Computer Vision 2 – Lecture 4

Tracking by Detection (28.04.2016)

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Visual Computing Institute
Computer Vision
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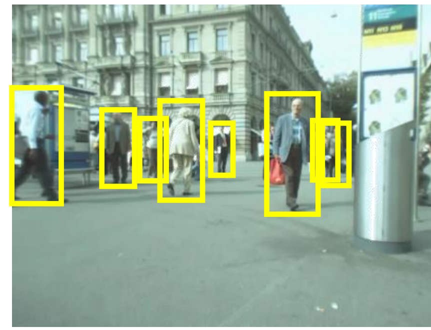
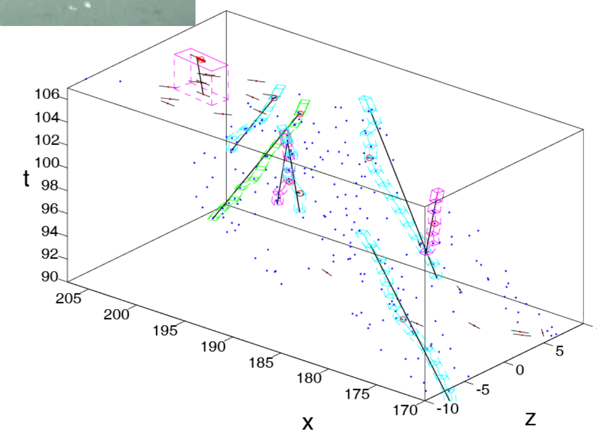
Content of the Lecture

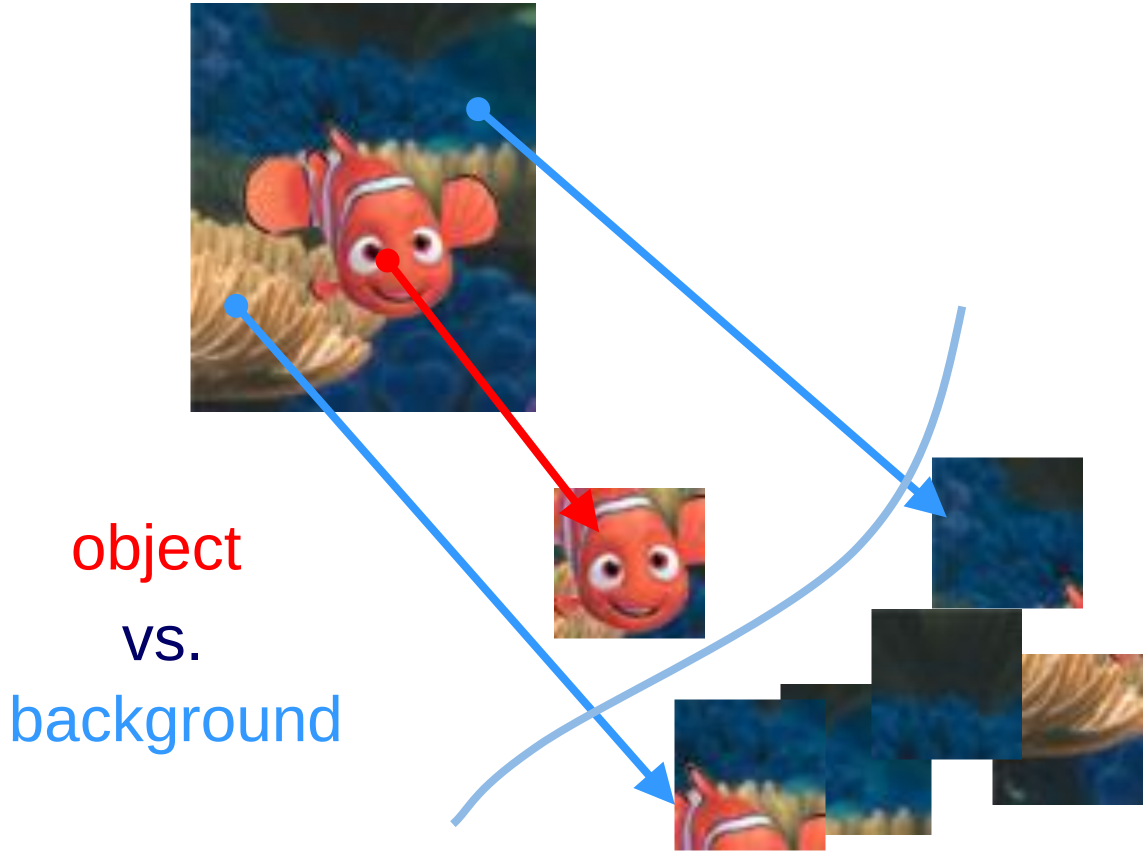
- Single-Object Tracking
  - *Background modeling*
  - Template based tracking
  - *Color based tracking*
  - *Contour based tracking*
  - Tracking by online classification
  - **Tracking-by-detection**
- Bayesian Filtering
- Multi-Object Tracking
- Visual Odometry
- Visual SLAM & 3D Reconstruction





Recap: Tracking as Online Classification

- Tracking as binary classification problem



Slide credit: Helmut Grabner

Image source: Disney/Pixar

Recap: Tracking as Online Classification

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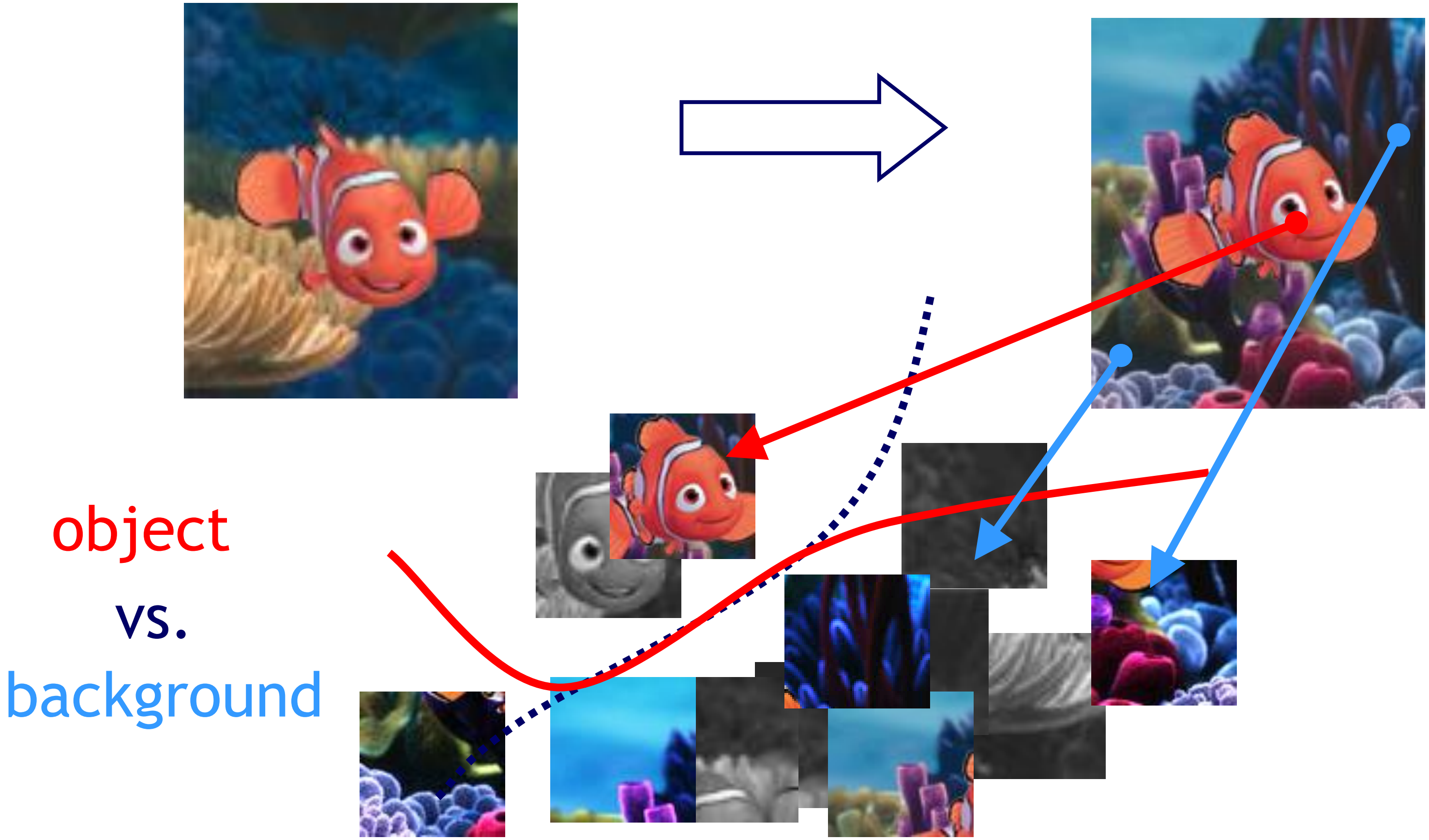


  - Handle object <u>and</u> background changes by **online updating**

Slide credit: Helmut Grabner

Image source: Disney/Pixar

Recap: AdaBoost – "Adaptive Boosting"

- Main idea [Freund & Schapire, 1996]
  - Iteratively select an ensemble of classifiers
  - Reweight misclassified training examples after each iteration to focus training on difficult cases.
- Components
  - $h_m(\mathbf{x})$: "weak" or base classifier
    - Condition: <50% training error over any distribution
  - $H(\mathbf{x})$: "strong" or final classifier
- AdaBoost:
  - Construct a strong classifier as a thresholded linear combination of the weighted weak classifiers:

$$H(\mathbf{x}) = sign\left(\sum_{m=1}^{M} \alpha_m h_m(\mathbf{x})\right)$$

Recap: AdaBoost – Algorithm

1. Initialization: Set $w_n^{(1)} = \frac{1}{N}$ for $n = 1,\ldots,N$.
2. For $m = 1,\ldots,M$ iterations
   a) Train a new weak classifier $h_m(\mathbf{x})$ using the current weighting coefficients $\mathbf{W}^{(m)}$ by minimizing the weighted error function
   $$J_m = \sum_{n=1}^{N} w_n^{(m)} I(h_m(\mathbf{x}) \neq t_n)$$
   $$I(A) = \begin{cases} 1, & \text{if } A \text{ is true} \\ 0, & \text{else} \end{cases}$$
   b) Estimate the weighted error of this classifier on $\mathbf{X}$:
   $$\epsilon_m = \frac{\sum_{n=1}^{N} w_n^{(m)} I(h_m(\mathbf{x}) \neq t_n)}{\sum_{n=1}^{N} w_n^{(m)}}$$
   c) Calculate a weighting coefficient for $h_m(\mathbf{x})$:
   $$\alpha_m = \ln\left\{\frac{1-\epsilon_m}{\epsilon_m}\right\}$$
   d) Update the weighting coefficients:
   $$w_n^{(m+1)} = w_n^{(m)} \exp\left\{\alpha_m I(h_m(\mathbf{x}_n) \neq t_n)\right\}$$

From Offline to Online Boosting

- Main issue
  - Computing the weight distribution for the samples.
  - We do not know a priori the difficulty of a sample!
    (Could already have seen the same sample before...)
- Idea of Online Boosting
  - Estimate the importance of a sample by propagating it through a set of weak classifiers.
  - This can be thought of as modeling the information gain w.r.t. the first n classifiers and code it by the importance weight λ for the $n+1$ classifier.
  - Proven [Oza]: Given the same training set, Online Boosting converges to the same weak classifiers as Offline Boosting in the limit of $N \to \infty$ iterations.

N. Oza and S. Russell. Online Bagging and Boosting.
Artificial Intelligence and Statistics, 2001.

Recap: From Offline to Online Boosting

off-line

Given:

- set of labeled training samples
$\mathcal{X} = \{\langle \mathbf{x_1}, y_1 \rangle, ..., \langle \mathbf{x_L}, y_L \rangle \mid y_i \pm 1\}$
- weight distribution over them
$D_0 = 1/L$

for n = 1 to N

- train a weak classifier using samples and weight dist.

$$h_n^{weak}(\mathbf{x}) = \mathcal{L}(\mathcal{X}, D_{n-1})$$

- calculate error e_n
- calculate weight $\alpha_n = f(e_n)$
- update weight dist. D_n

next

$$h^{strong}(\mathbf{x}) = \mathrm{sign}(\sum_{n=1}^{N} \alpha_n \cdot h_n^{weak}(\mathbf{x}))$$

on-line

Given:

- ONE labeled training sample
$\langle \mathbf{x}, y \rangle \mid y \pm 1$
- strong classifier to update

- initial importance $\lambda = 1$

for n = 1 to N

- update the weak classifier using samples and importance

$$h_n^{weak}(\mathbf{x}) = \mathcal{L}(h_n^{weak}, \langle x, y \rangle, \lambda)$$

- update error estimation $\widehat{e_n}$
- update weight $\alpha_n = f(\widehat{e_n})$
- update importance weight λ

next

$$h^{strong}(\mathbf{x}) = \mathrm{sign}(\sum_{n=1}^{N} \alpha_n \cdot h_n^{weak}(\mathbf{x}))$$

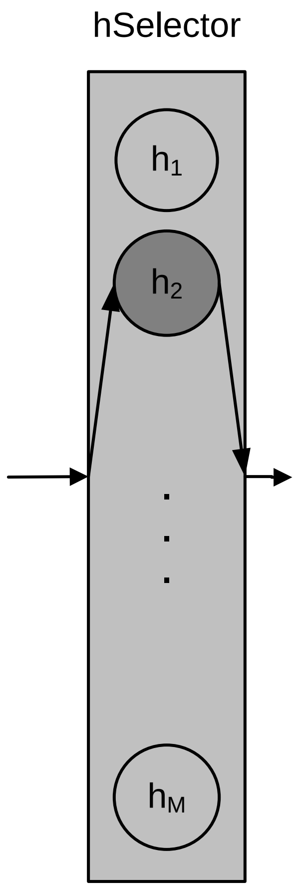
Slide credit: Helmut Grabner

Recap: Online Boosting for Feature Selection

- Introducing "Selector"
  - Selects one feature from its local feature pool

$$\mathcal{H}^{weak} = \{h_1^{weak}, \ldots, h_M^{weak}\}$$
$$\mathcal{F} = \{f_1, \ldots, f_M\}$$

$$h^{sel}(\mathbf{x}) = h_m^{weak}(\mathbf{x})$$
$$m = \arg\min_i e_i$$

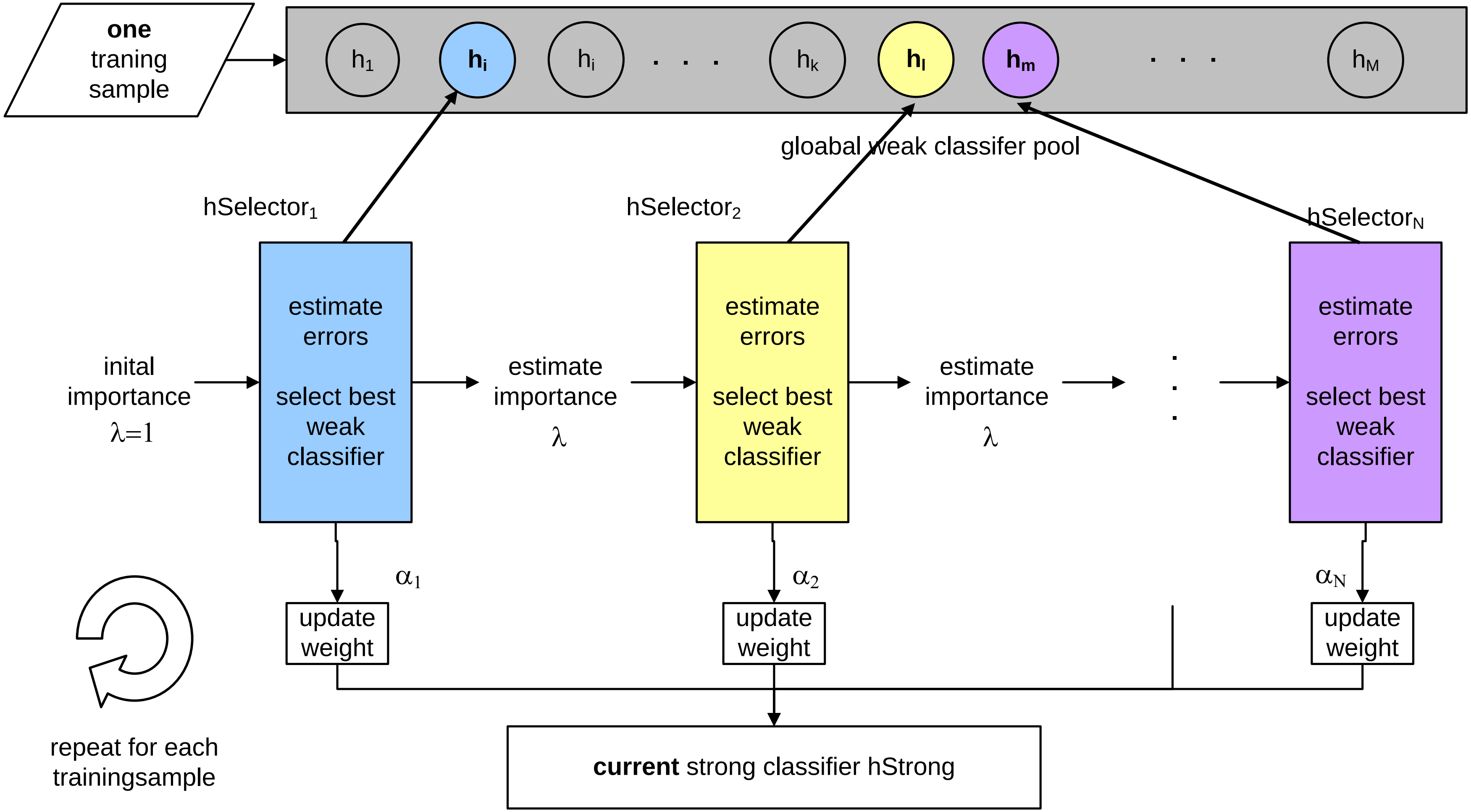


On-line boosting is performed on the Selectors and not on the weak classifiers directly.

