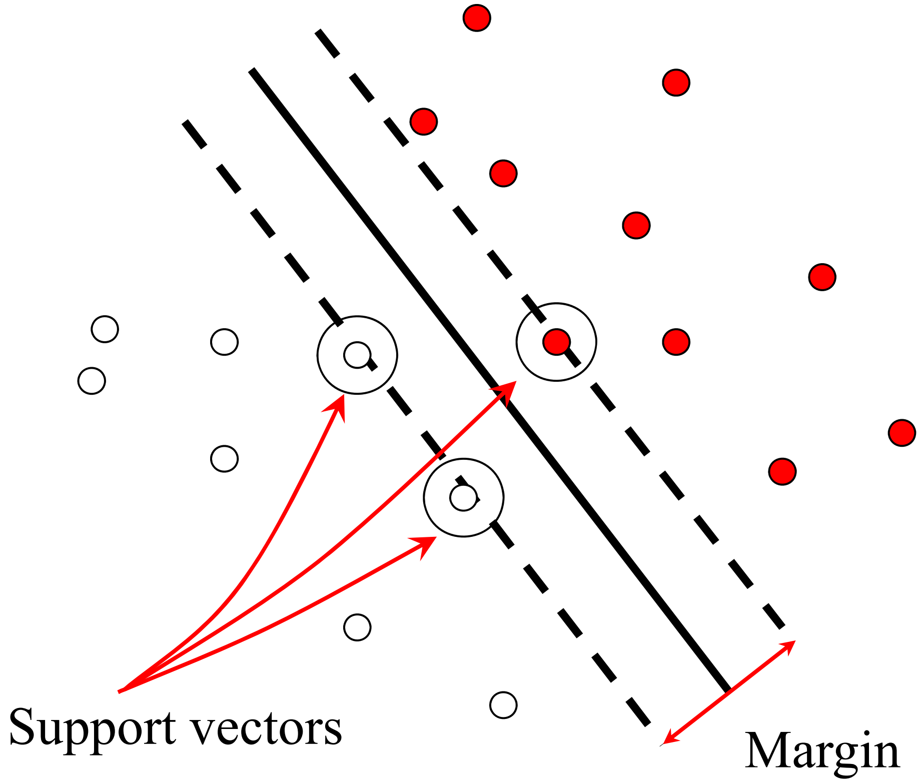


- Better if a margin is introduced:



Support vector machines

- Find hyperplane that maximizes the *margin* between the positive and negative examples



$\mathbf{x}_i$ positive $(y_i = 1)$: $\quad \mathbf{x}_i \cdot \mathbf{w} + b \geq 1$

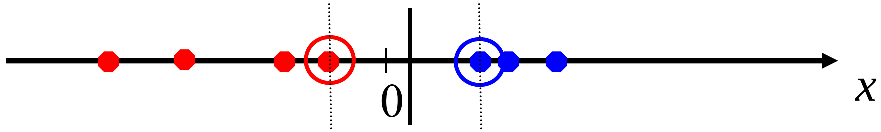
$\mathbf{x}_i$ negative $(y_i = -1)$: $\quad \mathbf{x}_i \cdot \mathbf{w} + b \leq -1$

For support, vectors, $\mathbf{x}_i \cdot \mathbf{w} + b = \pm 1$

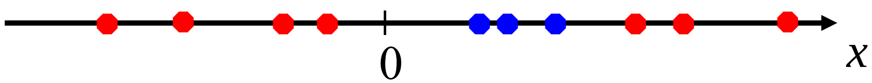
The margin is $2 / ||\mathbf{w}||$

Nonlinear SVMs

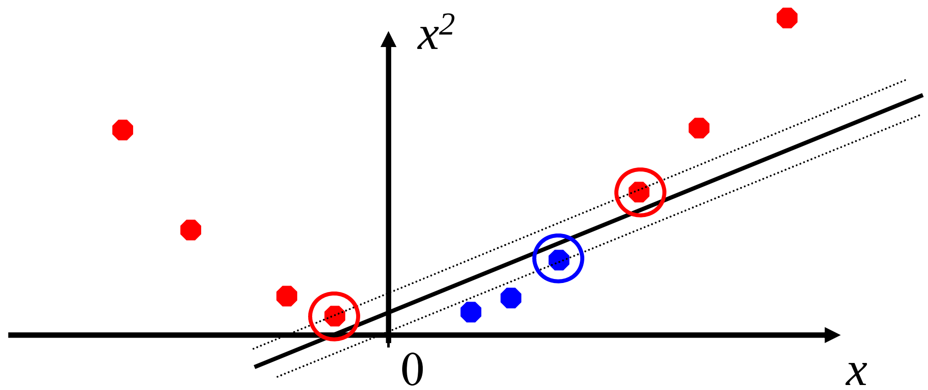
- Datasets that are linearly separable work out great:



- But what if the dataset is just too hard?

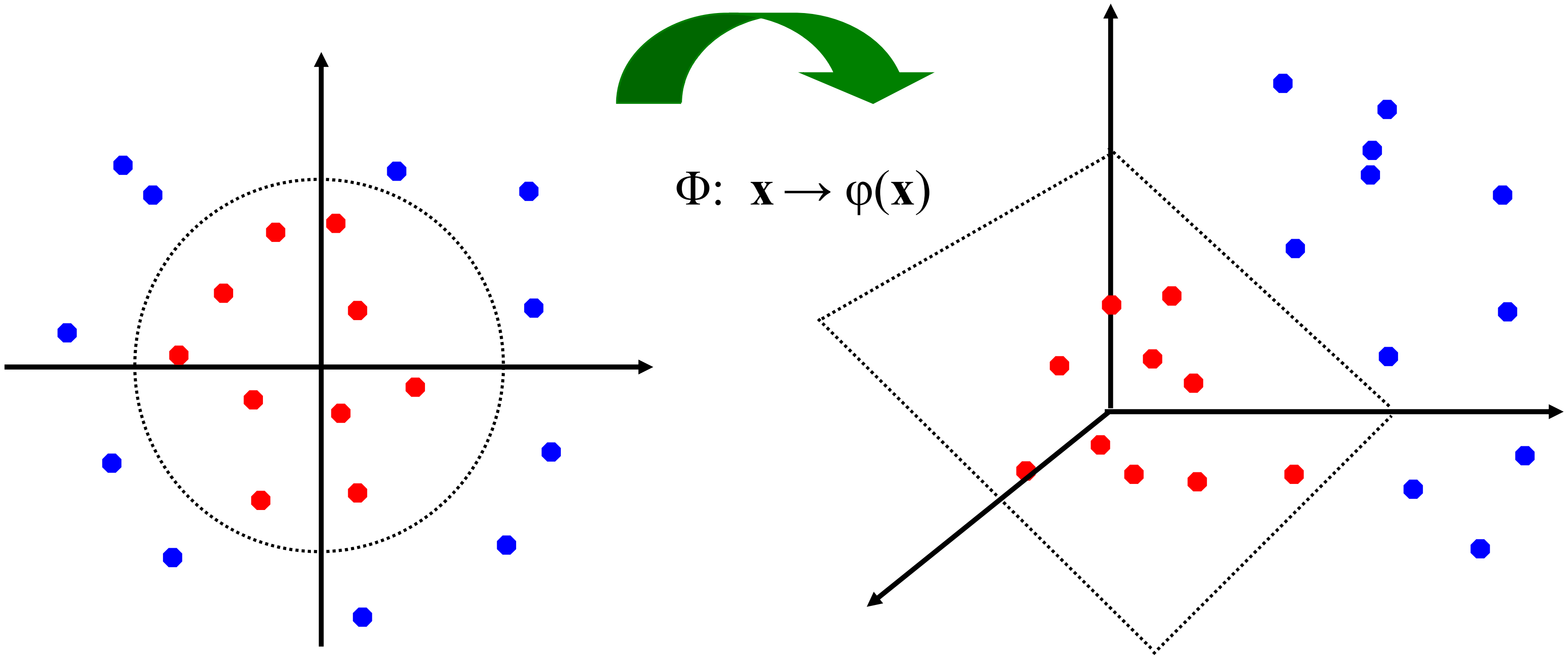


- We can map it to a higher-dimensional space:



Nonlinear SVMs

- General idea: the original input space can always be mapped to some higher-dimensional feature space where the training set is separable:



Nonlinear SVMs

- *The kernel trick*: instead of explicitly computing the lifting transformation $\boldsymbol{\varphi}(\mathbf{x})$, define a kernel function K such that

$$K(\mathbf{x}_i, \mathbf{x}_j) = \boldsymbol{\varphi}(\mathbf{x}_i) \cdot \boldsymbol{\varphi}(\mathbf{x}_j)$$

- This gives a nonlinear decision boundary in the original feature space:

$$\sum_i \alpha_i y_i K(\mathbf{x}_i, \mathbf{x}) + b$$

Kernels for bags of features

- Hellinger kernel $K(h_1, h_2) = \sum_{i=1}^{N} \sqrt{h_1(i) h_2(i)}$

- Histogram intersection kernel $I(h_1, h_2) = \sum_{i=1}^{N} \min(h_1(i), h_2(i))$

- Generalized Gaussian kernel $K(h_1, h_2) = \exp\left(-\frac{1}{A} D(h_1, h_2)^2 \right)$

- *D* can be Euclidean distance, χ^2 distance etc.

$$D_{\chi^2}(h_1, h_2) = \sum_{i=1}^{N} \frac{\left(h_1(i) - h_2(i)\right)^2}{h_1(i) + h_2(i)}$$

Combining features

- SVM with multi-channel chi-square kernel

$$K(H_i, H_j) = \exp\Big(-\sum_{c \in \mathcal{C}} \frac{1}{A_c} D_c(H_i, H_j)\Big)$$

- Channel *c* is a combination of detector, descriptor
- $D_c(H_i, H_j)$ is the chi-square distance between histograms

$$D_c(H_1, H_2) = \frac{1}{2} \sum_{i=1}^{m} [(h_{1i} - h_{2i})^2 / (h_{1i} + h_{2i})]$$

- A_c is the mean value of the distances between all training sample
- Extension: learning of the weights, for example with Multiple Kernel Learning (MKL)

J. Zhang, M. Marszalek, S. Lazebnik and C. Schmid. Local features and kernels for classification of texture and object categories: a comprehensive study, IJCV 2007.

Combining features

- For linear SVMs
  - Early fusion: concatenation the descriptors
  - Late fusion: learning weights to combine the classification scores
- Theoretically no clear winner
- In practice late fusion give better results
  - In particular if different modalities are combined

Multi-class SVMs

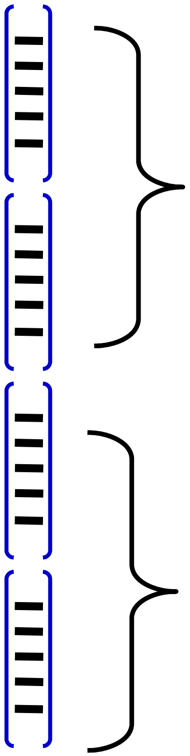
- Various direct formulations exist, but they are not widely used in practice. It is more common to obtain multi-class SVMs by combining two-class SVMs in various ways.

- One versus all:
  – Training: learn an SVM for each class versus the others
  – Testing: apply each SVM to test example and assign to it the class of the SVM that returns the highest decision value

- One versus one:
  – Training: learn an SVM for each pair of classes
  – Testing: each learned SVM "votes" for a class to assign to the test example

Why does SVM learning work?

- Learns foreground and background visual words

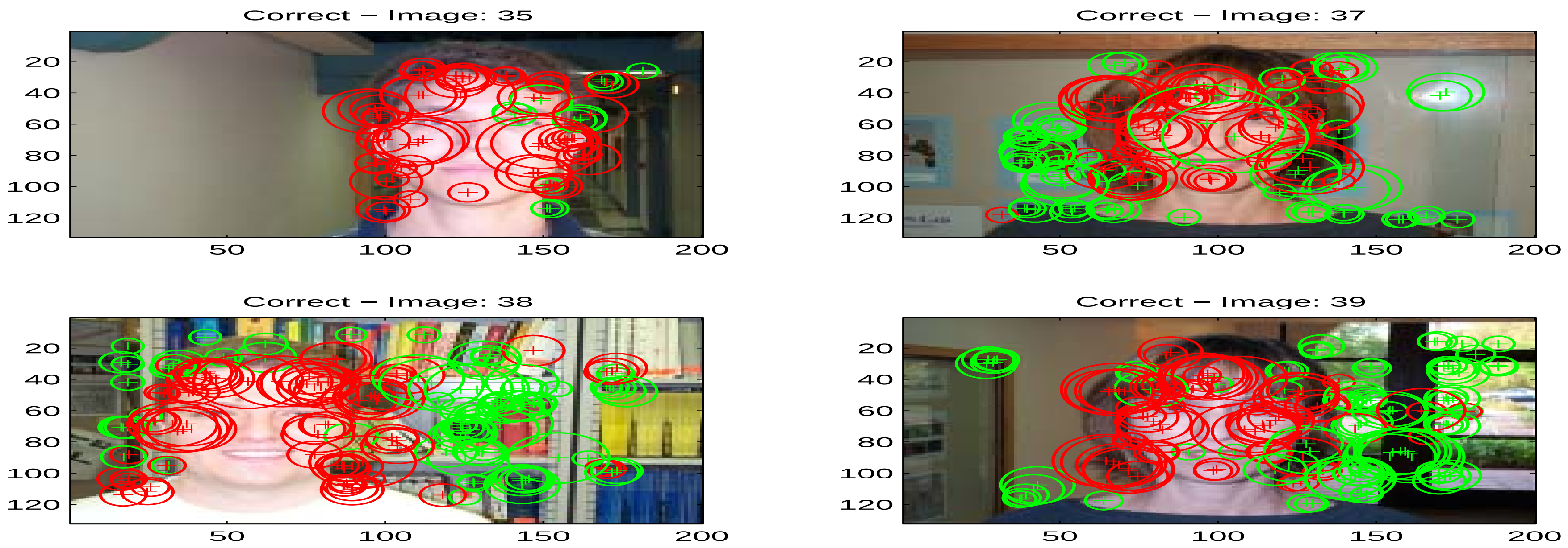


foreground words – high weight

background words – low weight

Illustration

Localization according to visual word probability



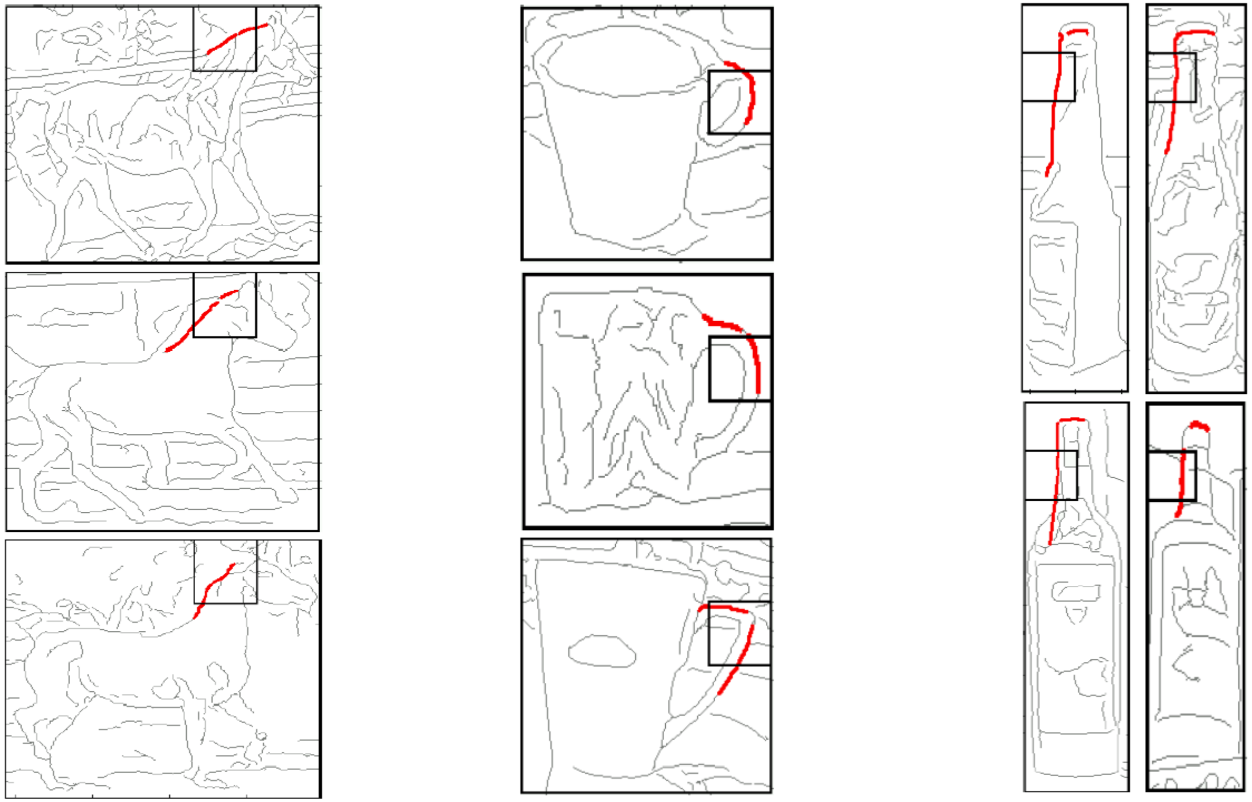
foreground word more probable

background word more probable

Illustration

A linear SVM trained from positive and negative window descriptors

A few of the highest weighed descriptor vector dimensions (= 'PAS + tile')



\+ lie on object boundary (= local shape structures common to many training exemplars)

Bag-of-features for image classification

- Excellent results in the presence of background clutter

bikes books building cars people phones trees

Examples for misclassified images

Books- misclassified into faces, faces, buildings

Buildings- misclassified into faces, trees, trees

Cars- misclassified into buildings, phones, phones

Bag of visual words summary

- Advantages:
  - largely unaffected by position and orientation of object in image
  - fixed length vector irrespective of number of detections
  - very successful in classifying images according to the objects they contain

- Disadvantages:
  - no explicit use of configuration of visual word positions
  - poor at localizing objects within an image

Evaluation of image classification

- PASCAL VOC [05-10] datasets

- PASCAL VOC 2007
  - Training *and* test dataset available
  - Used to report state-of-the-art results
  - Collected January 2007 from Flickr
  - 500 000 images downloaded and random subset selected
  - 20 classes
  - Class labels per image + bounding boxes
  - 5011 training images, 4952 test images

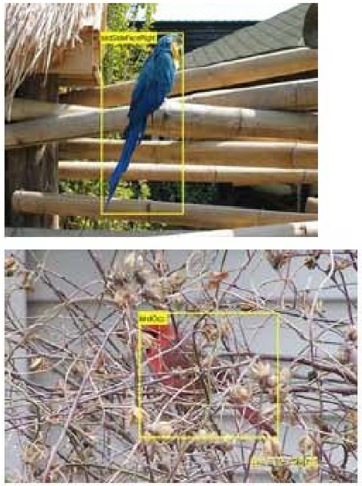
- Evaluation measure: average precision

PASCAL 2007 dataset

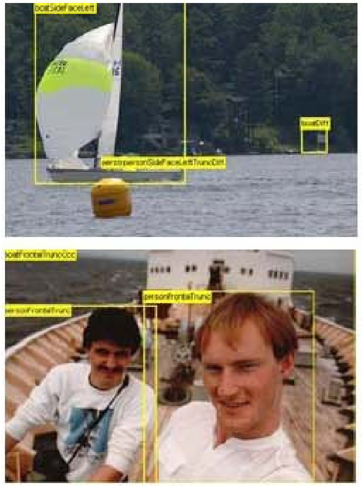
Aeroplane

Bicycle

Bird



Boat



Bottle

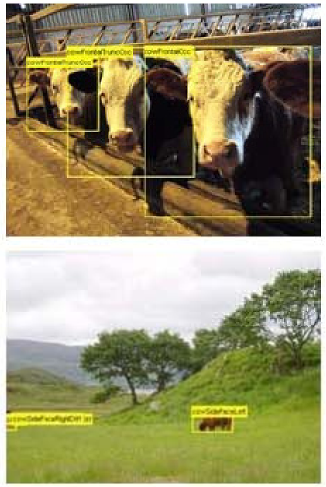
Bus

Car

Cat

Chair

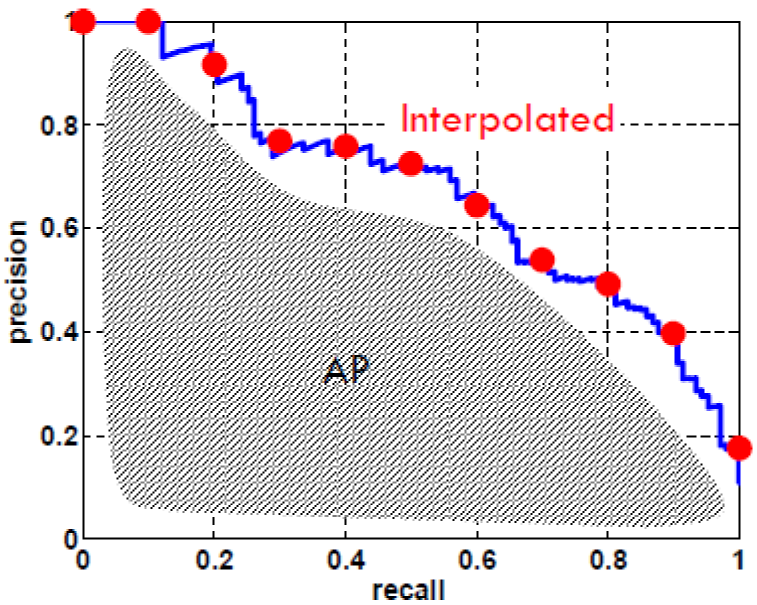
Cow



PASCAL 2007 dataset

Evaluation

- Average Precision [TREC] averages precision over the entire range of recall
  - Curve interpolated to reduce influence of "outliers"