H. Grabner and H. Bischof. On-line boosting and vision. CVPR, 2006.

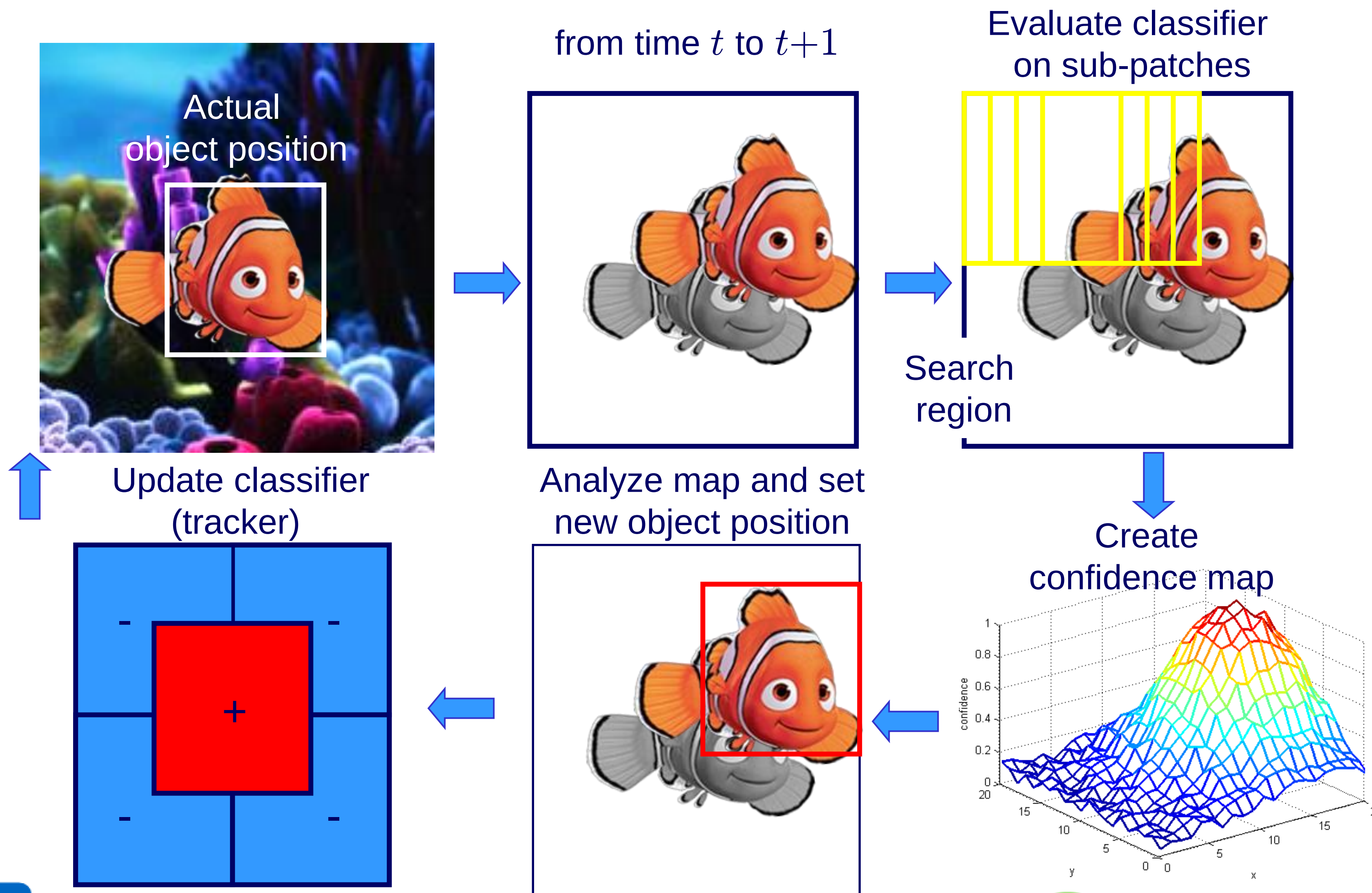
Slide credit: Helmut Grabner

Recap: Direct Feature Selection



Slide credit: Helmut Grabner

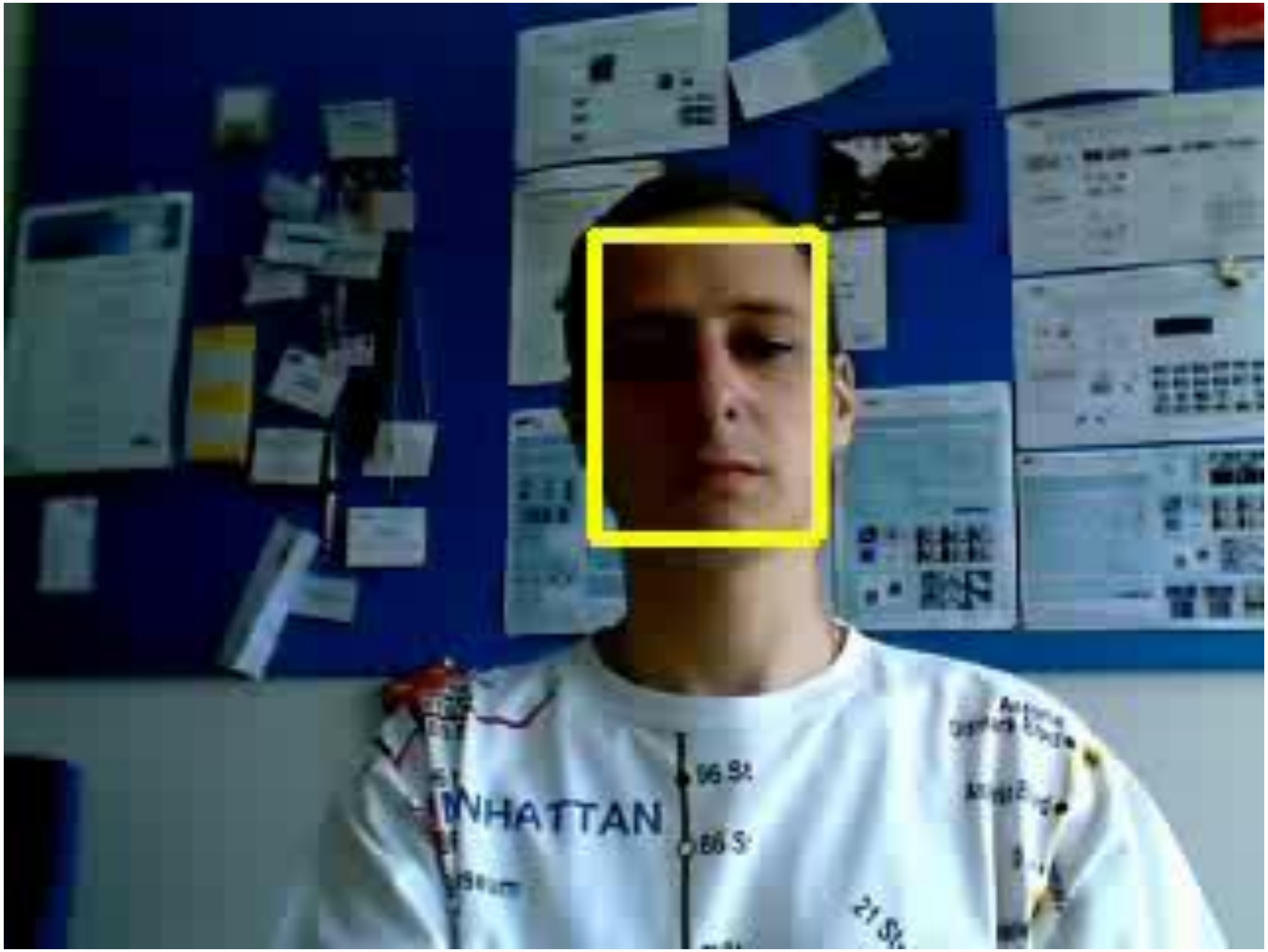
Recap: Tracking by Online Classification



Slide credit: Helmut Grabner

Image source: Disney/Pixar

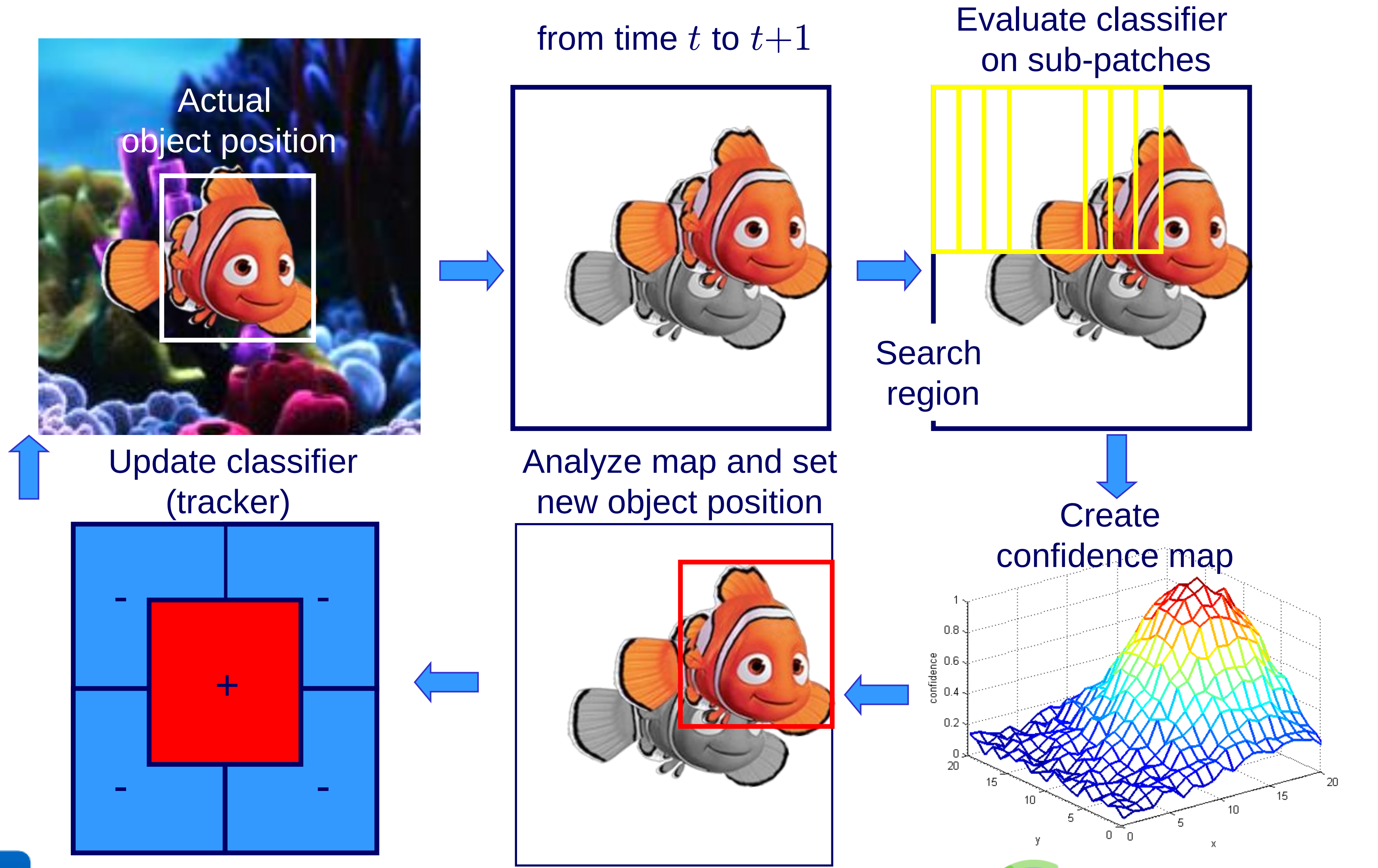
When Does It Fail...



Slide credit: Helmut Grabner

Video source: Grabner et al., ECCV'08

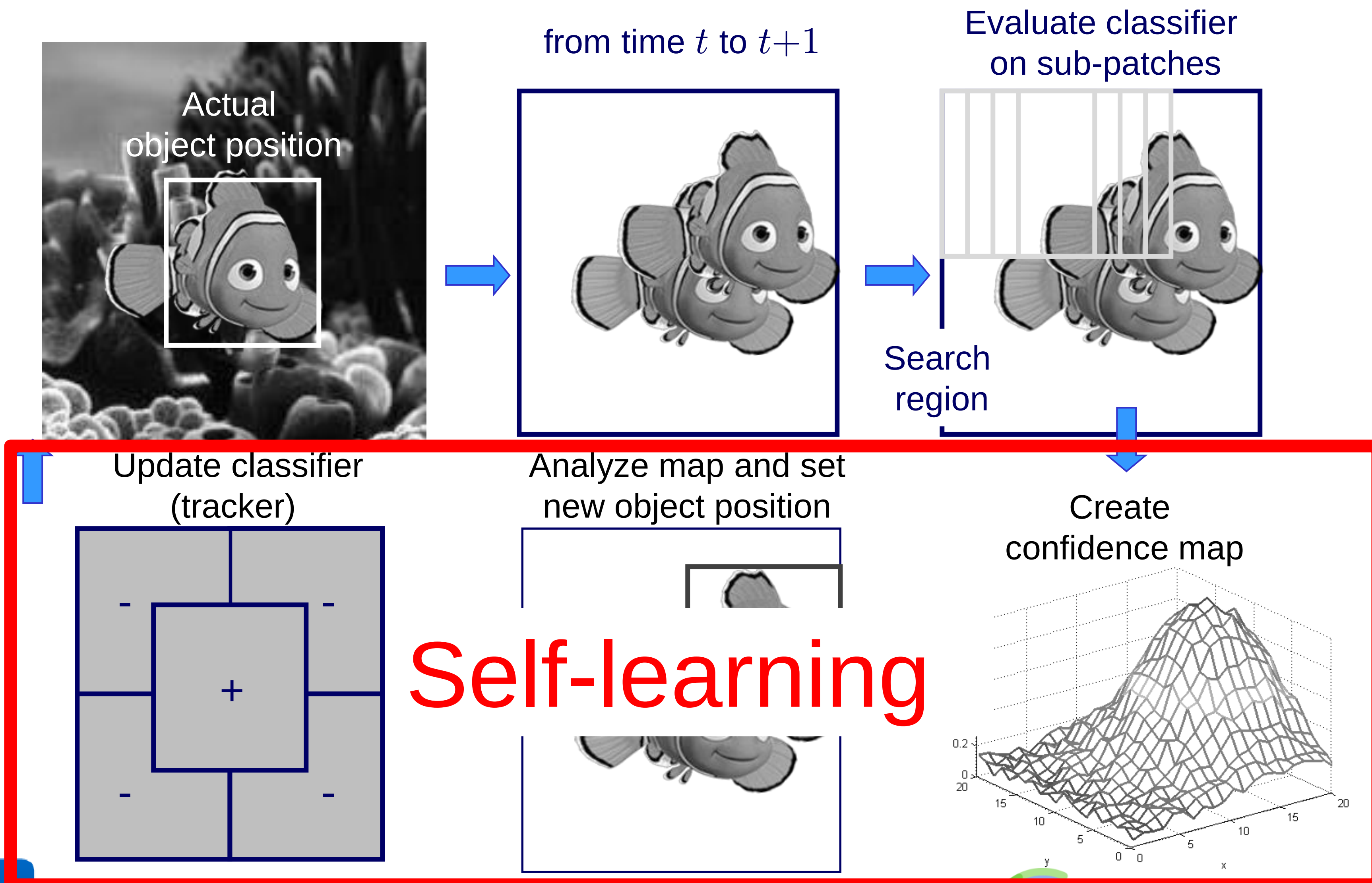
Why Does It Fail?



Slide credit: Helmut Grabner

Image source: Disney/Pixar

Why Does It Fail?

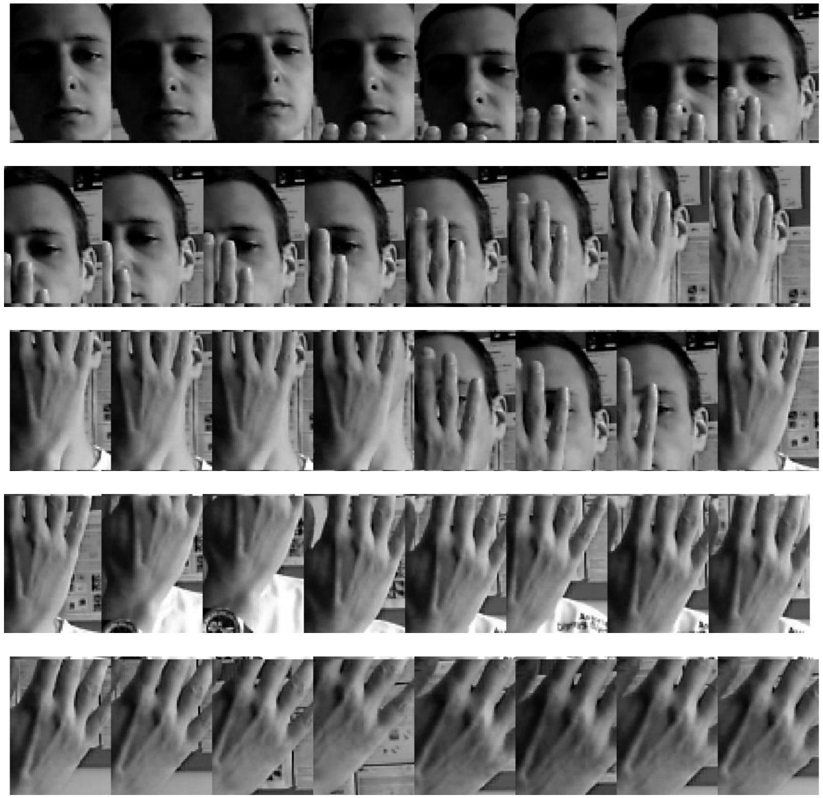


Slide credit: Helmut Grabner

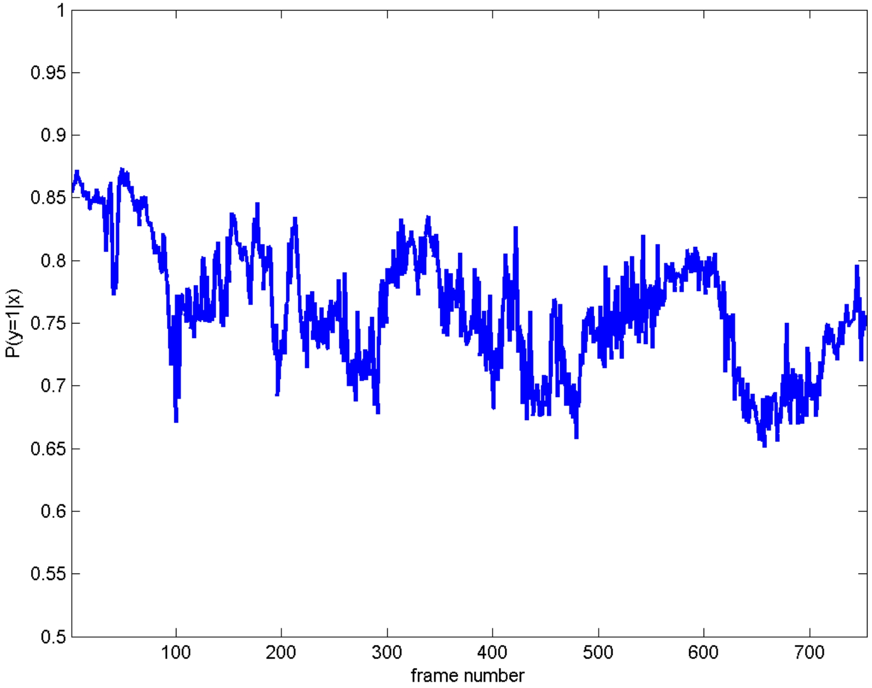
Image source: Disney/Pixar

Drifting Due to Self-Learning Policy

Tracked Patches



Confidence



⇒ Not only does it drift, it also remains confident about it!

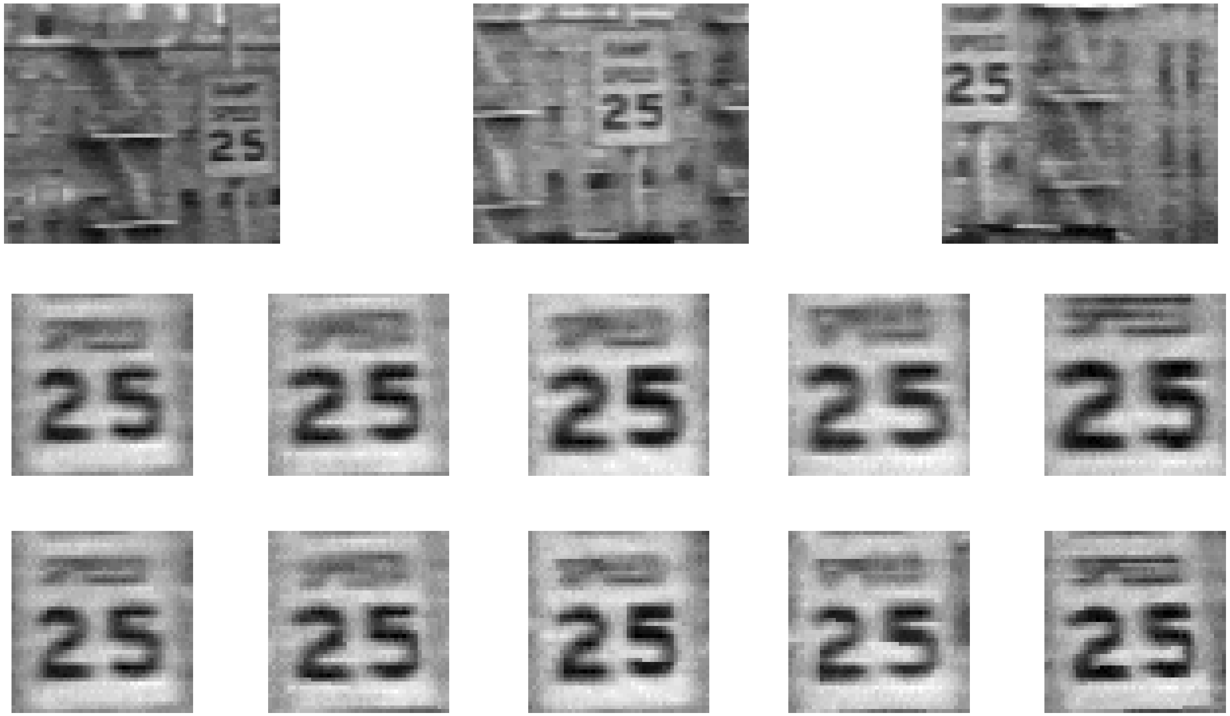
Slide credit: Helmut Grabner

Image source: Grabner et al., ECCV'08

Self-Learning and Drift

- Drift
  - Major problem in all adaptive or self-learning trackers.
  - Difficulty: distinguish “allowed” appearance change due to lighting or viewpoint variation from “unwanted” appearance change due to drifting.
  - Cannot be decided based on the tracker confidence!
    - Since the confidence is always dependent on the learned model
    - Model may already be affected by drift when the confidence is measured.
  - Several approaches have been proposed to address this.