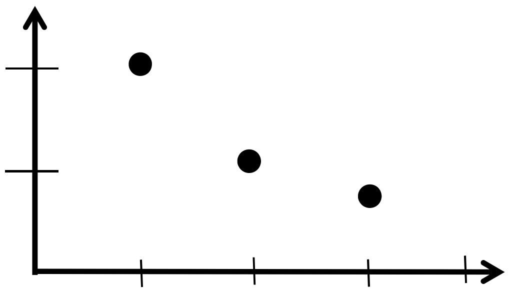


- A good score requires both high recall and high precision
- Application-independent
- Penalizes methods giving high precision but low recall

Precision/Recall

- Ranked list for category A :

A, C, B, A, B, C, C, A ; in total four images with category A



Results for PASCAL 2007

- Winner of PASCAL 2007 [Marszalek et al.] : mAP 59.4
  - Combination of several different channels (dense + interest points, SIFT + color descriptors, spatial grids)
  - Non-linear SVM with Gaussian kernel
- Multiple kernel learning [Yang et al. 2009] : mAP 62.2
  - Combination of several features
  - Group-based MKL approach
- Combining object localization and classification [Harzallah et al.'09] : mAP 63.5
  - Use detection results to improve classification
- Adding objectness boxes [Sanchez at al.'12] : mAP 66.3

Spatial pyramid matching

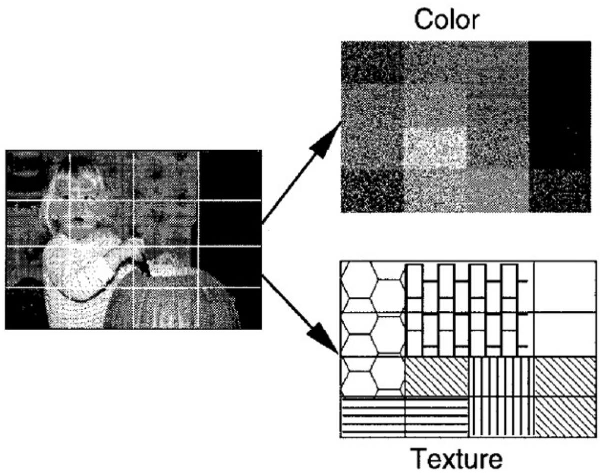
- Add spatial information to the bag-of-features
- Perform matching in 2D image space

[Lazebnik, Schmid & Ponce, CVPR 2006]

Related work

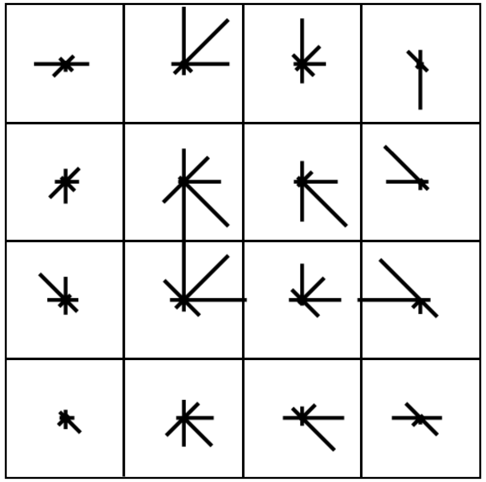
Similar approaches:

- Subblock description [Szummer & Picard, 1997]
- SIFT [Lowe, 1999]
- GIST [Torralba et al., 2003]



Szummer & Picard (1997)

SIFT



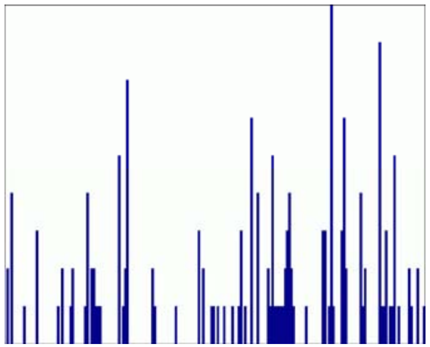
Lowe (1999, 2004)

Gist

Torralba et al. (2003)