Strategy 1: Match Against Initialization

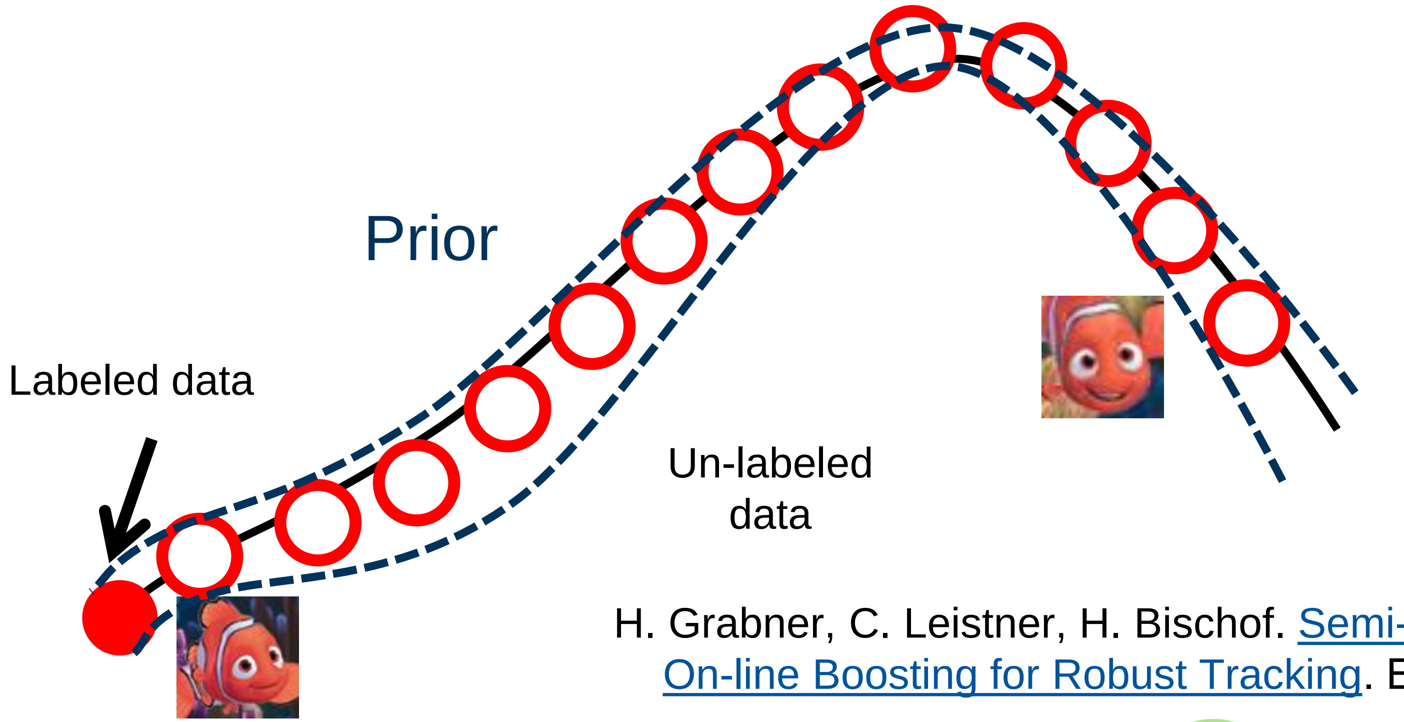


- Used mostly in low-level trackers (e.g., KLT)
  - Advantage: robustly catches drift
  - Disadvantage: cannot follow appearance changes

J. Shi and C. Tomasi. Good Features to Track. CVPR 1994.

Strategy 2: Semi-Supervised Learning

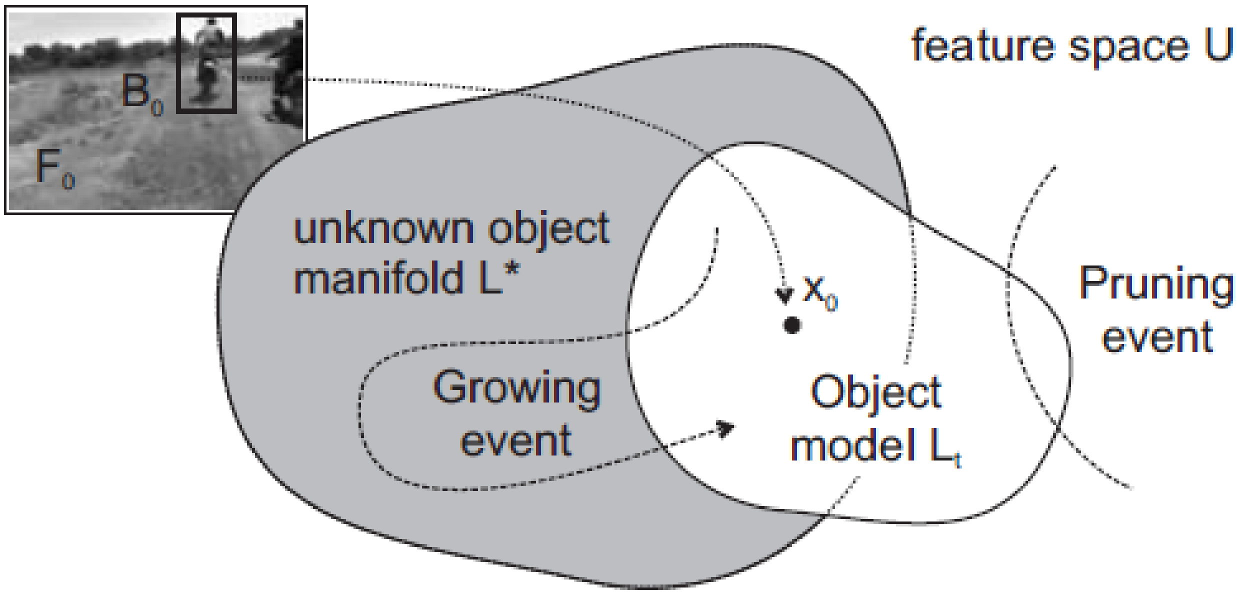
Object Detector	**Our approach**	**Object Tracker**
Fixed Training set **General object detector**	**Fixed Prior for updating an** **Adaptive on-line classifier**	**On-line update** **Object vs. Background**



H. Grabner, C. Leistner, H. Bischof. Semi-Supervised On-line Boosting for Robust Tracking. ECCV'08.

Slide credit: Helmut Grabner

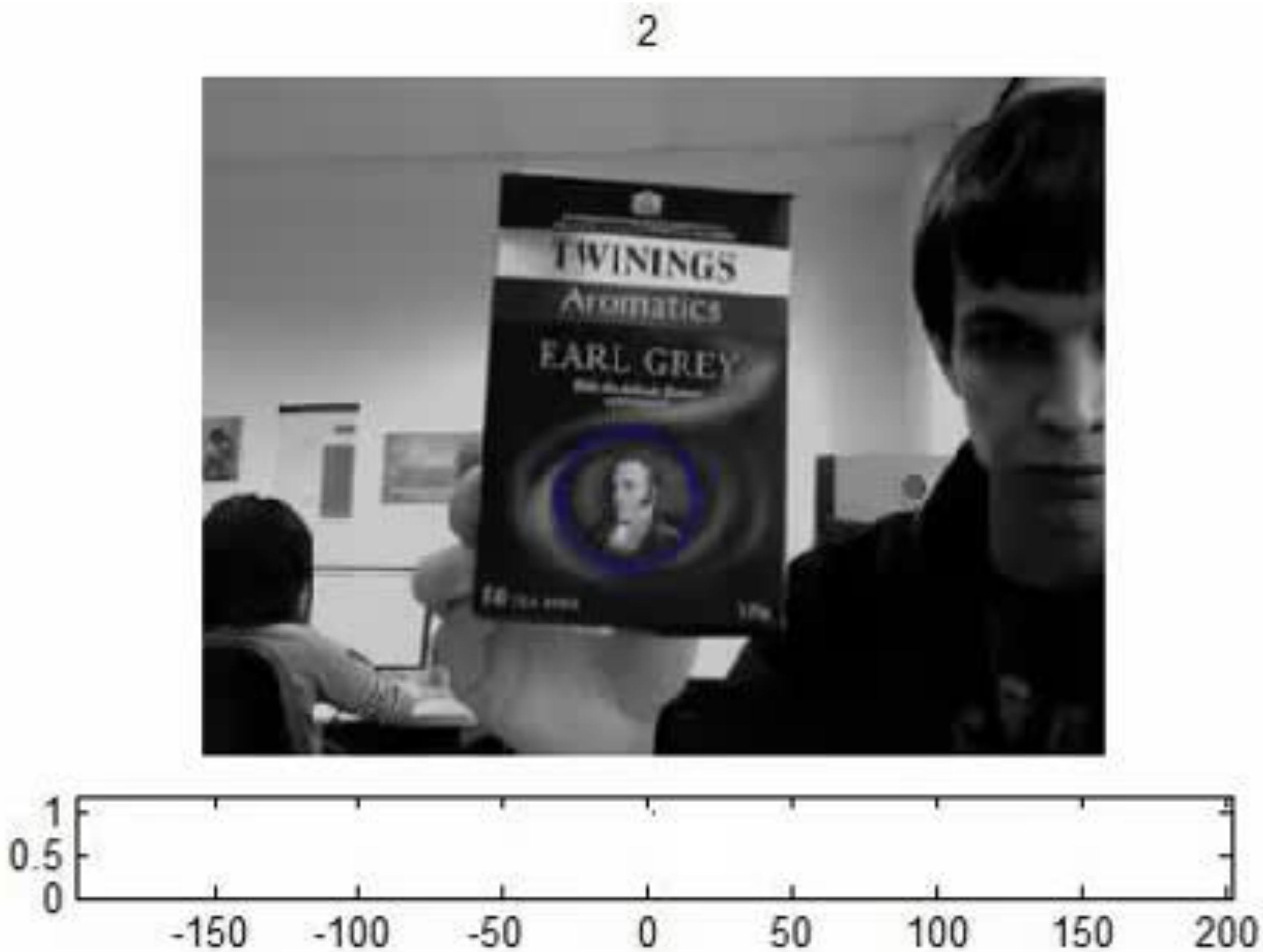
Strategy 3: Using Additional Cues



- Tracking-Learning-Detection
  - Combination of KLT and Tracking-by-Detection
  - Use a KLT tracker as additional cue to generate confident (positive and negative) training examples.
  - Learn an object detector on the fly using Online Random Ferns.

Z. Kalal, K. Mikolajczyk, J. Matas. Tracking-Learning-Detection. PAMI 2011.

TLD Results



Video source: Z. Kalal

Accumulated Training Examples

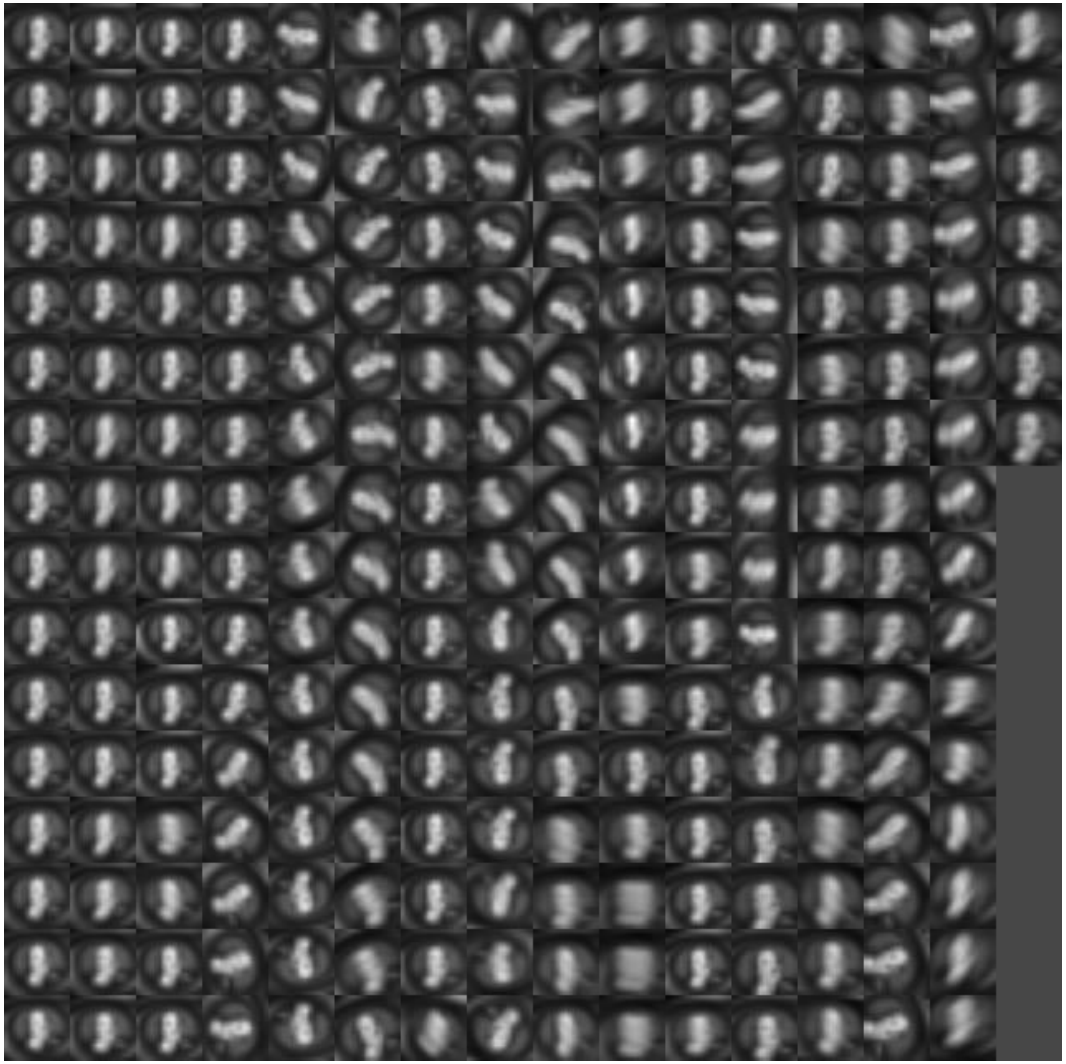
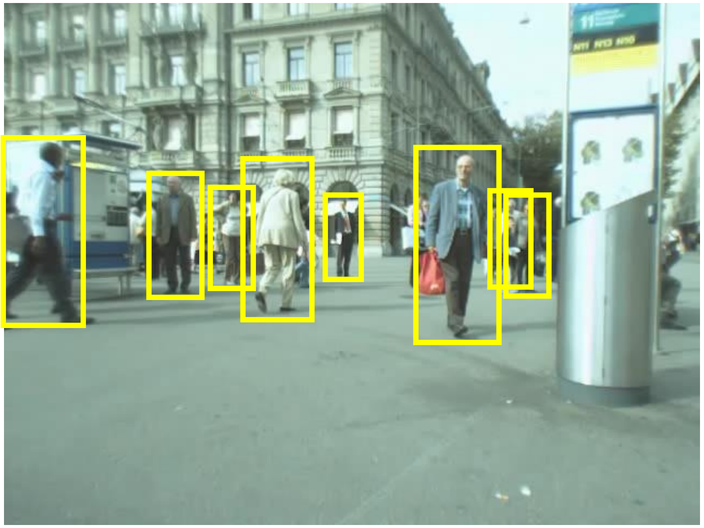


Image source: Z. Kalal

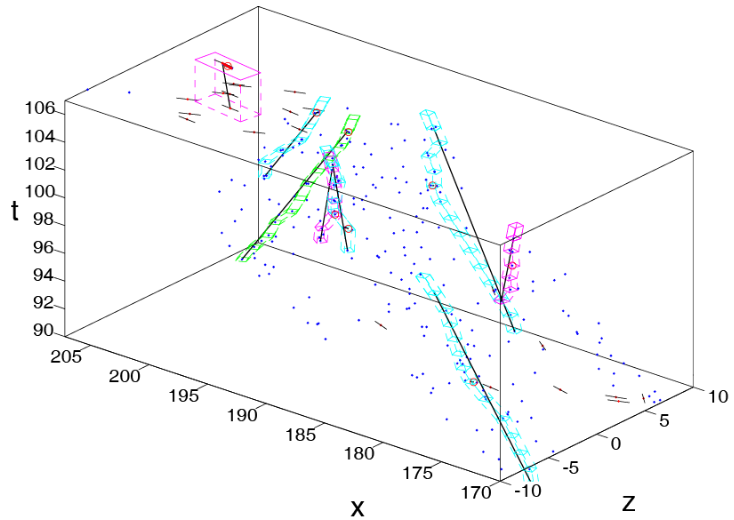
TLD Results

Video source: Z. Kalal

Today: Tracking by Detection



Object detections



Spacetime trajectories

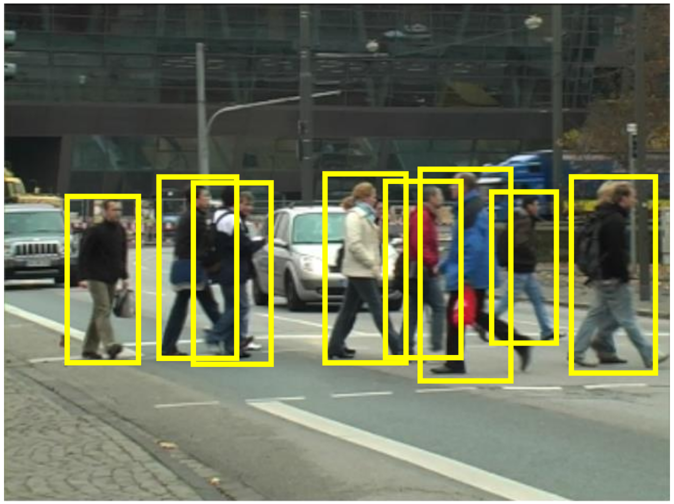
Can we use generic object detection to track people?

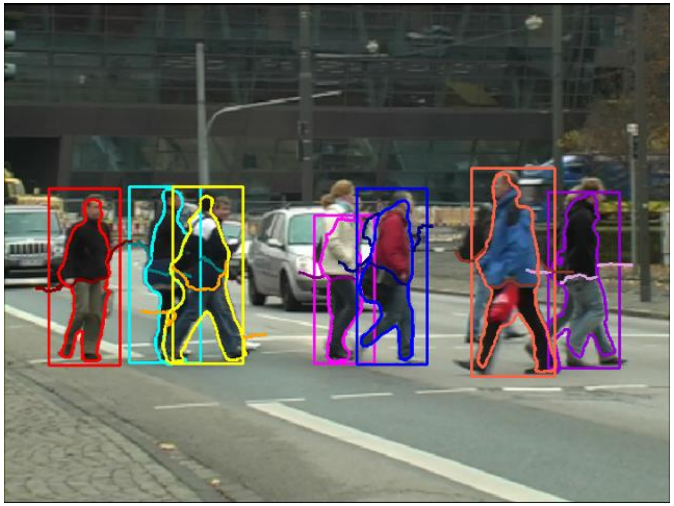
Image source: B. Leibe

Topics of This Lecture

- Tracking by Detection
  - Motivation
  - Recap: Object detection
- SVM based Detectors
  - Recap: HOG
  - DPM
- AdaBoost based Detectors
  - Recap: Viola-Jones
  - Integral Channel features
  - VeryFast/Roerei
- CNN-based Detectors
  - Recap: CNNs
  - R-CNN

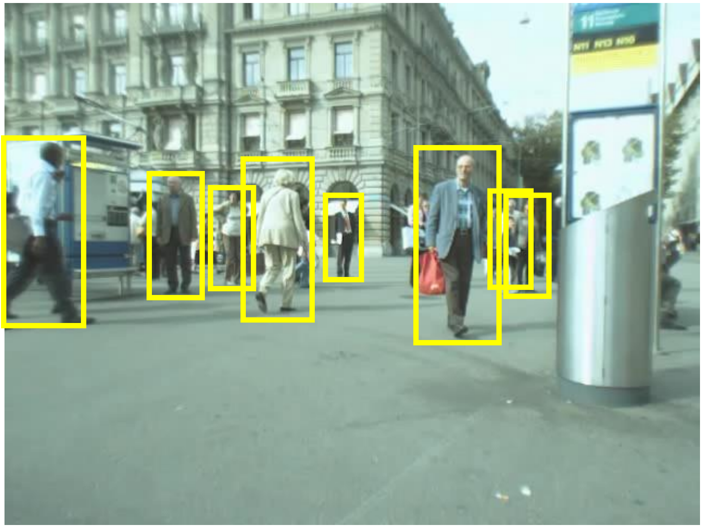
Detection-Based Tracking



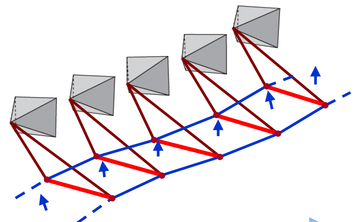


- Main ideas
  - Apply a generic object detector to find objects of a certain class
  - Based on the detections, extract object appearance models
    - Even possible to derive figure-ground segmentations from detection results
  - Link detections into trajectories

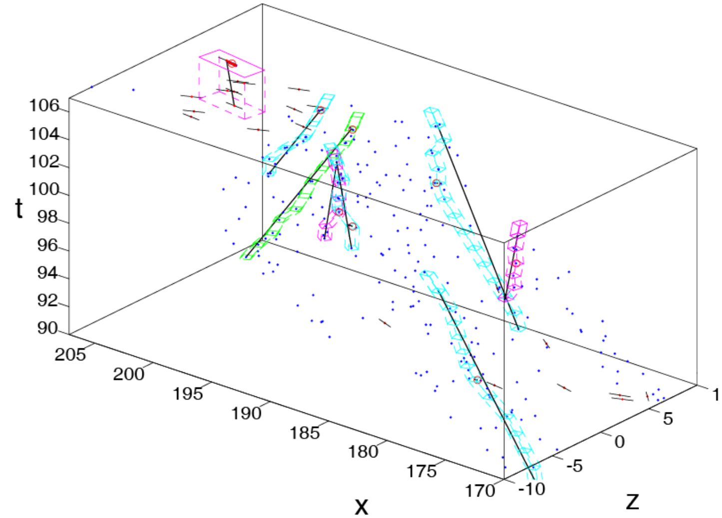
Tracking-by-Detection in 3D



Object detections



3D Camera path estimation



Spacetime trajectories

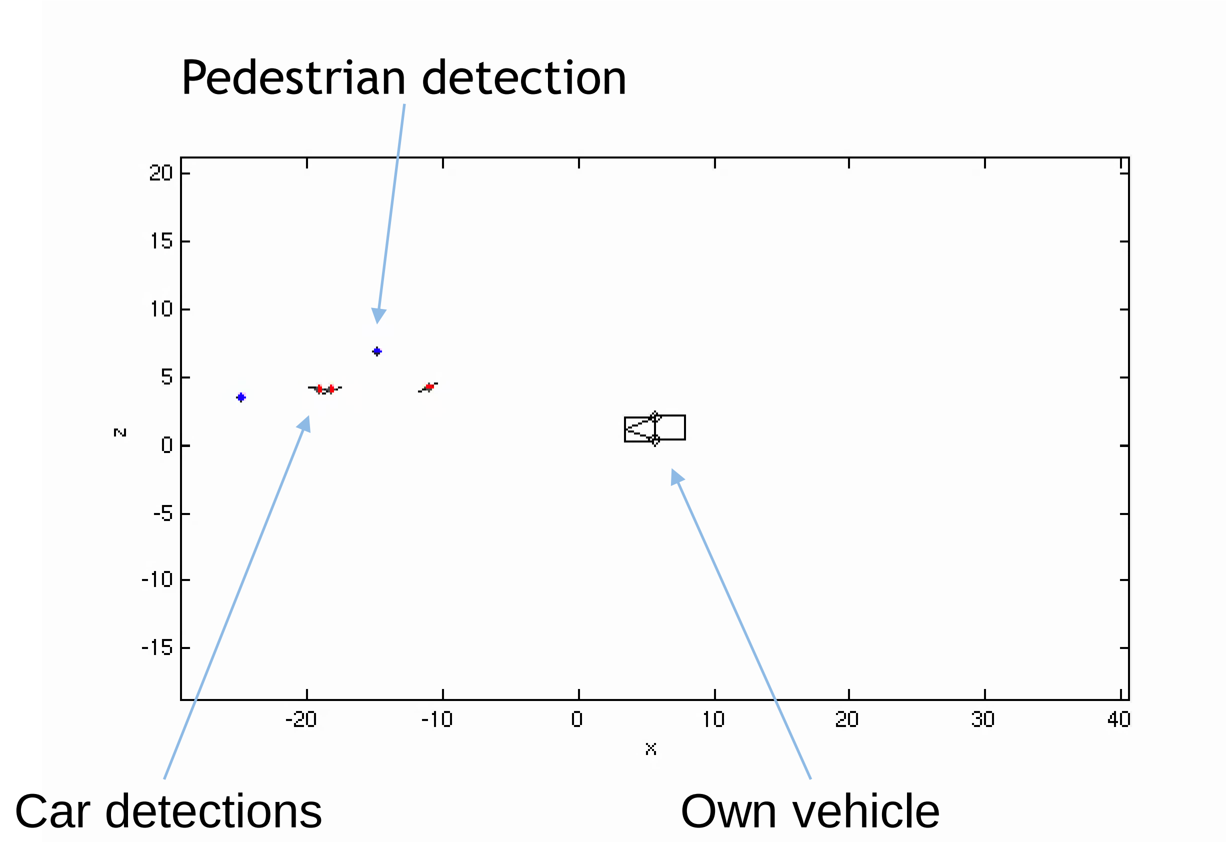
Simple f/g model:
E.g., elliptical region in detection box

Main Issue: Data Association

(We'll come to that later…)

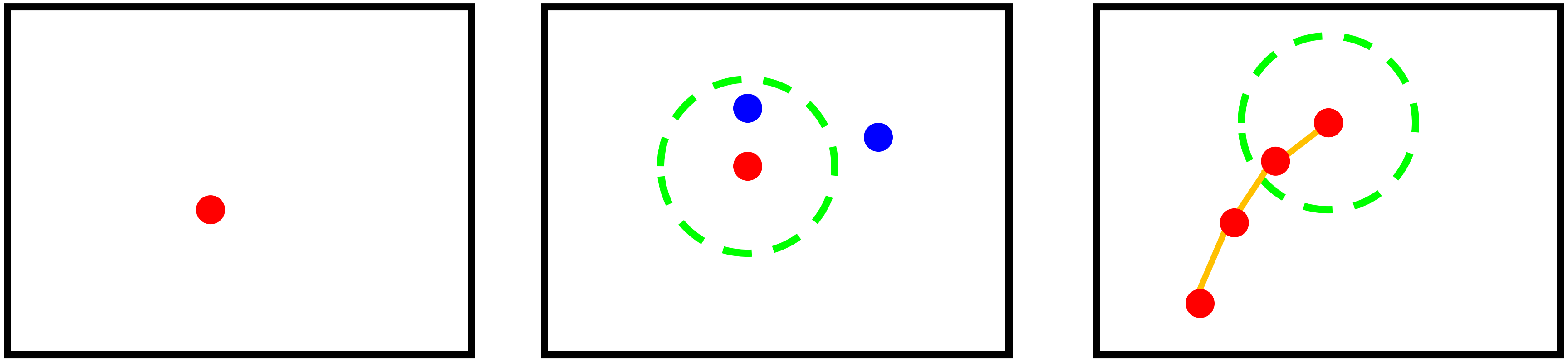
[Leibe, Cornelis, Schindler, Van Gool, PAMI'08]

Spacetime Trajectory Analysis



[Leibe, Cornelis, Schindler, Van Gool, CVPR'07]

Elements of Tracking



Detection | Data association | Prediction

- Detection
  - *Where are candidate objects?*

Today's topic

- Data association
  - *Which detection corresponds to which object?*
- Prediction
  - *Where will the tracked object be in the next time step?*

Recap: Sliding-Window Object Detection

- Basic component: a binary classifier

Car/non-car Classifier

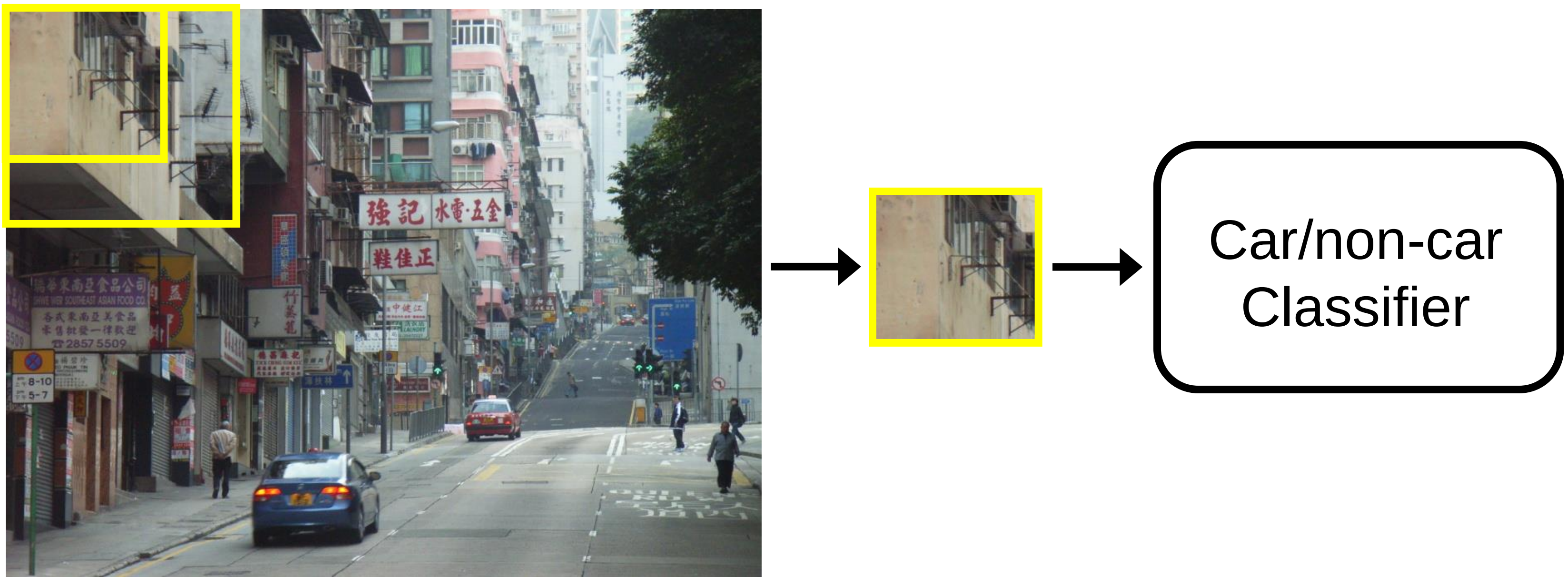
No, not a car.

Yes, car.

Slide credit: Kristen Grauman

Recap: Sliding-Window Object Detection

- If object may be in a cluttered scene, slide a window around looking for it.



- Essentially, this is a brute-force approach with many local decisions.

Slide credit: Kristen Grauman

What *is* a Sliding Window Approach?

- Search over space and scale

- Detection as subwindow classification problem
- *"In the absence of a more intelligent strategy, any global image classification approach can be converted into a localization approach by using a sliding-window search."*

Recap: Non-Maximum Suppression

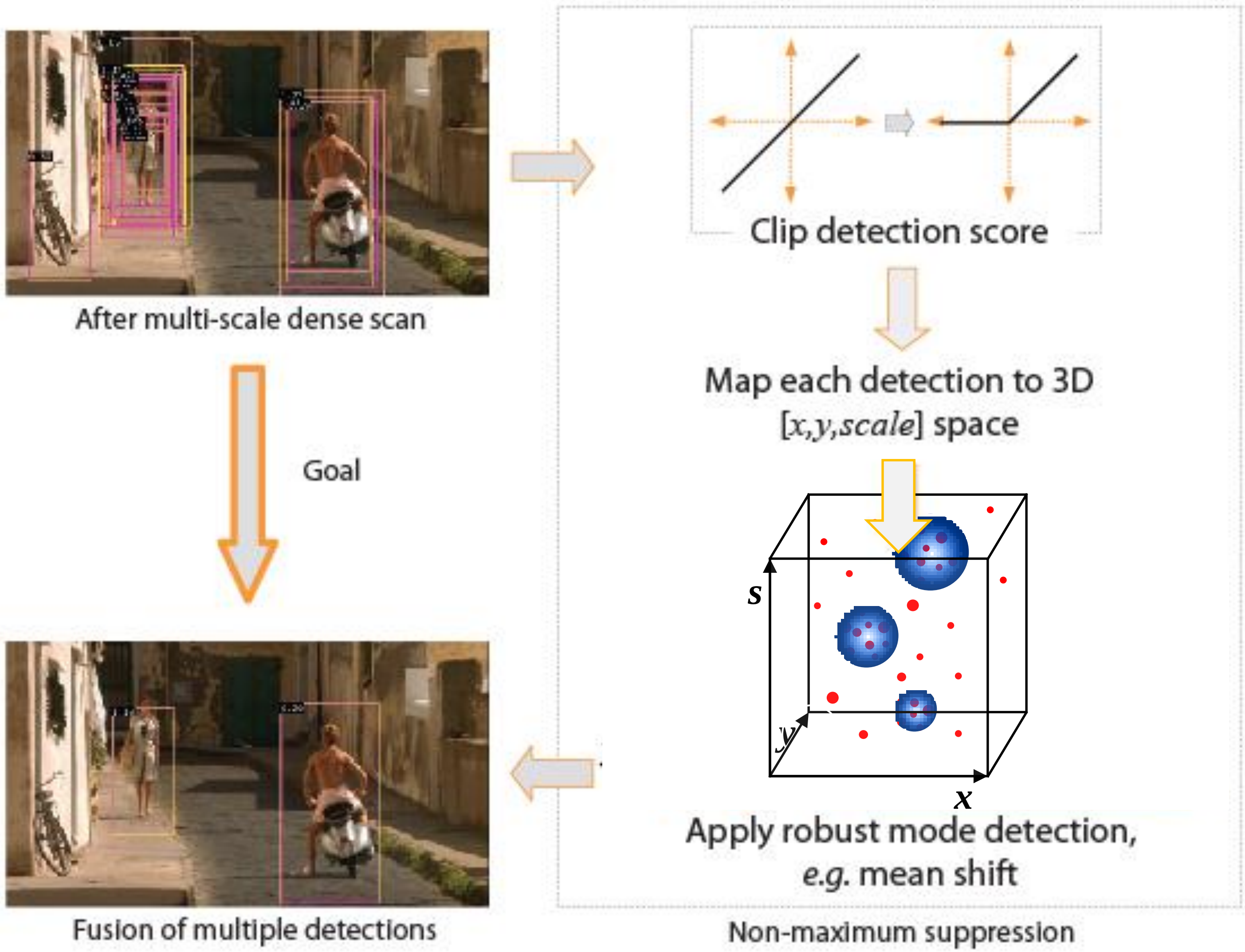
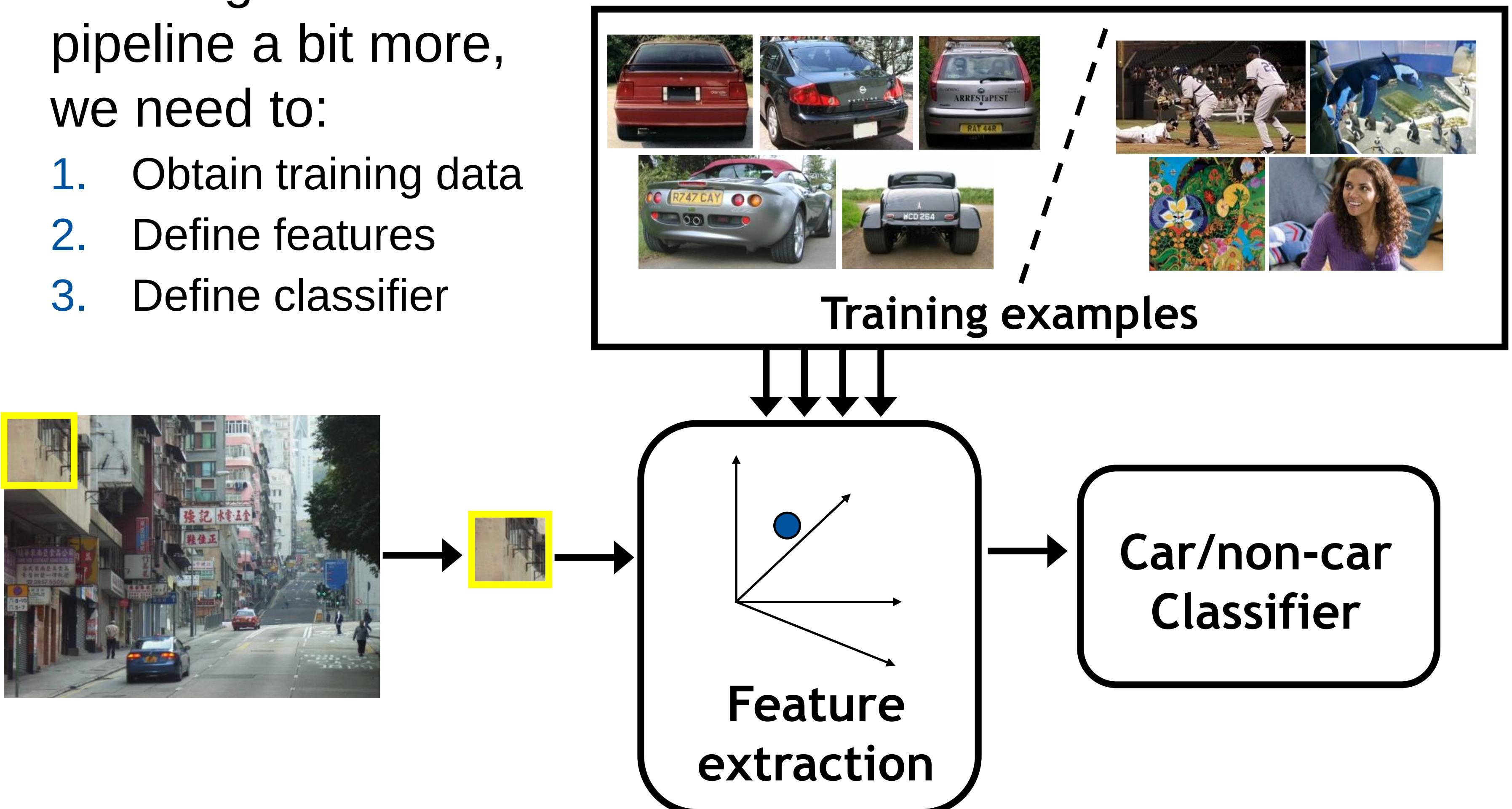


Image source: Navneet Dalal, PhD Thesis

Recap: Sliding-Window Object Detection

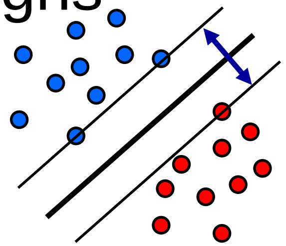
- Fleshing out this pipeline a bit more, we need to:
  1. Obtain training data
  2. Define features
  3. Define classifier



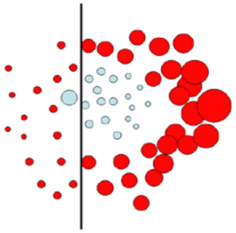
Slide credit: Kristen Grauman

Object Detector Design

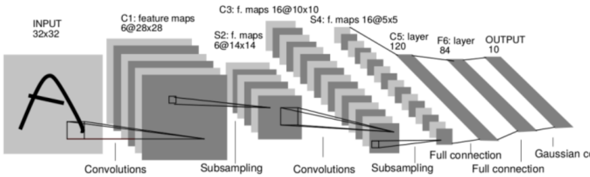
- In practice, the classifier often determines the design.
  - Types of features
  - Speedup strategies
- Today, we'll look at 3 state-of-the-art detector designs
  - Based on SVMs



  - Based on Boosting



  - Based on CNNs



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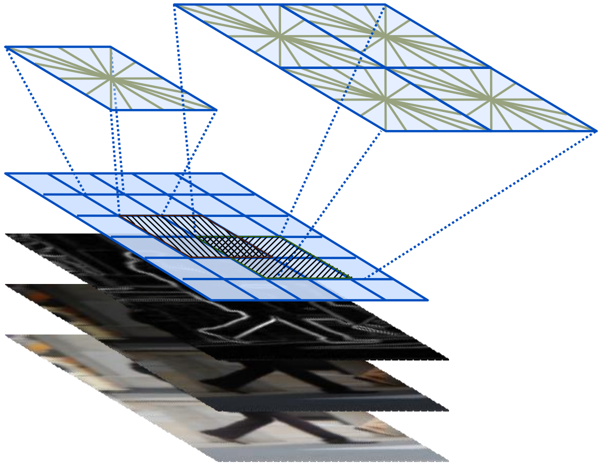
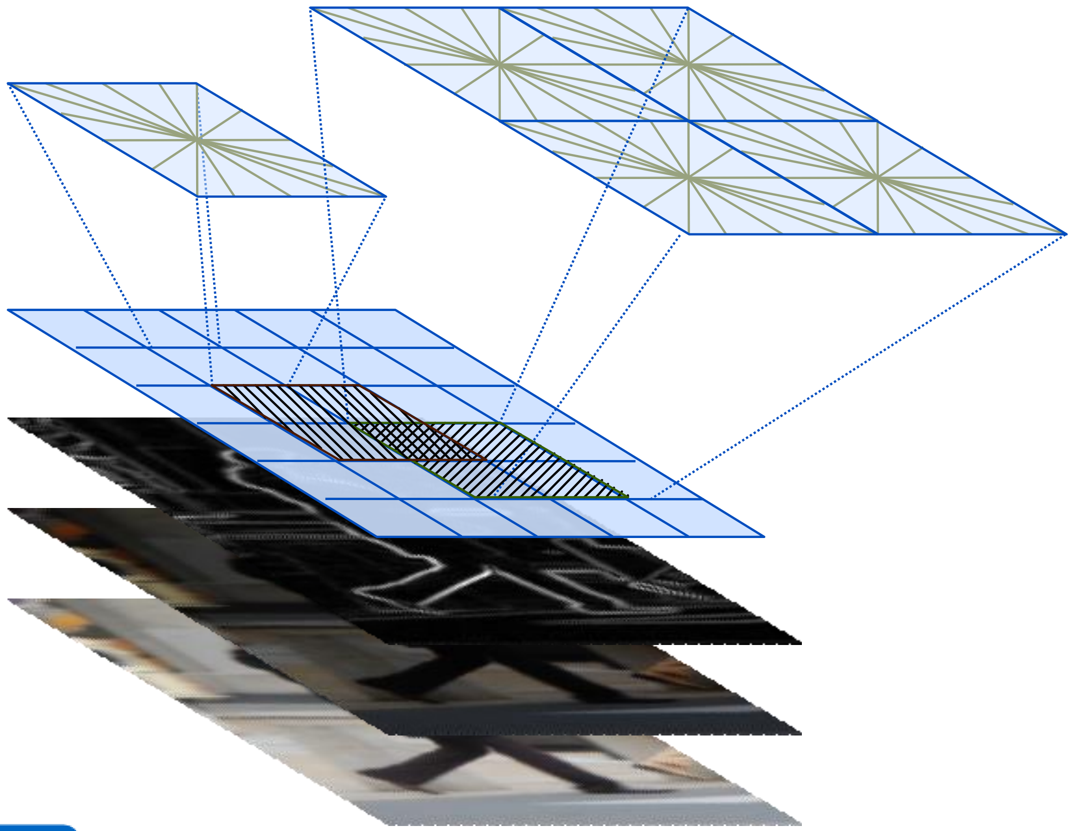


Recap: Histograms of Oriented Gradients (HOG)

- Holistic object representation
  - Localized gradient orientations



Object/Non-object

Linear SVM

Collect HOGs over detection window

Contrast normalize over overlapping spatial cells

Weighted vote in spatial & orientation cells

Compute gradients

Gamma compression

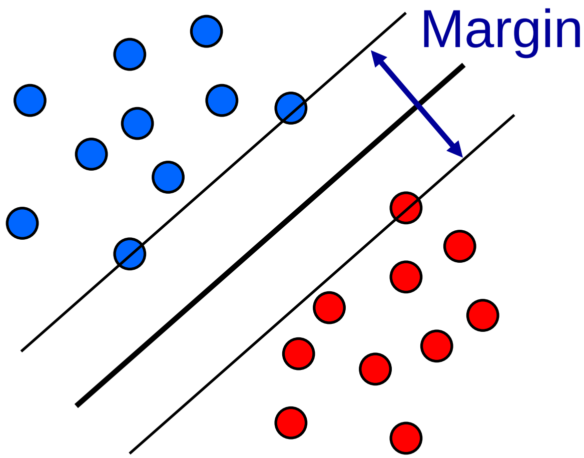
Image Window

Slide adapted from Navneet Dalal

Recap: Support Vector Machine (SVM)

- Basic idea
  - The SVM tries to find a classifier which maximizes the margin between pos. and neg. data points.
  - Up to now: consider linear classifiers

$$\mathbf{w}^{\mathrm{T}}\mathbf{x} + b = 0$$



- Formulation as a convex optimization problem
  - Find the hyperplane satisfying

$$\arg\min_{\mathbf{w},b} \frac{1}{2}\|\mathbf{w}\|^2$$

under the constraints

$$t_n(\mathbf{w}^{\mathrm{T}}\mathbf{x}_n + b) \geq 1 \quad \forall n$$

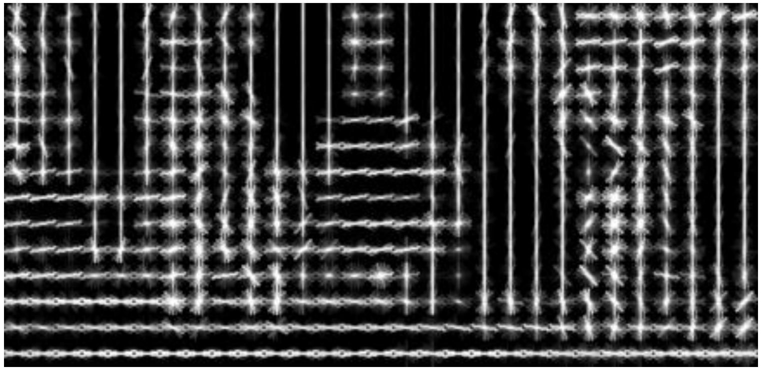
based on training data points $\mathbf{x}_n$ and target values $t_n \in \{-1, 1\}$