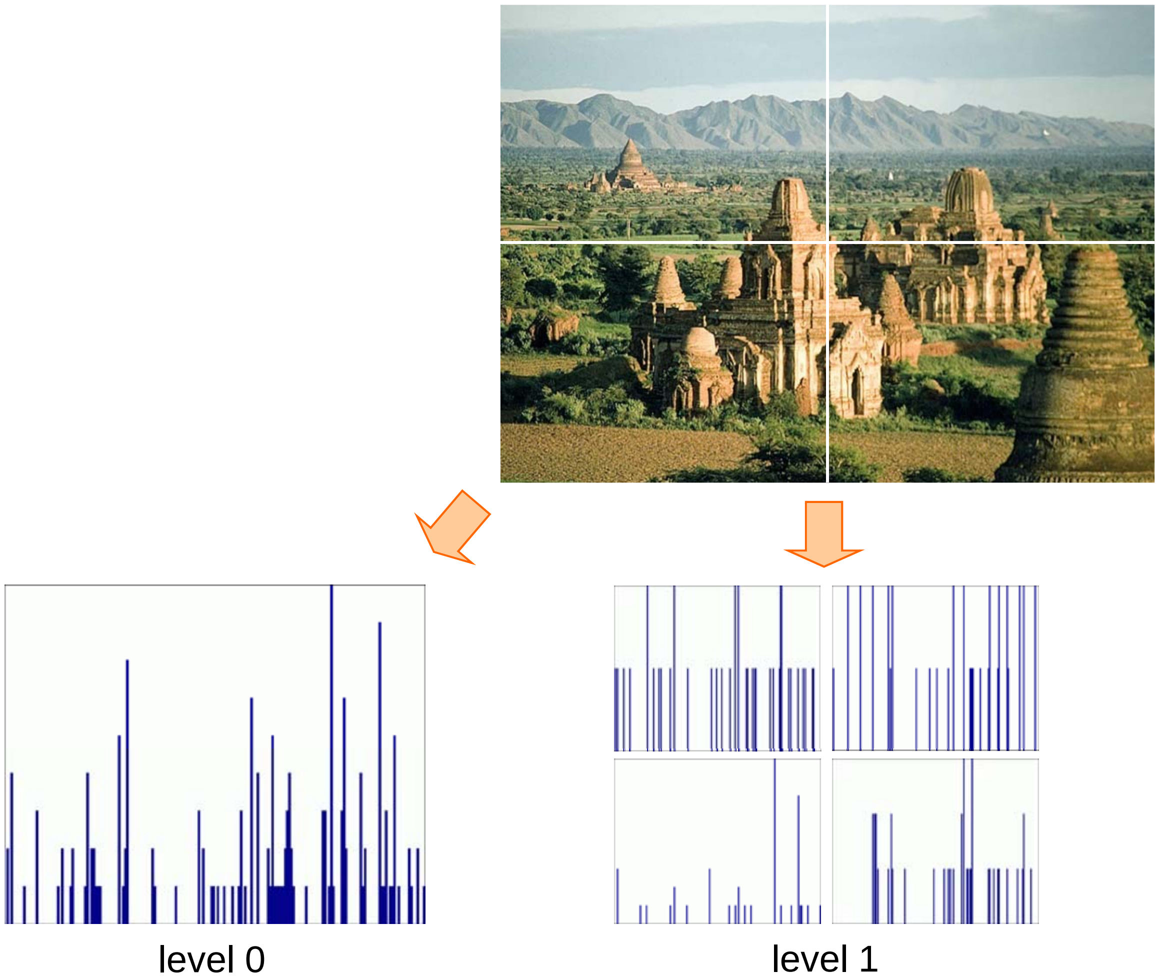
Spatial pyramid representation

Locally orderless representation at several levels of spatial resolution



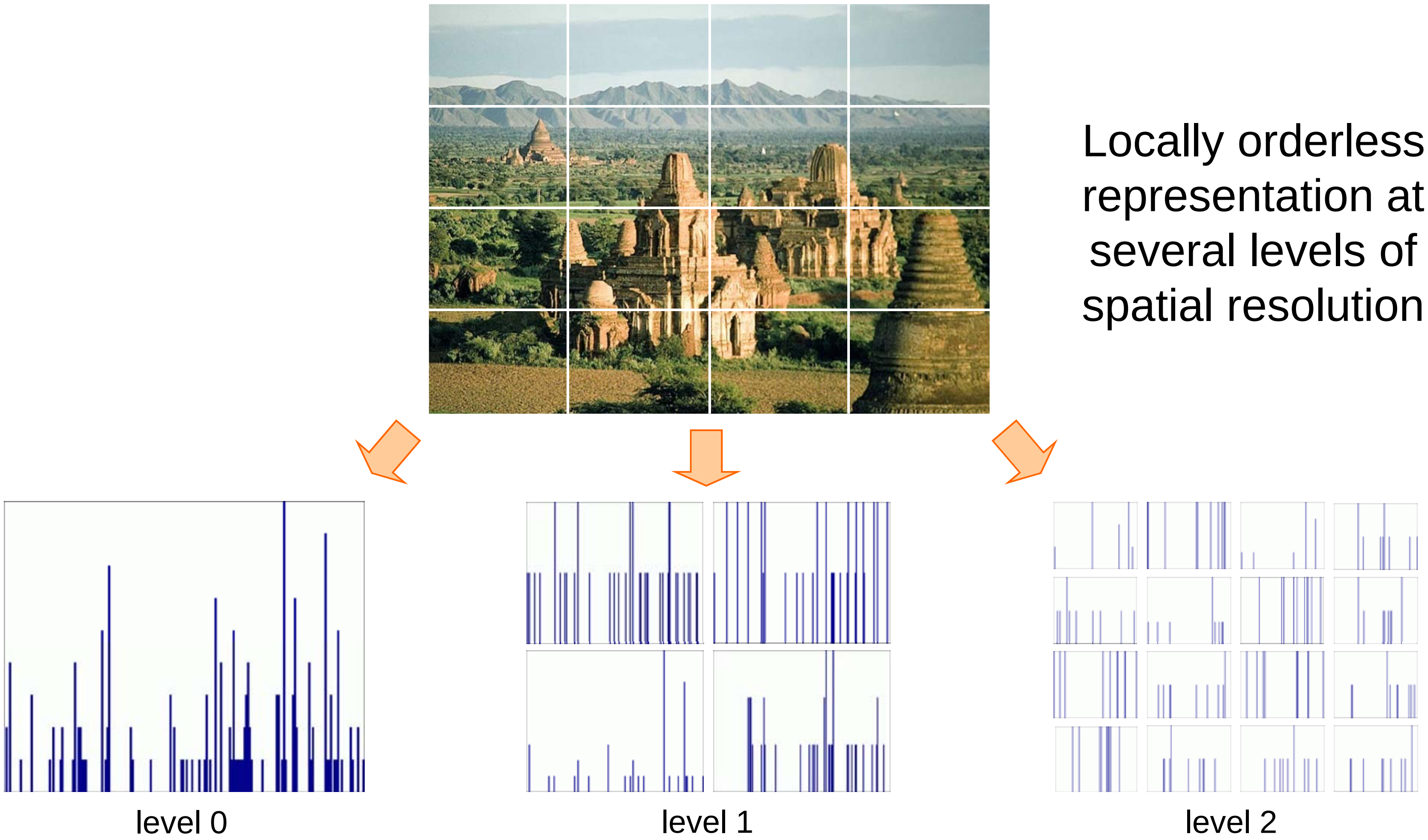
level 0

Spatial pyramid representation



Locally orderless representation at several levels of spatial resolution

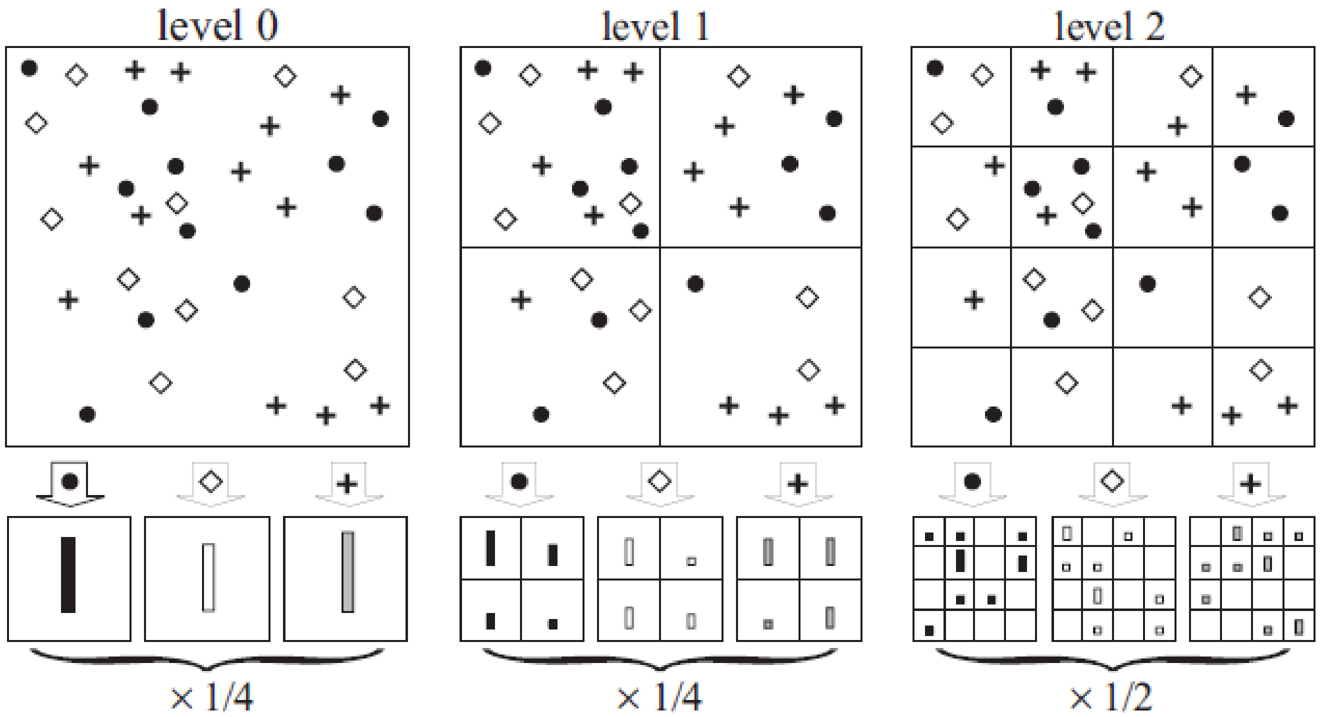
Spatial pyramid representation



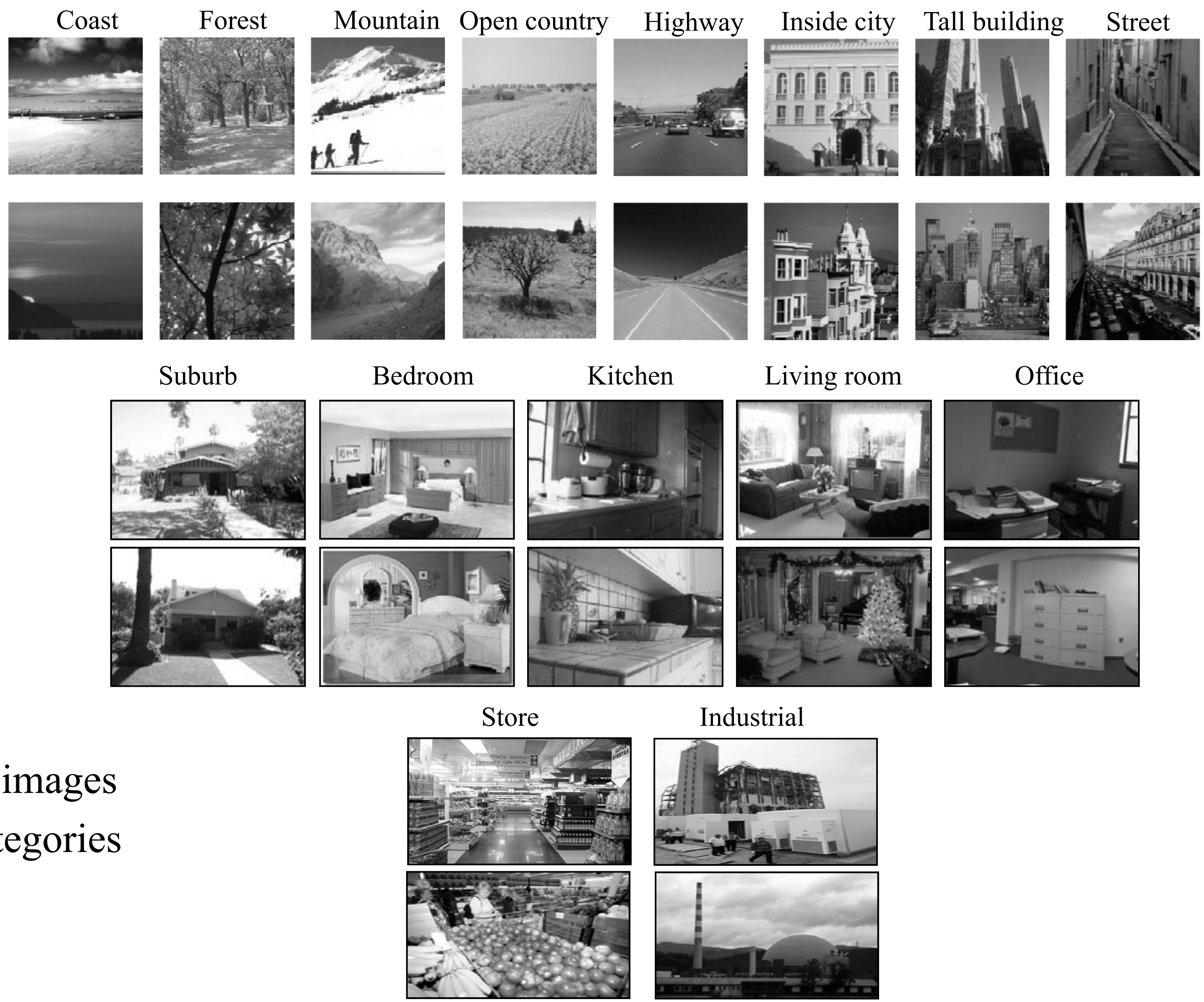