Recap: Pedestrian Detection with HOG

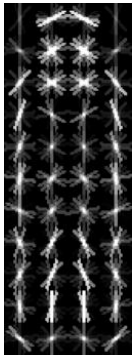
- Train a pedestrian template using a linear SVM
- At test time, convolve feature map with template

$$y(\mathbf{x}) = \mathbf{w}^{\mathrm{T}}\mathbf{x} + b$$

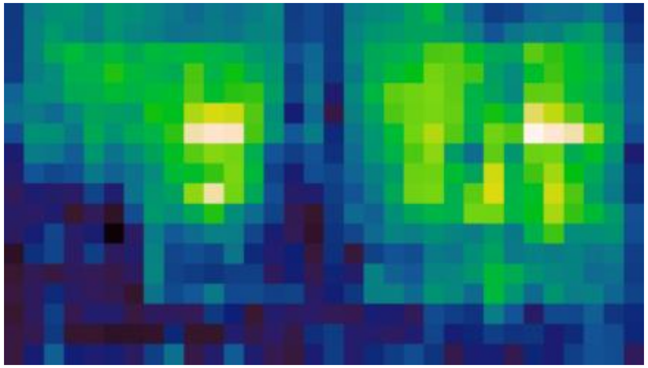
HOG feature map



Template



Detector response map



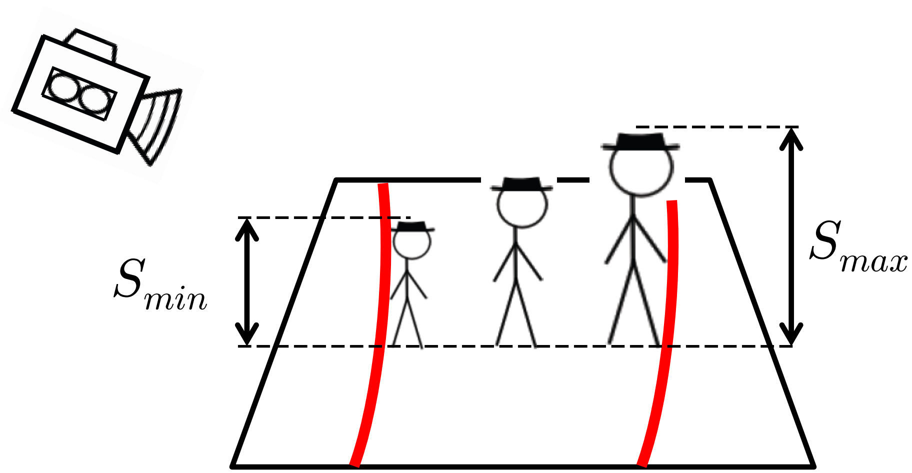
N. Dalal and B. Triggs, [Histograms of Oriented Gradients for Human Detection](), CVPR 2005

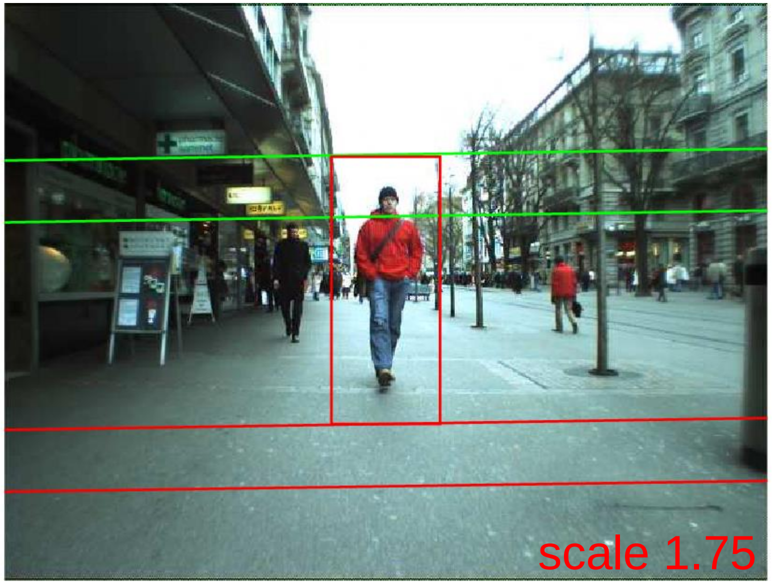
Slide credit: Svetlana Lazebnik

Pedestrian detection with HoGs & SVMs

N. Dalal and B. Triggs, Histograms of Oriented Gradients for Human Detection, CVPR 2005

Incorporating Ground Plane Constraints





- Efficient integration into detector design (*groundHOG*)
  - Idea: only evaluate geometrically valid detection windows
  - Derivation: Region of interest lies between two parabolas…
  - …that can in most cases be approximated by straight lines.

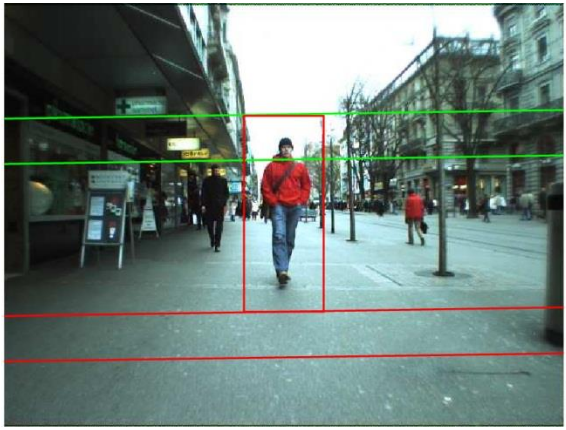
  ⇒ *Only touch pixels inside the ROI for all computations*.

  ⇒ Factor 2-4 speed improvement *on top of all other optimizations*

[P. Sudowe, B. Leibe, ICVS'11]

Real-Time Pedestrian Detection

- Efficient CUDA HOG implementation (equivalent to original HOG code)
- Code made publicly available as open source under GPL
- Run-time comparison:



run-time	1280×960		640×480	
	cuda	ground	cuda	ground
Laptop GTX 285M	1.6 fps	9.6 fps	7.2 fps	26 fps
Desktop GTX 280	5.5 fps	17.2 fps	22.7 fps	56 fps
Desktop GTX 580	9.8 fps	27.8 fps	41.6 fps	83 fps

$\Rightarrow$ *Detection at video frame rate possible even on laptops with mobile GPUs!*

[P. Sudowe, B. Leibe, ICVS'11]

You Can Try It At Home…

- groundHOG GPU detector code publicly available
  - Highly optimized for speed
  - Can be used with or without ground plane constraints
  - Supports general ROI processing
  - Supports multi-class detection with feature sharing
  - Published under GPL license (other licensing negotiable)

  - http://www.vision.rwth-aachen.de/projects/groundhog

P. Sudowe, B. Leibe, Efficient Use of Geometric Constraints for Sliding Window Object Detection in Video, ICVS 2011

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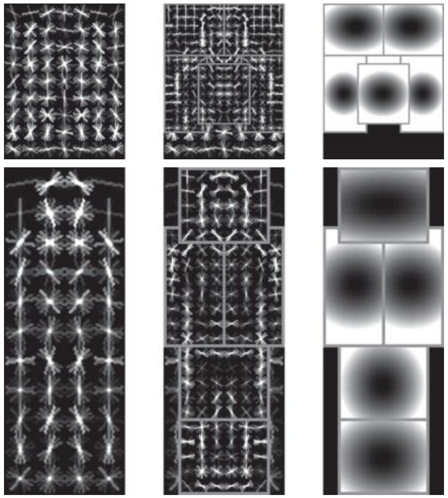
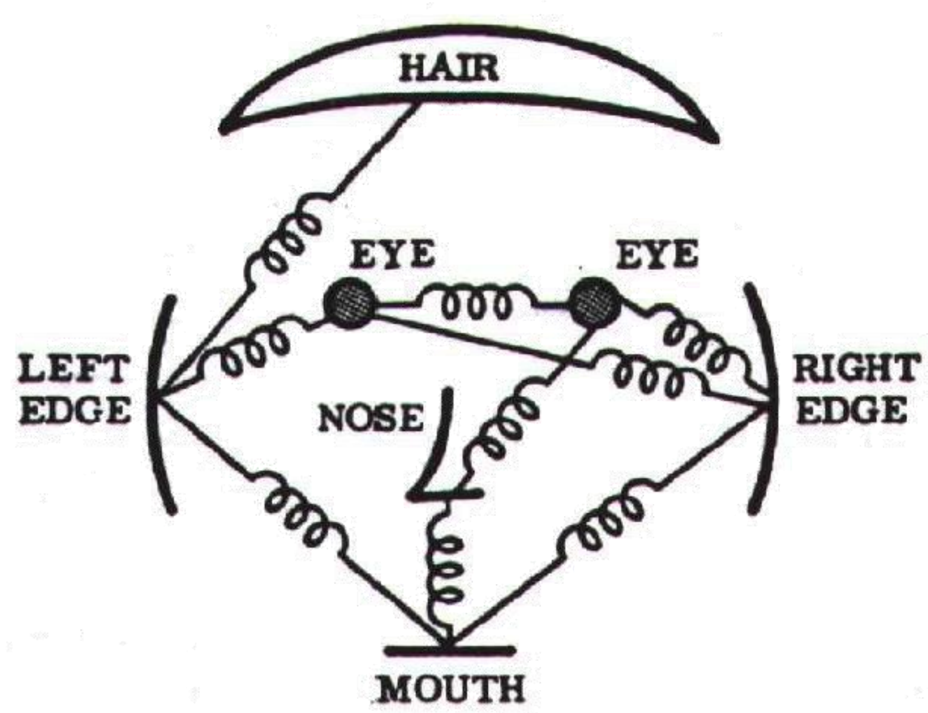
  - Motivation
  - Recap: Object detection
- SVM based Detectors
  - Recap: HOG
  - DPM
- AdaBoost based Detectors
  - Recap: Viola-Jones
  - Integral Channel features
  - VeryFast/Roerei
- CNN-based Detectors
  - Recap: CNNs
  - R-CNN



Recap: Part-Based Models

- Pictorial Structures model
  - [Fischler & Elschlager 1973]

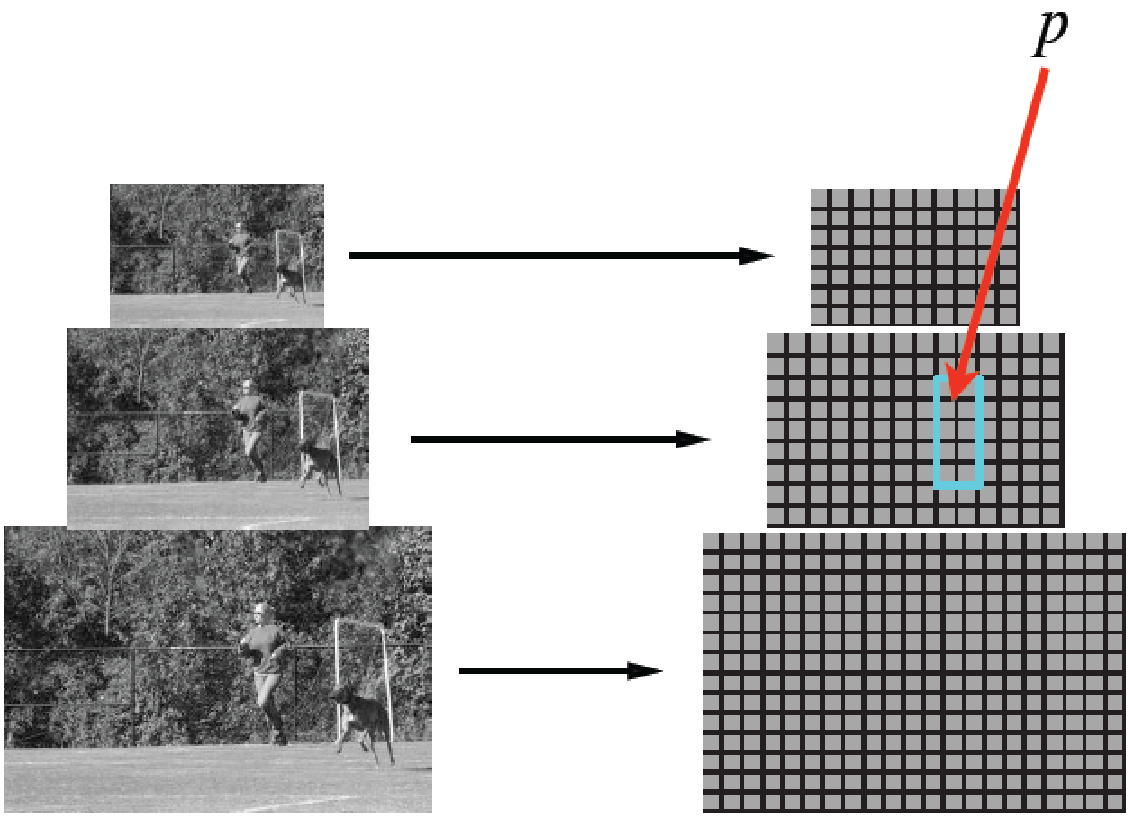
- Model has two components
  - Parts
    (2D image fragments)
  - Structure
    (configuration of parts)



- Use in Deformable Part-based Model (DPM)
  - Parts ≡ 5-7 semantically meaningful parts
  - Probabilistic model enabling efficient inference

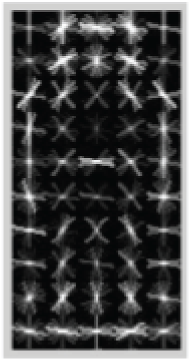
Slide adapted from Kristen Grauman

Starting Point: HOG Sliding-Window Detector



HOG pyramid H

Filter F



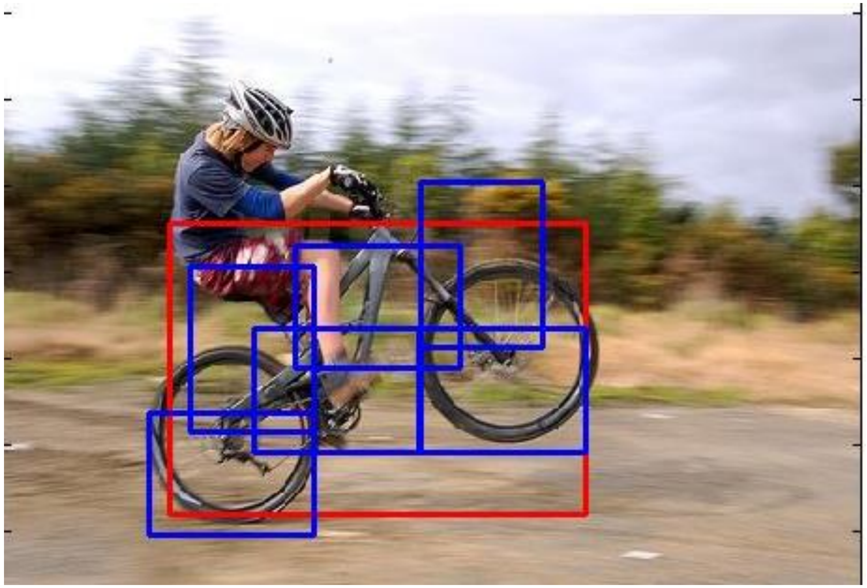
Score of F
at position p is
$F \cdot \phi(p, H)$

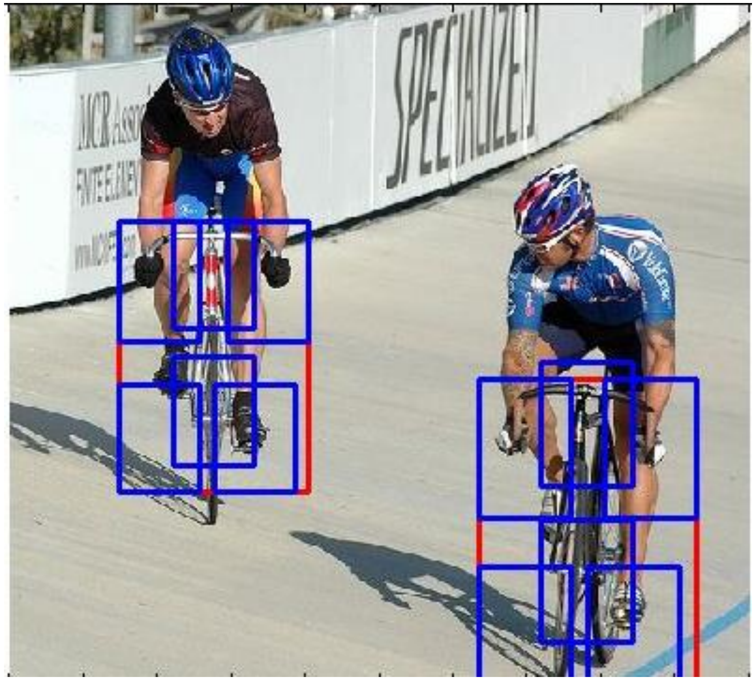
$\phi(p, H)$ = concatenation of HOG features from window specified by p.

- Array of weights for features in window of HOG pyramid
- Score is dot product of filter and vector

Slide adapted from Pedro Felzenszwalb, Deva Ramanan

Deformable Part-based Models



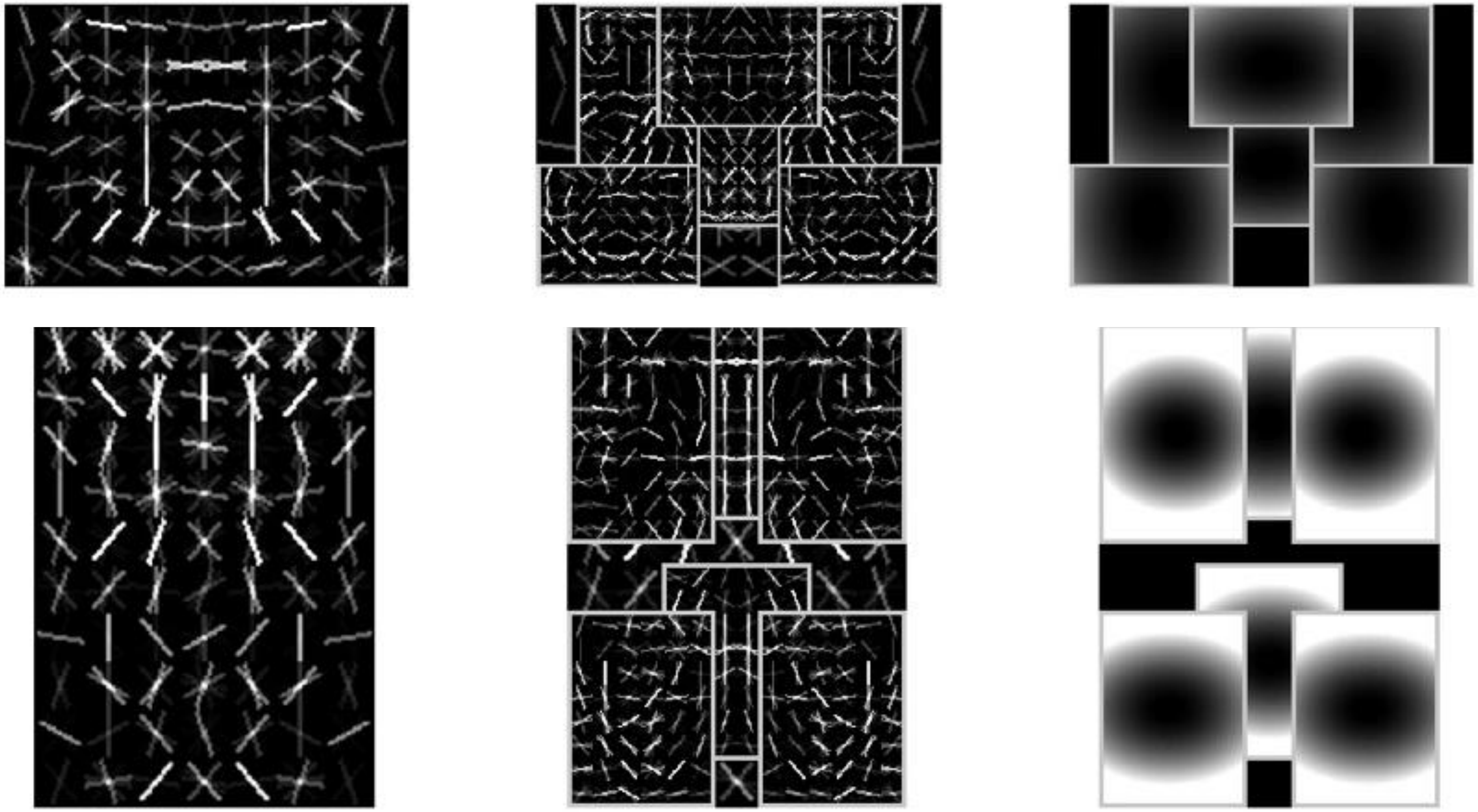


- Mixture of deformable part models (Pictorial Structures)
- Each component has global template + deformable parts
- Fully trained from bounding boxes alone

[Felzenszwalb, McAllister, Ramanan, CVPR'08]