Locally orderless representation at several levels of spatial resolution

Spatial pyramid matching

- Combination of spatial levels with pyramid match kernel [Grauman & Darell'05]
- Intersect histograms, more weight to finer grids



Scene dataset [Labzenik et al.’06]



4385 images

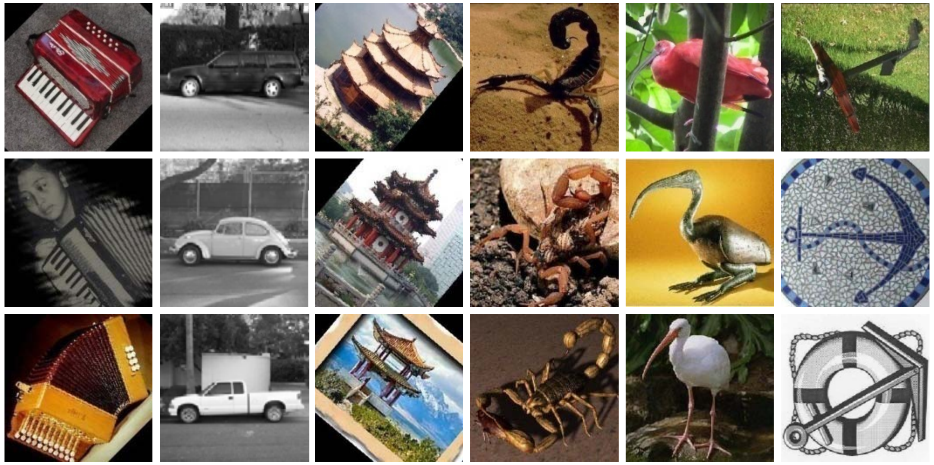
15 categories

Scene classification

L	Single-level	Pyramid
0(1x1)	72.2±0.6	
1(2x2)	77.9±0.6	79.0 ±0.5
2(4x4)	79.4±0.3	*81.1 ±0.3*
3(8x8)	77.2±0.4	80.7 ±0.3

Retrieval examples

Category classification – CalTech101

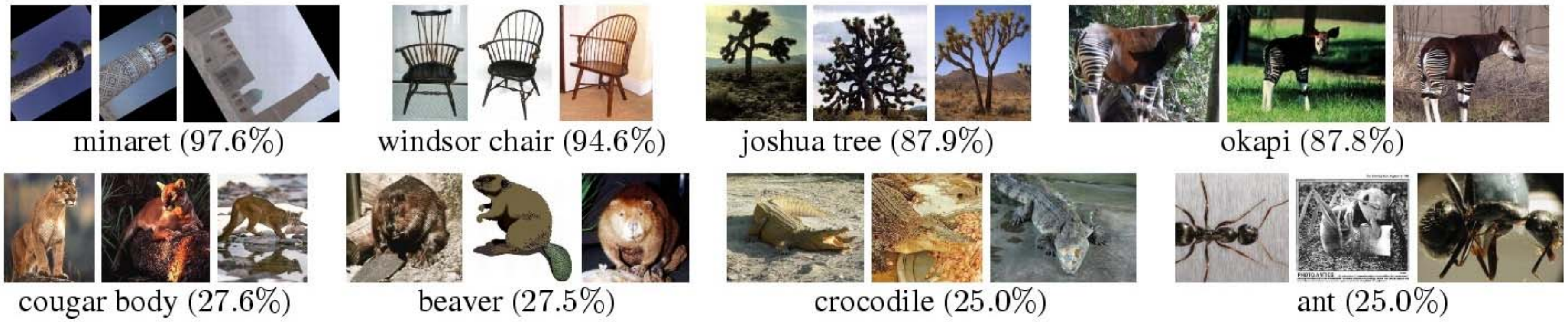


L	Single-level	Pyramid
0(1x1)	41.2±1.2	
1(2x2)	55.9±0.9	57.0 ±0.8
2(4x4)	63.6±0.9	*64.6 ±0.8*
3(8x8)	60.3±0.9	64.6 ±0.7

Bag-of-features approach by Zhang et al.’07: 54 %

CalTech101

Easiest and hardest classes



- Sources of difficulty:
  - Lack of texture
  - Camouflage
  - Thin, articulated limbs
  - Highly deformable shape

Evaluation BoF – spatial

Image classification results on PASCAL'07 train/val set

(SH, Lap, MSD) x (SIFT,SIFTC) spatial layout	AP
1	0.53
2x2	
3x1	
1,2x2,3x1	

Evaluation BoF – spatial

Image classification results on PASCAL'07 train/val set

(SH, Lap, MSD) x (SIFT,SIFTC) spatial layout	AP
1	0.53
2x2	0.52
3x1	0.52
1,2x2,3x1	0.54

Spatial layout not dominant for PASCAL'07 dataset

Combination improves average results, i.e., it is appropriate for some classes

Evaluation BoF - spatial

Image classification results on PASCAL'07 train/val set for individual categories

	1	3x1
Sheep	**0.339**	0.256
Bird	**0.539**	0.484
DiningTable	0.455	**0.502**
Train	0.724	**0.745**

Results are category dependent!

➔ Combination helps somewhat

Discussion

- Summary
  - Spatial pyramid representation: appearance of local image patches + coarse global position information
  - Substantial improvement over bag of features
  - Depends on the similarity of image layout

- Recent extensions
  - Flexible, object-centered grid
    - Shape masks [Marszalek'12] => additional annotations
  - Weakly supervised localization of objects
    - [Russakovsky et al.'12]

Recent extensions

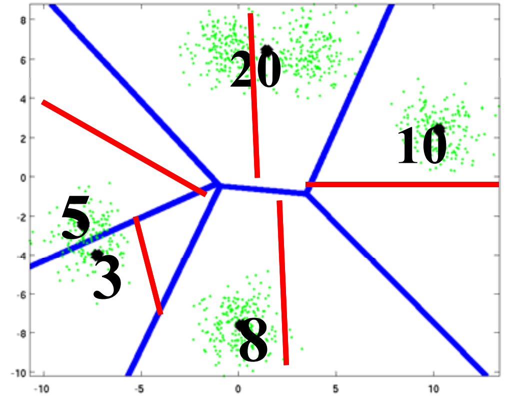
- Linear Spatial Pyramid Matching Using Sparse Coding for Image Classification. J. Yang et al., CVPR’09.
  - Local coordinate coding, linear SVM, excellent results in 2009 PASCAL challenge
- Learning Mid-level features for recognition, Y. Boureau et al., CVPR’10.
  - Use of sparse coding techniques and max pooling

Recent extensions

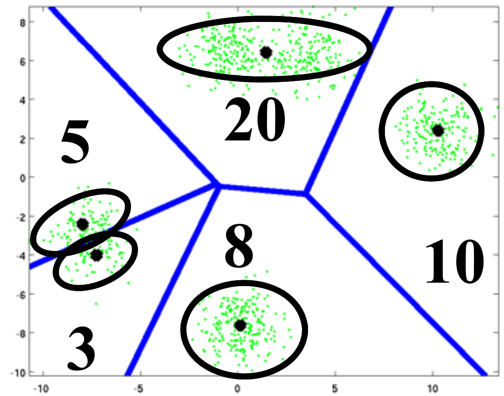
- Efficient Additive Kernels via Explicit Feature Maps, A. Vedaldi and Zisserman, CVPR'10.
  - approximation by linear kernels
- Improving the Fisher Kernel for Large-Scale Image Classification, Perronnin et al., ECCV'10
  - More discriminative descriptor, power normalization, linear SVM
- Excellent results of the Fisher vector in a recent evaluation, Chatfield et al. BMVC 2011

Fisher vector image representation

- Mixture of Gaussian/ k-means stores nr of points per cell



- Fisher vector adds 1st & 2nd order moments
  - More precise description of regions assigned to cluster
  - Fewer clusters needed for same accuracy
  - Per cluster store: mean and variance of data in cell
  - Representation 2D times larger, at same computational cost
  - High dimensional, robust representation



Fisher vector image representation

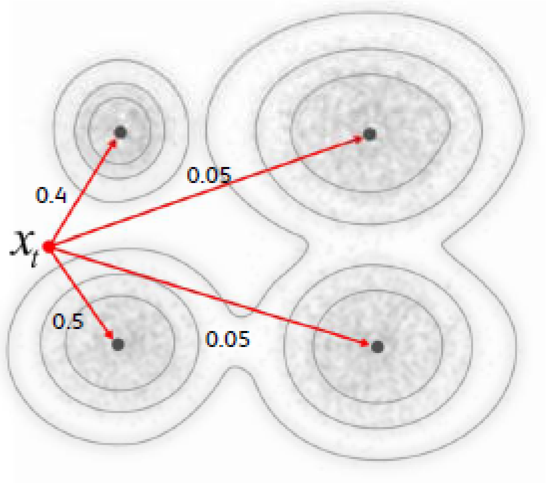
$X = \{x_t, t = 1 \ldots T\}$ is the set of T i.i.d. D-dim local descriptors (e.g. SIFT) extracted from an image:

$u_\lambda(x) = \sum_{i=1}^{K} w_i u_i(x)$ is a Gaussian Mixture Model (GMM) with parameters $\lambda = \{w_i, \mu_i, \Sigma_i, i = 1 \ldots N\}$ trained on a large set of local descriptors: a **visual vocabulary**