Slide credit: Pedro Felzenszwalb

2-Component Bicycle Model



Root filters
coarse resolution

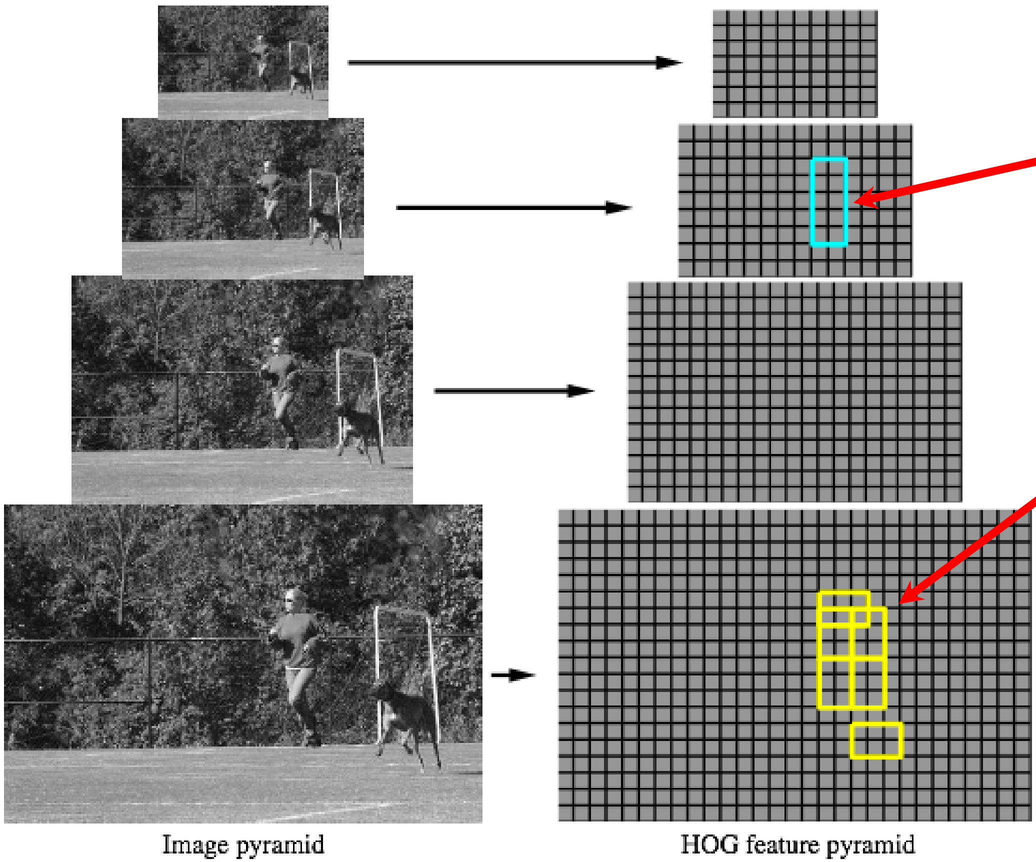
Part filters
finer resolution

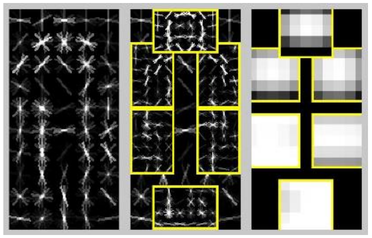
Deformation
models

[Felzenszwalb, McAllister, Ramanan, CVPR'08]

Slide credit: Pedro Felzenszwalb

Object Hypothesis





Score of filter:
dot product of filter with HOG features underneath it

Score of object hypothesis is sum of filter scores minus deformation costs

- Multiscale model captures features at two resolutions

[Felzenszwalb, McAllister, Ramanan, CVPR'08]

Slide credit: Pedro Felzenszwalb

Score of a Hypothesis

“data term”

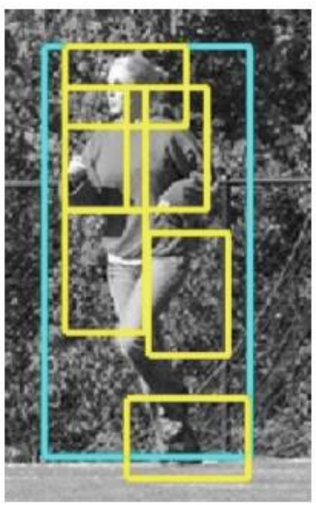
“spatial prior”

$$\text{score}(p_0, \ldots, p_n) = \sum_{i=0}^{n} F_i \cdot \phi(H, p_i) - \sum_{i=1}^{n} d_i \cdot (dx_i^2, dy_i^2)$$

filters

deformation parameters

displacements



$$\text{score}(z) = \beta \cdot \Psi(H, z)$$

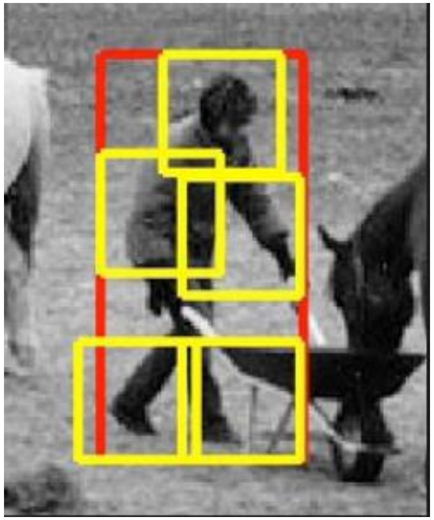
concatenation filters and deformation parameters

concatenation of HOG features and part displacement features

[Felzenszwalb, McAllister, Ramanan, CVPR’08]

Recognition Model

$$f_w(x) = w \cdot \Phi(x)$$

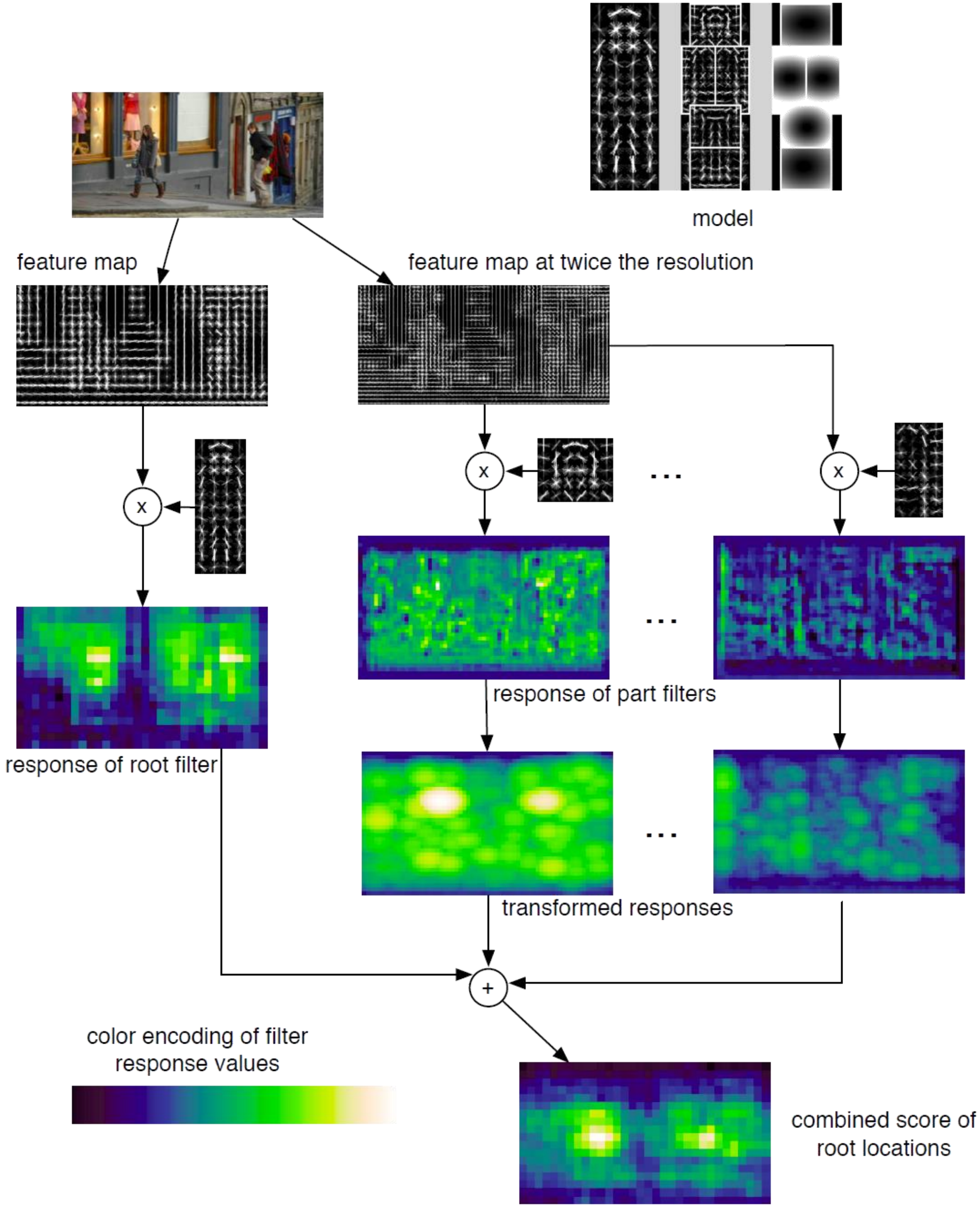


$$f_w(x) = \max_z w \cdot \Phi(x, z)$$

- Difference to standard HOG model
  - Hidden variable z: vector of part offsets
  - $\Phi(x,z)$: vector of HOG features (from root filter & appropriate part sub-windows) and part offsets

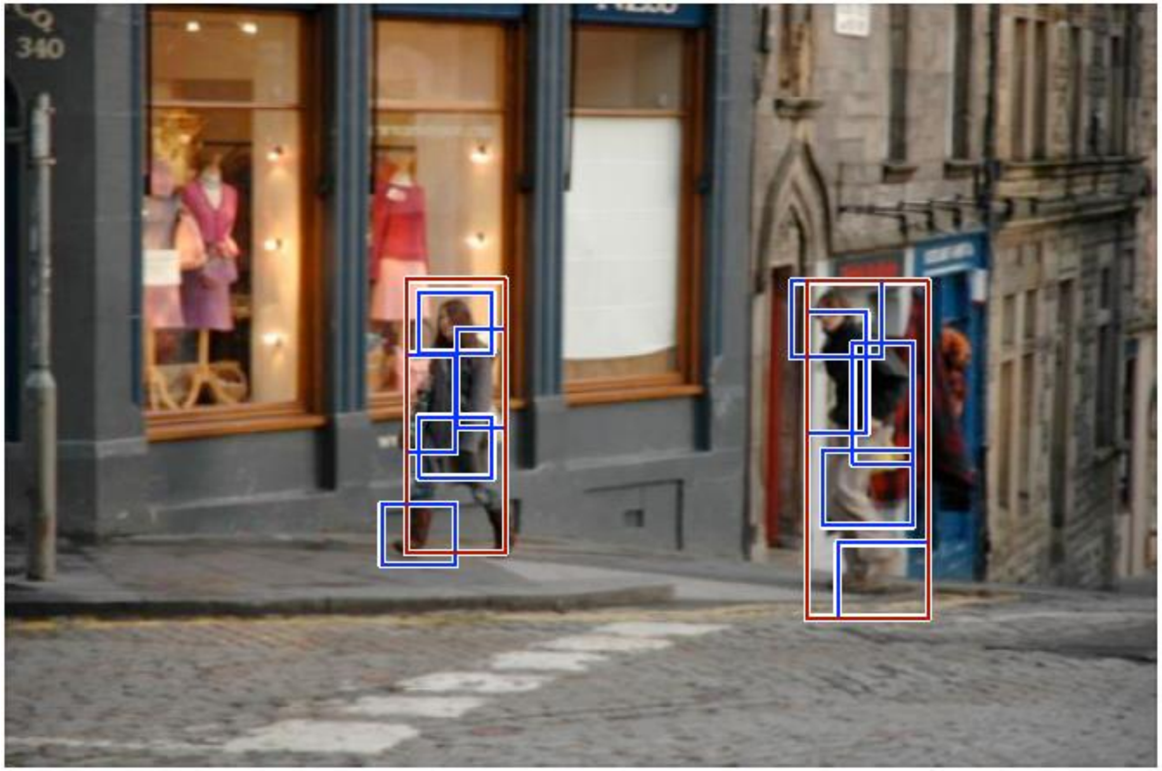
    $\Rightarrow$ Need to optimize over all possible part positions

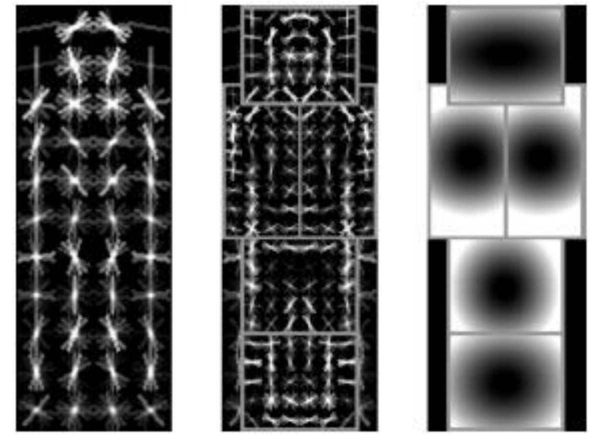
Slide credit: Pedro Felzenszwalb



Slide credit: Pedro Felzenszwalb

Results: Persons

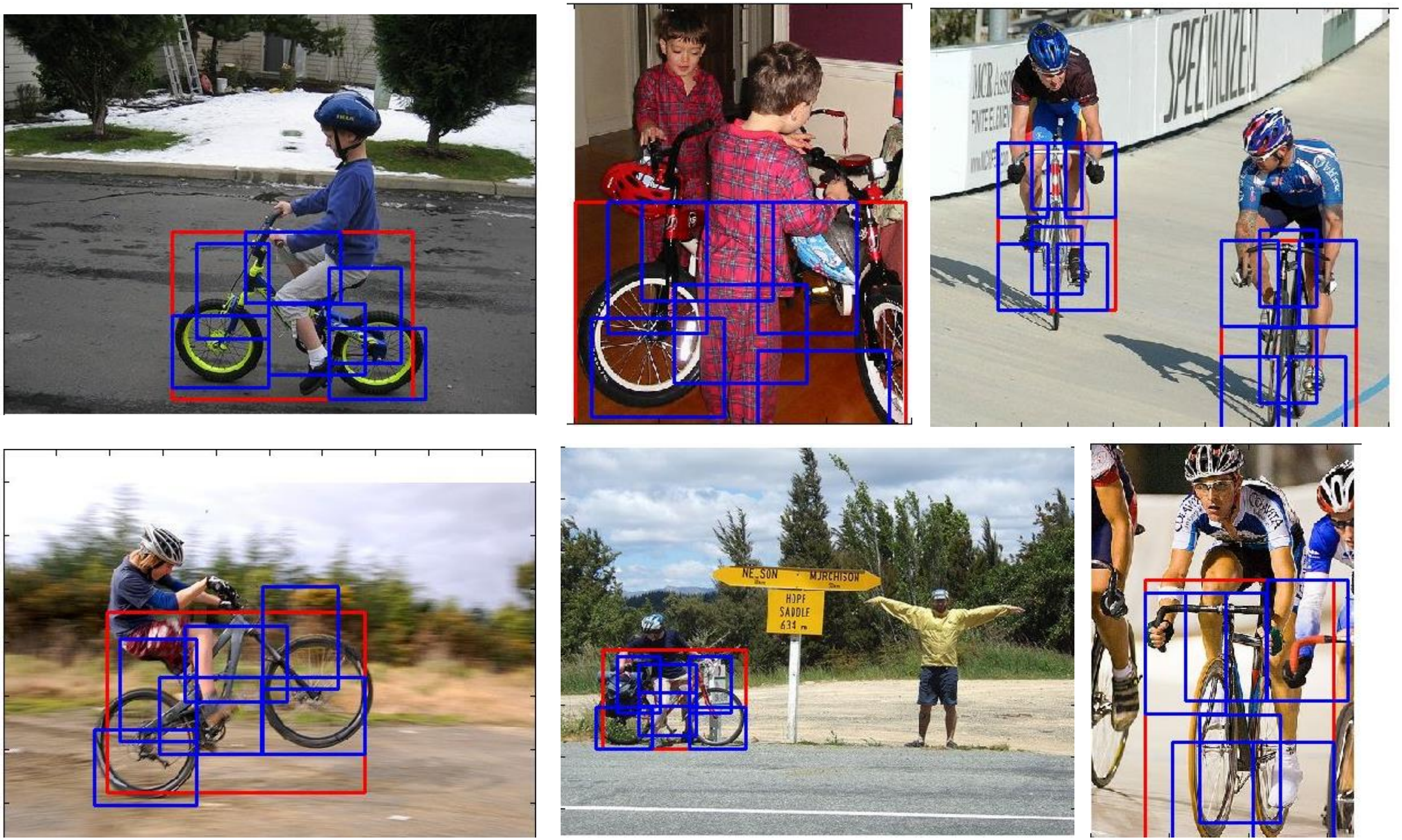




- Results (after non-maximum suppression)
  - ~1s to search all scales

Slide credit: Pedro Felzenszwalb

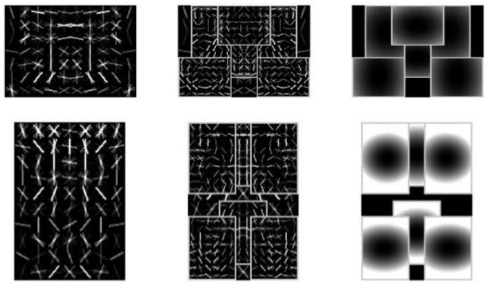
Results: Bicycles



Slide adapted from Trevor Darrell

Extensions and Detailed Improvements

- More efficient features
  - Very simplified version of HOG
- Latent part (re-)learning
  - Perform several rounds of training, adapting the annotation bboxes
- Multi-aspect detection
  - Mixture model of different aspects to capture different viewpoints of objects
- Bounding box prediction
  - Infer final detection bounding box from detected part locations
- Multi-resolution models
- Cascaded evaluation



[Felzenszwalb, McAllister, Ramanan, PAMI'10]

You Can Try It At Home…

- Deformable part-based models have been very successful at several recent evaluations.

  $\Rightarrow$ One of the state-of-the-art approaches in object detection

- Source code and models trained on PASCAL 2006, 2007, and 2008 data are available here:

  http://www.cs.uchicago.edu/~pff/latent

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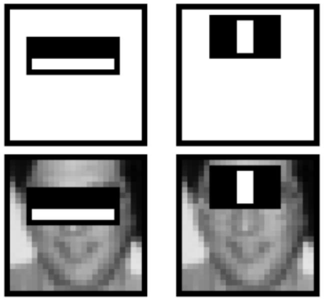
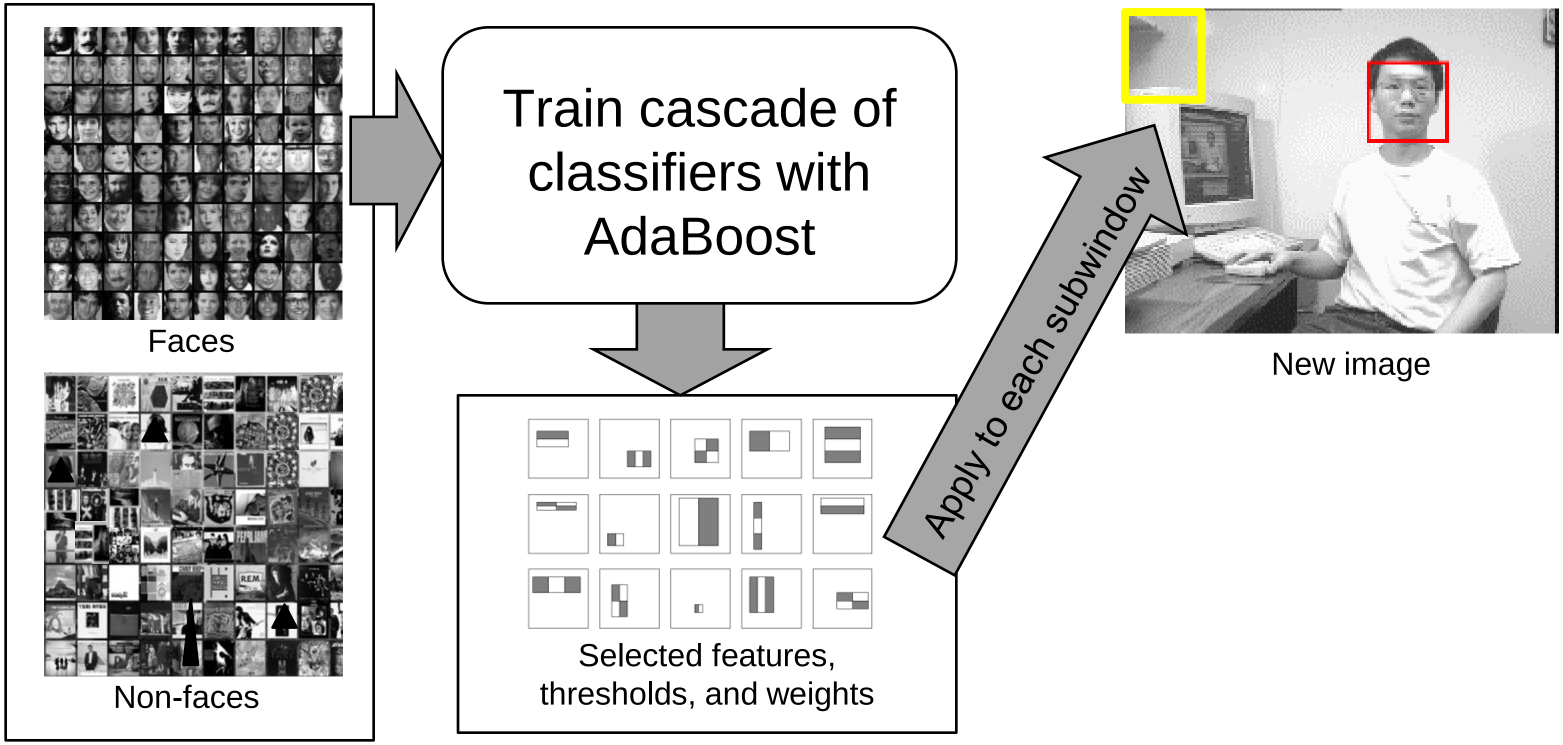


Recap: Viola-Jones Face Detector

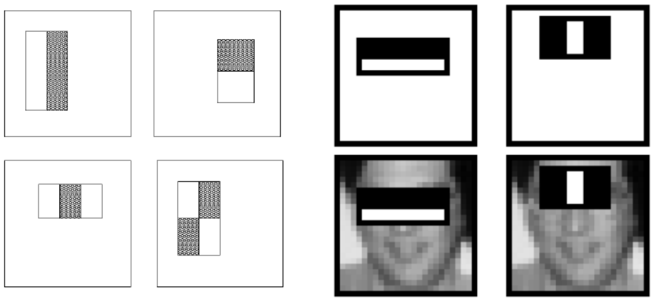


- Train with 5K positives, 350M negatives
- Real-time detector using 38 layer cascade (6061 features in final layer)
- [Implementation available in OpenCV: http://sourceforge.net/projects/opencvlibrary/]

Slide credit: Kristen Grauman

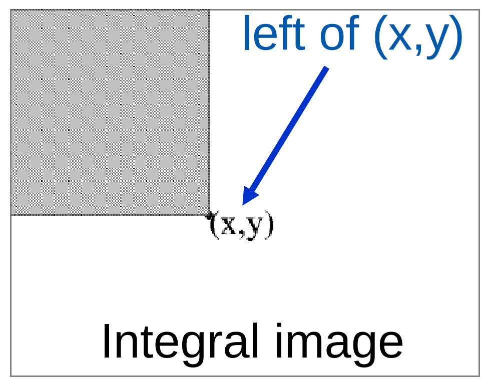
Recap: Haar Wavelets

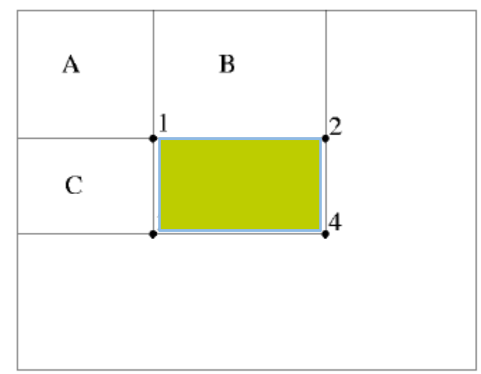
"Rectangular" filters



Feature output is difference between adjacent regions

Value at (x,y) is sum of pixels above and to the left of (x,y)





Efficiently computable with integral image: any sum can be computed in constant time

Avoid scaling images
$\Rightarrow$ Scale features directly for same cost

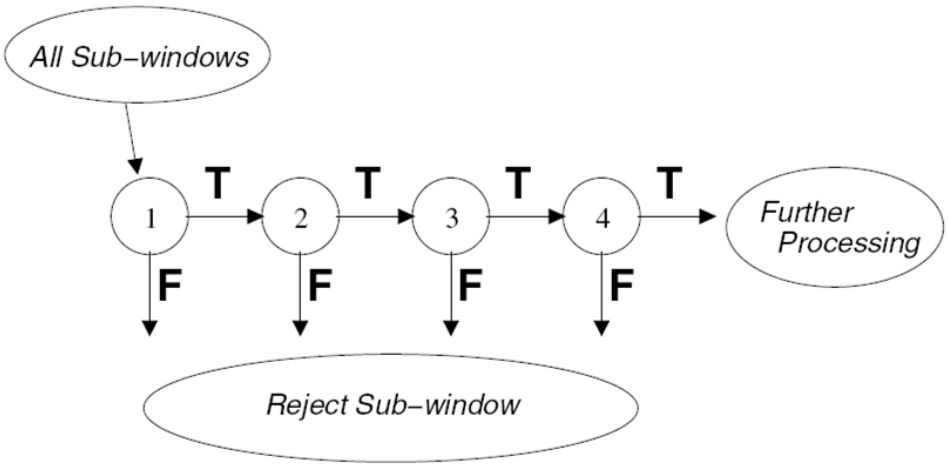
$$
\begin{aligned}
D &= 1 + 4 - (2 + 3) \\
&= A + (A + B + C + D) - (A + C + A + B) \\
&= D
\end{aligned}
$$

Slide credit: Kristen Grauman

[Viola & Jones, CVPR 2001]

Recap: Cascading Classifiers for Detection

- Even if the filters are fast to compute, each new image has a lot of possible windows to search...



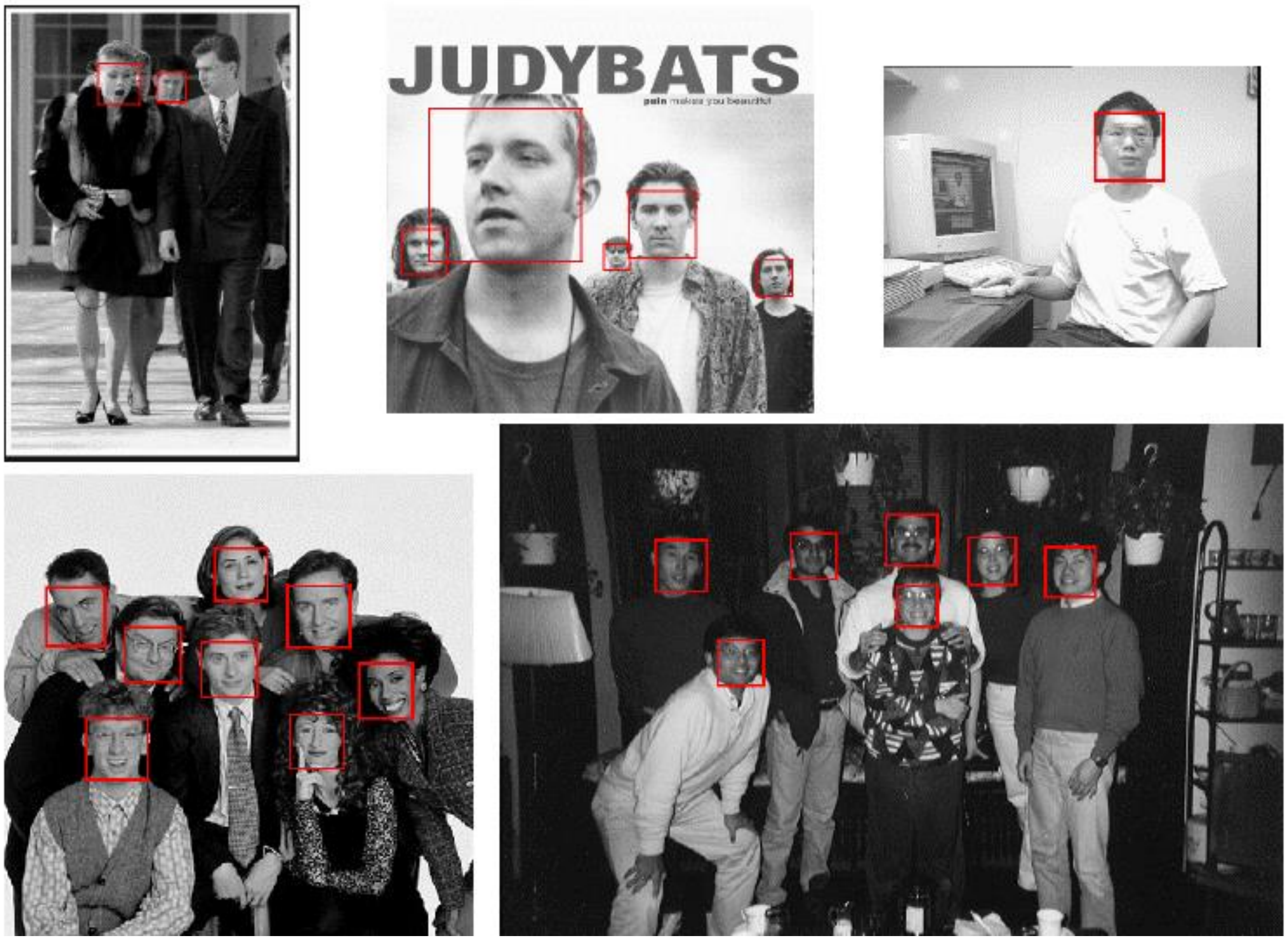
- Idea: Classifier cascade
  - Observation: most image windows are negative and look very different from the searched object class.
  - Filter for promising regions with an initial inexpensive classifier
  - Build a chain of classifiers, choosing cheap ones with low false negative rates early in the chain

[Fleuret & Geman, IJCV'01; Rowley et al., PAMI'98; Viola & Jones, CVPR'01]

Slide credit: Kristen Grauman

Figure from [Viola & Jones, CVPR 2001]

Viola-Jones Face Detector: Results



Slide credit: Kristen Grauman

You Can Try It At Home…

- The Viola & Jones detector was a huge success
  - First real-time face detector available
  - Many derivative works and improvements

- C++ implementation available in OpenCV [Lienhart, 2002]
  - http://sourceforge.net/projects/opencvlibrary/
- Matlab wrappers for OpenCV code available, e.g. here
  - http://www.mathworks.com/matlabcentral/fileexchange/19912

P. Viola, M. Jones, Robust Real-Time Face Detection, IJCV, Vol. 57(2), 2004

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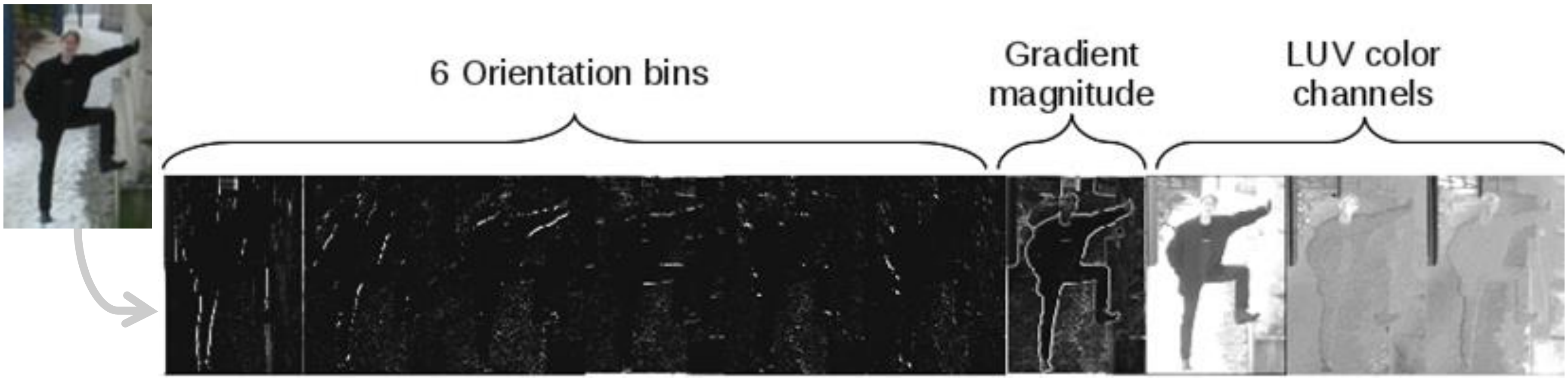
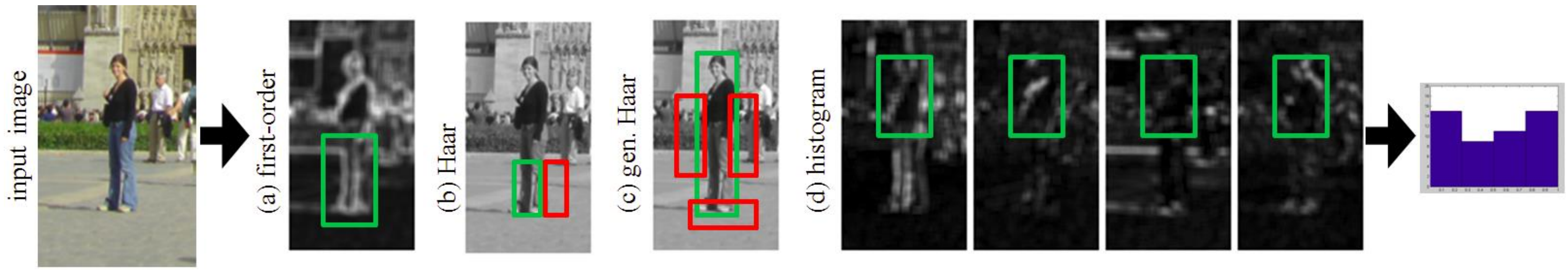
Integral Channel Features



- Generalization of Haar Wavelet idea from Viola-Jones
  - Instead of only considering intensities, also take into account other feature channels (gradient orientations, color, texture).
  - Still efficiently represented as integral images.

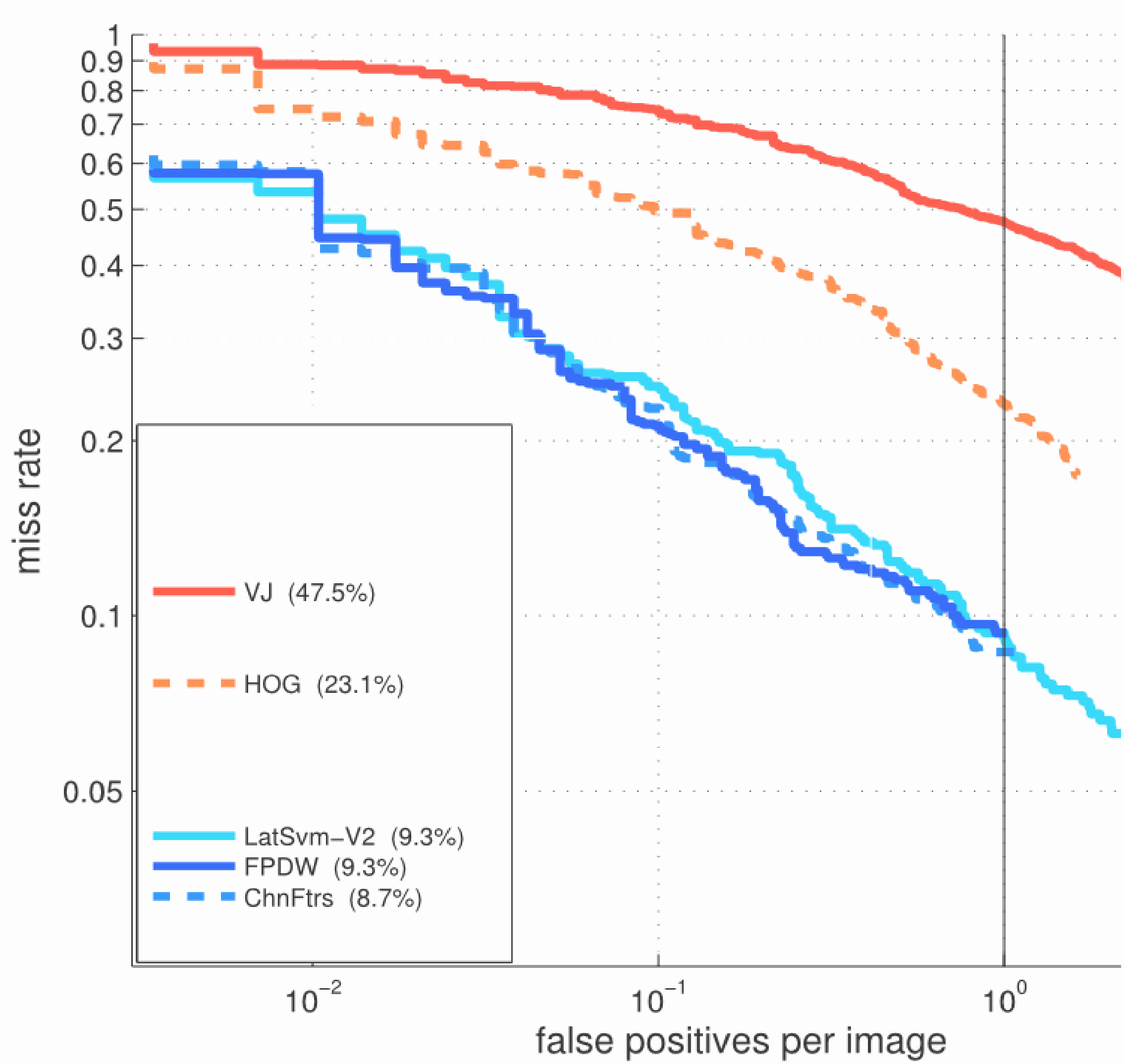
P. Dollar, Z. Tu, P. Perona, S. Belongie. [Integral Channel Features](), BMVC'09.

Integral Channel Features



- Generalize also block computation
  - 1^{st} order features:
    - Sum of pixels in rectangular region.
  - 2^{nd}-order features:
    - Haar-like difference of sum-over-blocks
  - Generalized Haar:
    - More complex combinations of weighted rectangles
  - Histograms
    - Computed by evaluating local sums on quantized images.

Results: Integral Channel Features



[Viola&Jones 2004]

fastHOG
~10 Hz on GPU
[Prisacariu 2009]

DPM
[Felzenszwalb 2008]

ChnFtrs/FPDW
~5 Hz on CPU
[Dollar 2009+2010]

Slide credit: Rodrigo Benenson

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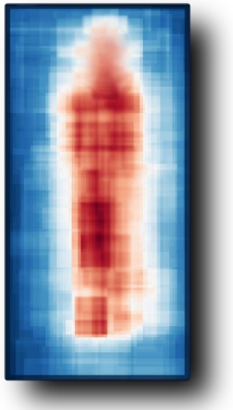
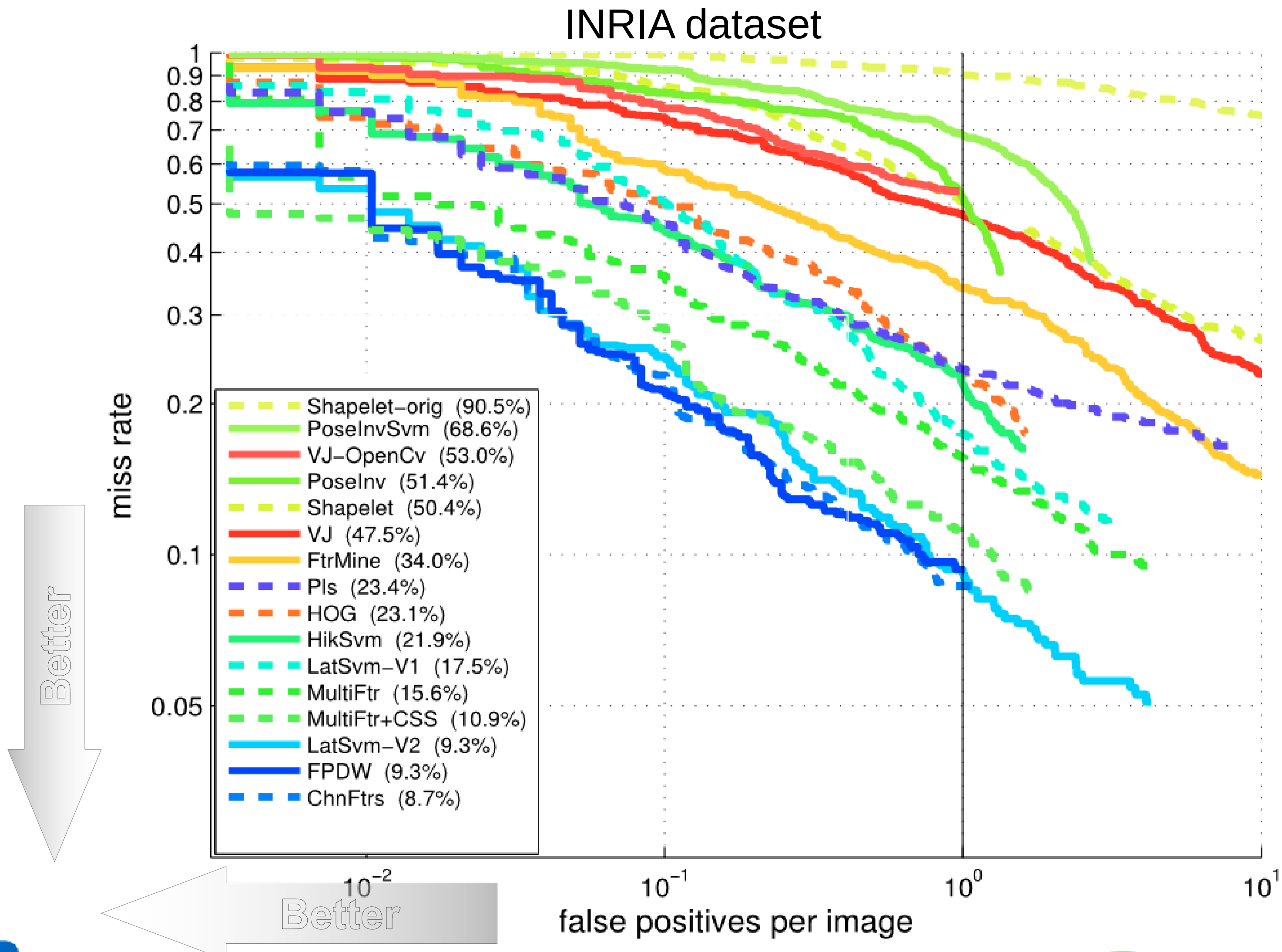
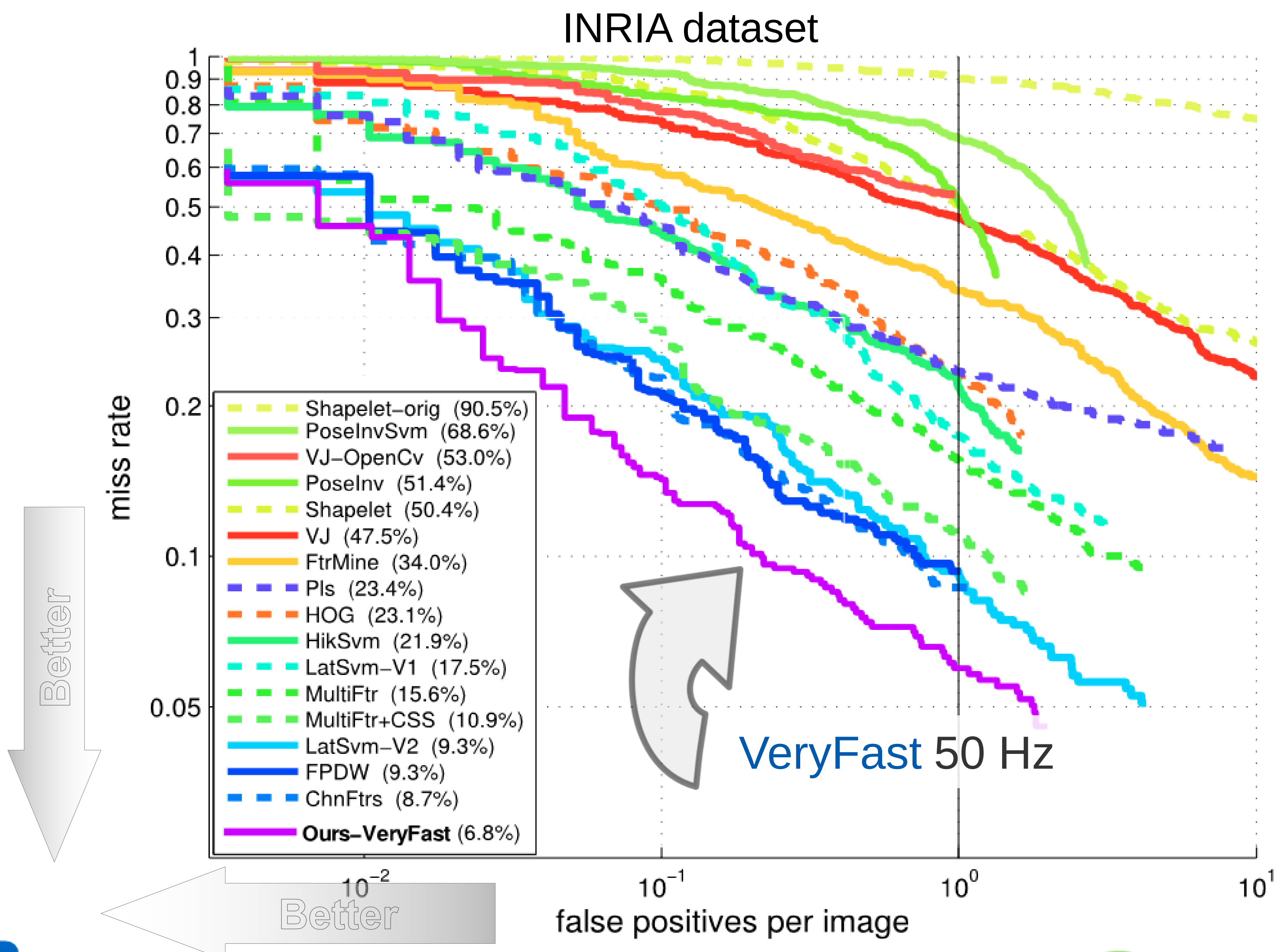