FV formulas:

$$\mathcal{G}_{\mu,i}^{X} = \frac{1}{T\sqrt{w_i}} \sum_{t=1}^{T} \gamma_t(i) \left(\frac{x_t - \mu_i}{\sigma_i} \right)$$

$$\mathcal{G}_{\sigma,i}^{X} = \frac{1}{T\sqrt{2w_i}} \sum_{t=1}^{T} \gamma_t(i) \left[\frac{(x_t - \mu_i)^2}{\sigma_i^2} - 1 \right]$$



$\gamma_t(i)$ = soft-assignment of patch x_t to Gaussian i

Relation to BOF

FV formulas:

$$\boxed{\begin{aligned}\mathcal{G}^X_{\mu,i} &= \frac{1}{T\sqrt{w_i}}\sum_{t=1}^{T}\gamma_t(i)\left(\frac{x_t-\mu_i}{\sigma_i}\right)\\ \mathcal{G}^X_{\sigma,i} &= \frac{1}{T\sqrt{2w_i}}\sum_{t=1}^{T}\gamma_t(i)\left[\frac{(x_t-\mu_i)^2}{\sigma_i^2}-1\right]\end{aligned}}$$

Soft BOV formula:

$\frac{1}{T}\sum_{t=1}^{T}\gamma_t(i)$

Like the (original) BOV the FV is an average of local statistics.

The FV extends the BOV and includes higher-order statistics (up to 2nd order)

Results on VOC 2007: BOV = 43.6 % $\rightarrow$ FV = 57.7 % $\rightarrow$ √FV = 62.1 %

Large-scale image classification

- Image classification: assigning a class label to the image

Car: present
Cow: present
Bike: not present
Horse: not present
...

- What makes it large-scale?
  - number of images
  - number of classes
  - dimensionality of descriptor

IMAGENET has 14M images from 22k classes

Large-scale image classification

- Image descriptors
  - Fisher vector (high dimensional)
  - Normalization: square-rooting or latent MOG+ L2 normalization

    [Image categorization using Fisher kernels of non-iid image models, Cinbis, Verbeek, Schmid, CVPR'12] [Perronnin'10]

- Classification approach
  - Linear classifiers
  - One versus rest classifier
  - Stochastic gradient descent optimization

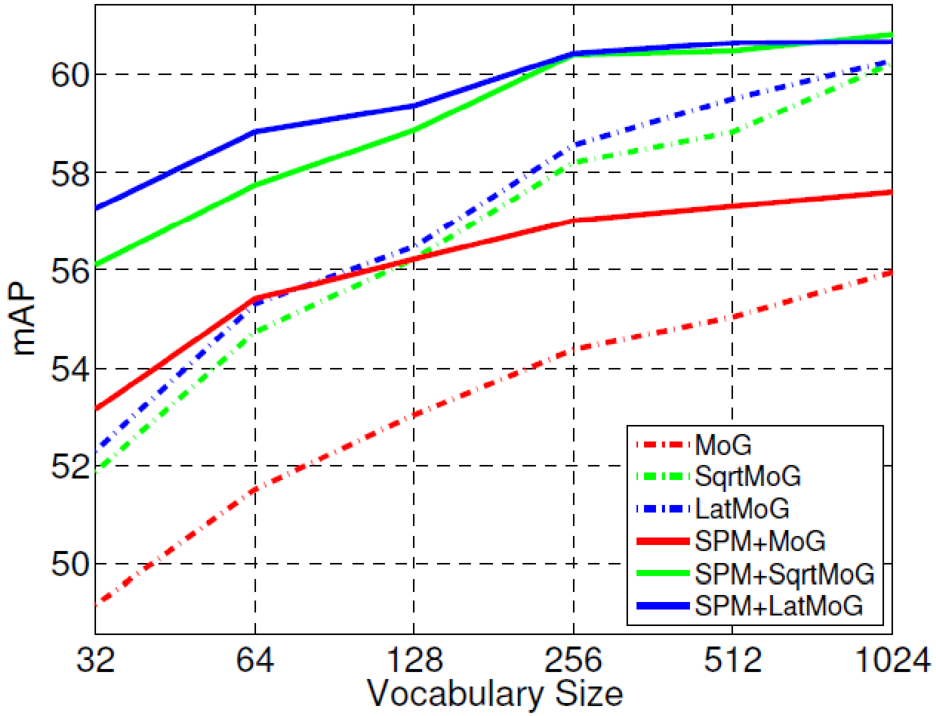
    [Towards good practice in large-scale learning for image classification, Perronnin, Akata, Harchaoui, Schmid, CVPR'12]

Evaluation image description

- Comparing on PASCAL VOC'07 linear classifiers with
  - Fisher vector
  - Sqrt transformation of Fisher vector
  - Latent GMM of Fisher vector

- Sqrt transform + latent MOG models lead to improvement

- State-of-the-art performance obtained with linear classifier



Evaluation image description

Fisher versus BOF vector + linear classifier on Pascal Voc'07

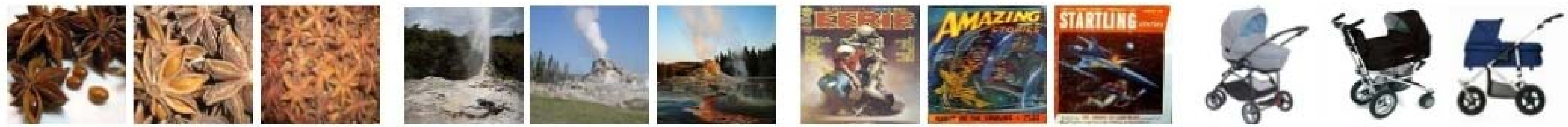
SPM	Method	64	128	256	512	1024
No	BoW	20.1	29.0	36.2	40.7	44.1
No	SqrtBoW	21.0	29.5	37.4	**41.3**	**46.1**
No	LatBoW	**22.9**	**30.1**	**38.9**	41.2	44.5
Yes	BoW	37.1	40.1	42.4	46.4	48.9
Yes	SqrtBoW	37.8	41.2	44.6	47.8	51.6
Yes	LatBoW	**39.3**	**41.7**	**45.3**	**48.7**	**52.2**

SPM	Method	32	64	128	256	512	1024
No	MoG	49.2	51.5	53.0	54.4	55.0	55.9
No	SqrtMoG	51.9	54.7	56.2	58.2	58.8	60.2
No	LatMoG	**52.3**	**55.3**	**56.5**	**58.6**	**59.5**	**60.3**
Yes	MoG	53.2	55.4	56.2	57.0	57.3	57.6
Yes	SqrtMoG	56.1	57.7	58.9	**60.4**	60.5	**60.8**
Yes	LatMoG	**57.3**	**58.8**	**59.4**	**60.4**	**60.6**	60.7

- Fisher improves over BOF
- Fisher comparable to BOF + non-linear classifier
- Limited gain due to SPM on PASCAL
- Sqrt helps for Fisher and BOF

Experimental results on ImageNet

- Datasets
  - ImageNet Large Scale Visual Recognition Challenge 2010 (ILSVRC)
    - 1000 classes and 1.4M images
  - ImageNet10K dataset
    - 10184 classes and ~ 9 M images



(a) Star Anise (92.45%) (b) Geyser (85.45%) (c) Pulp Magazine (83.01%) (d) Carrycot (81.48%)

(e) European gallinule (15.00%) (f) Sea Snake (10.00 %) (g) Paintbrush (4.68 %) (h) Mountain Tent (0.00%)