Performance Comparison of Detectors



Slide credit: Rodrigo Benenson

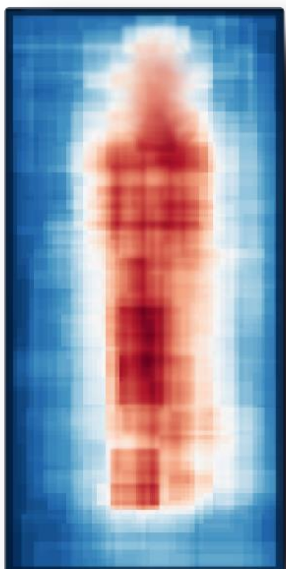
Performance Comparison of Detectors

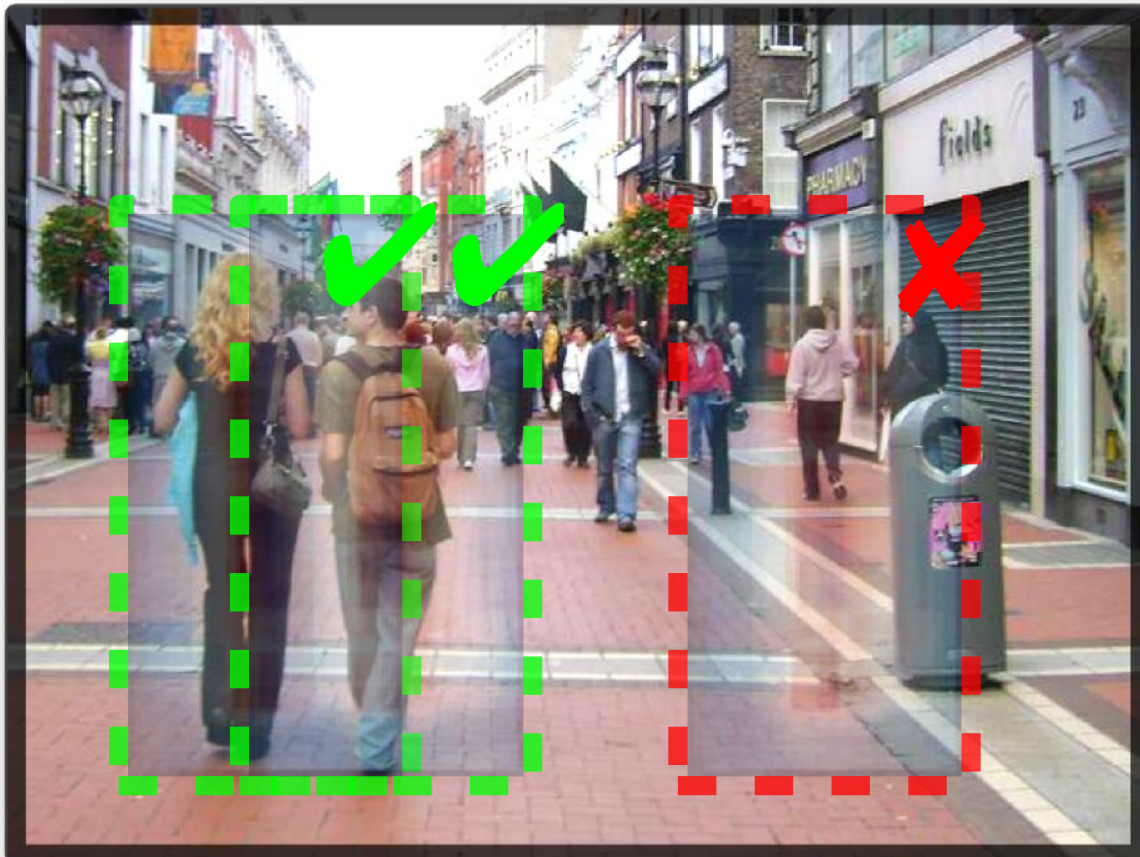


Slide credit: Rodrigo Benenson

Issues for Efficient Detection

- One template cannot detect at multiple scales...



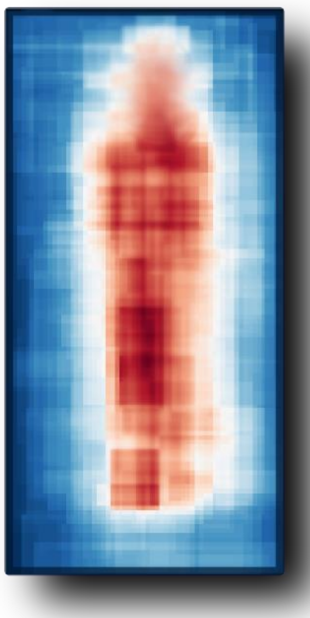


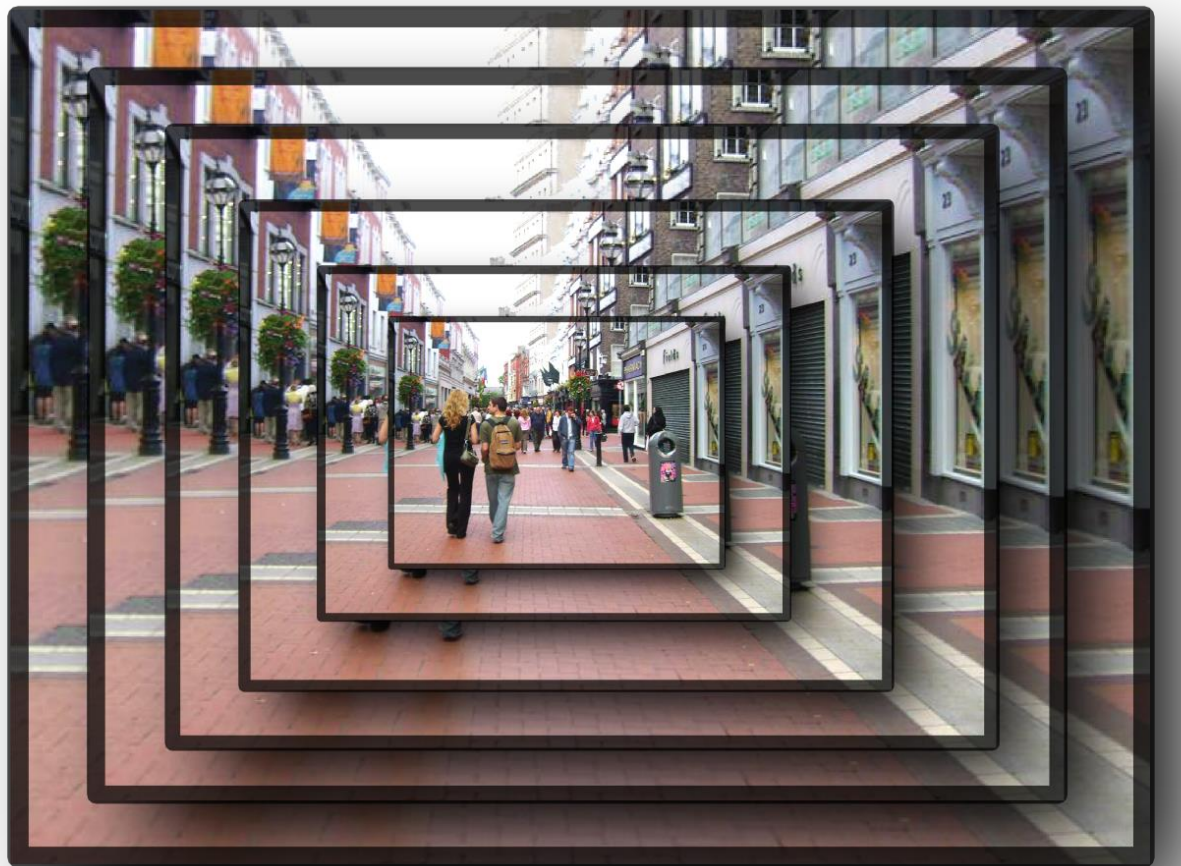
Slide credit: Rodrigo Benenson

Issues for Efficient Detection

- Typically, features are computed many times

~50 scales





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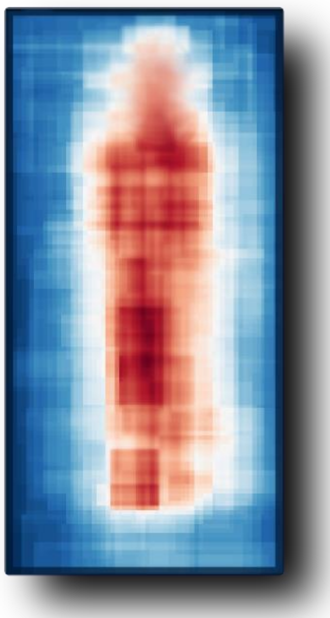
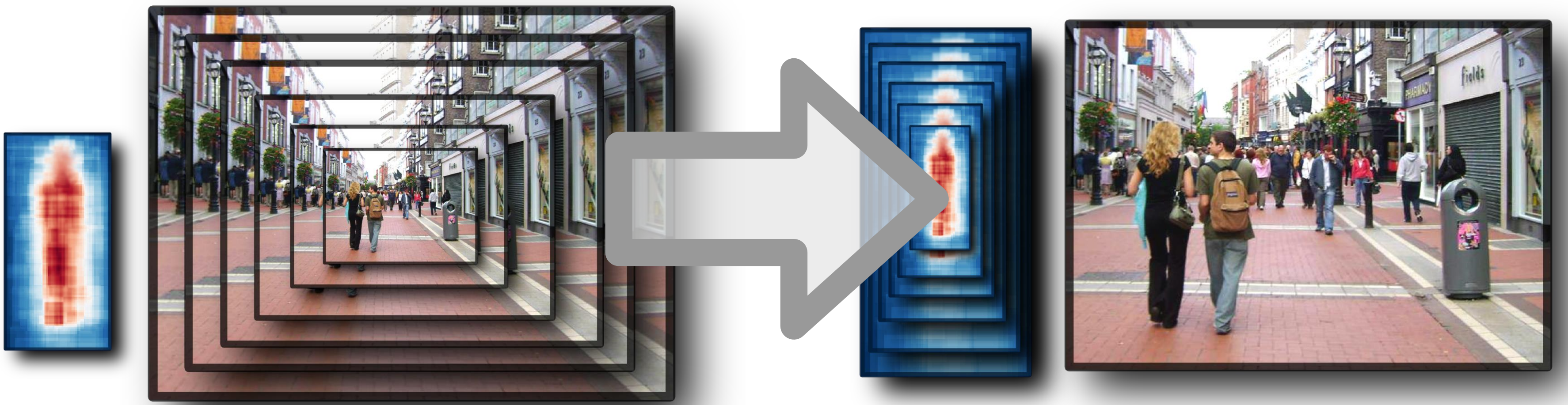


Slide credit: Rodrigo Benenson

VeryFast Detector

- Idea 1: Invert the relation



1 model,
50 image scales

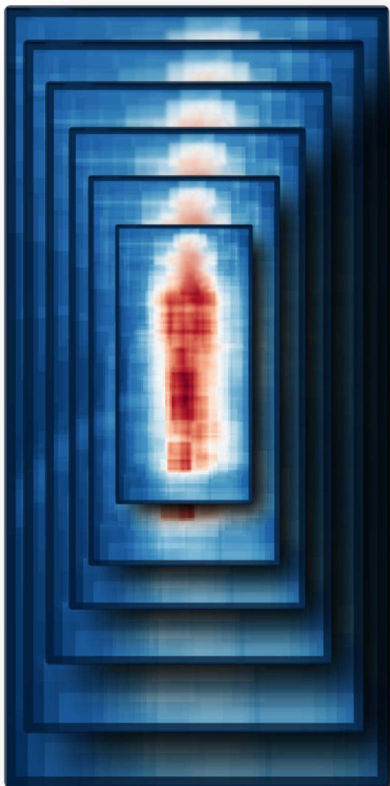
50 models,
1 image scale

R. Benenson, M. Mathias, R. Timofte, L. Van Gool. Pedestrian Detection at 100 Frames per Second, CVPR’12.

Slide credit: Rodrigo Benenson

Practical Considerations

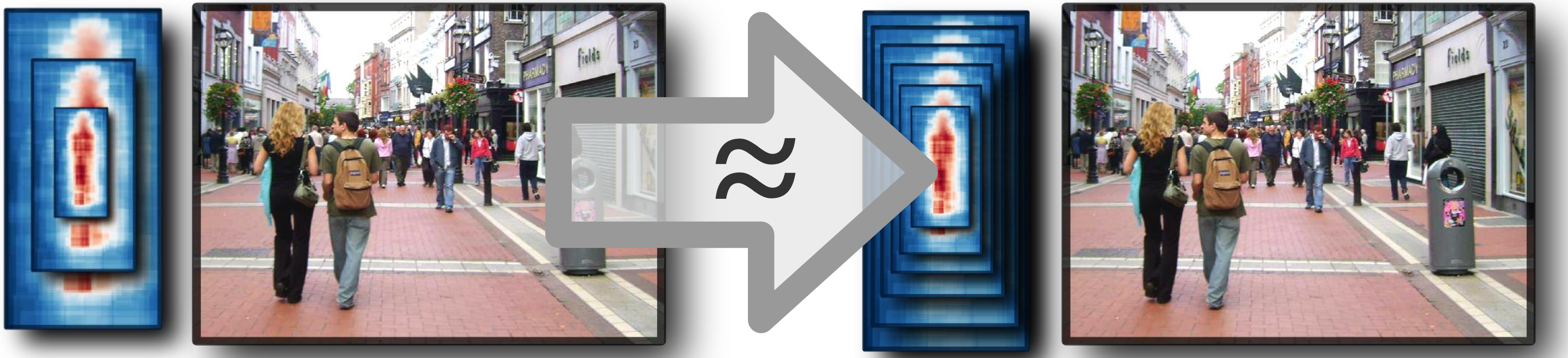
- Training and running 1 model/scale is too expensive



Slide credit: Rodrigo Benenson

VeryFast Detector

- Idea 2: Reduce training time by feature interpolation



5 models,
1 image scale

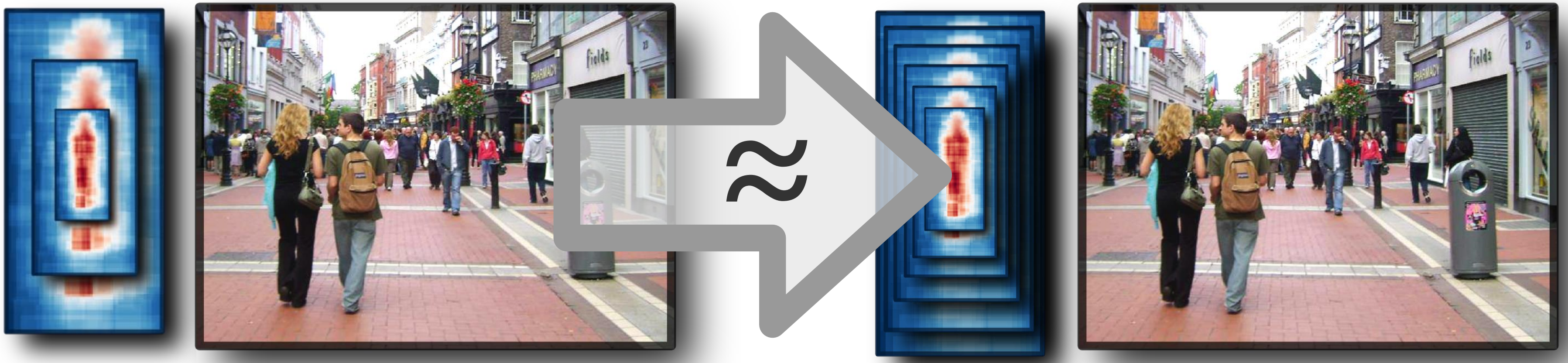
50 models,
1 image scale

- Shown to be possible for Integral Channel features
  – P. Dollár, S. Belongie, Perona. The Fastest Pedestrian Detector in the West, BMVC 2010.

Slide credit: Rodrigo Benenson

VeryFast Detector

- Effect: Transfer test time computation to training time



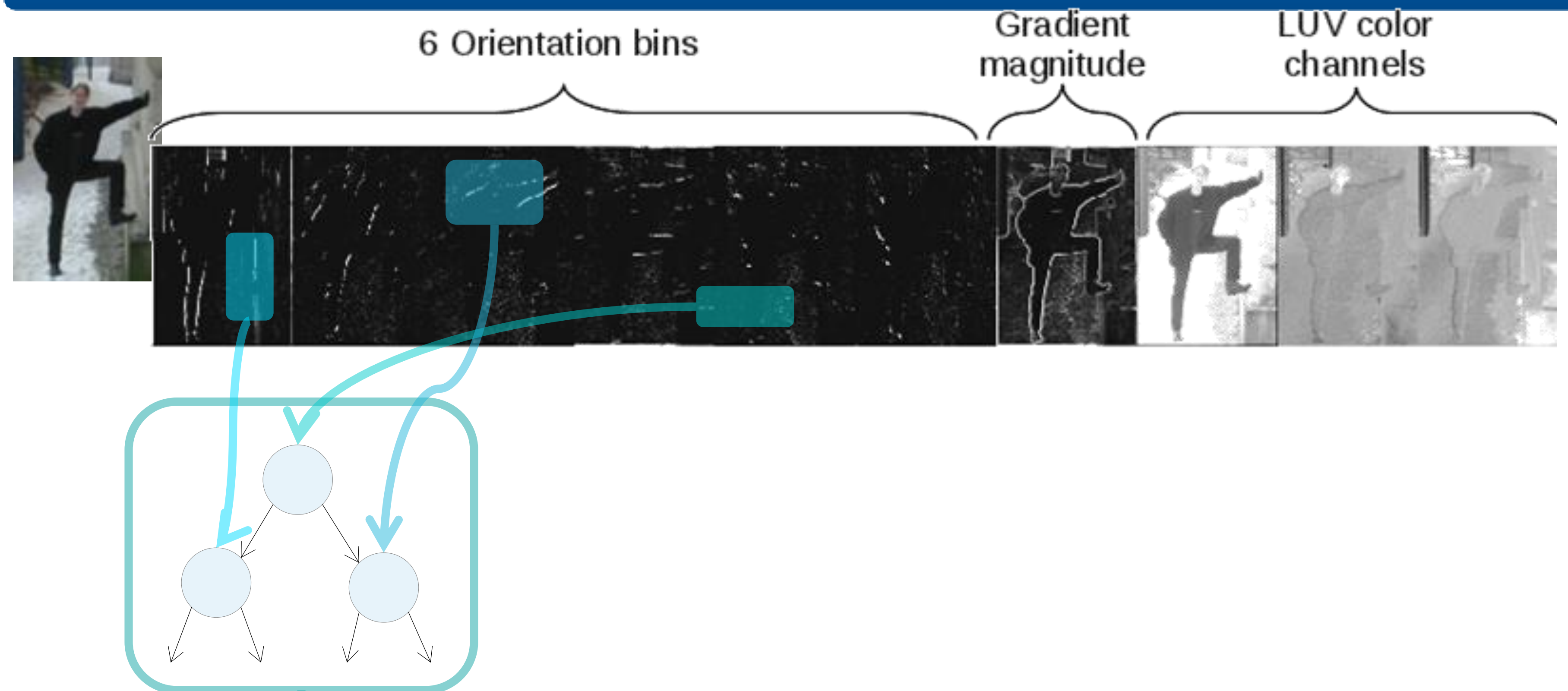
5 models,
1 image scale

50 models,
1 image scale

⇒ *Result: 3x reduction in feature computation*

Slide credit: Rodrigo Benenson

VeryFast: Classifier Construction

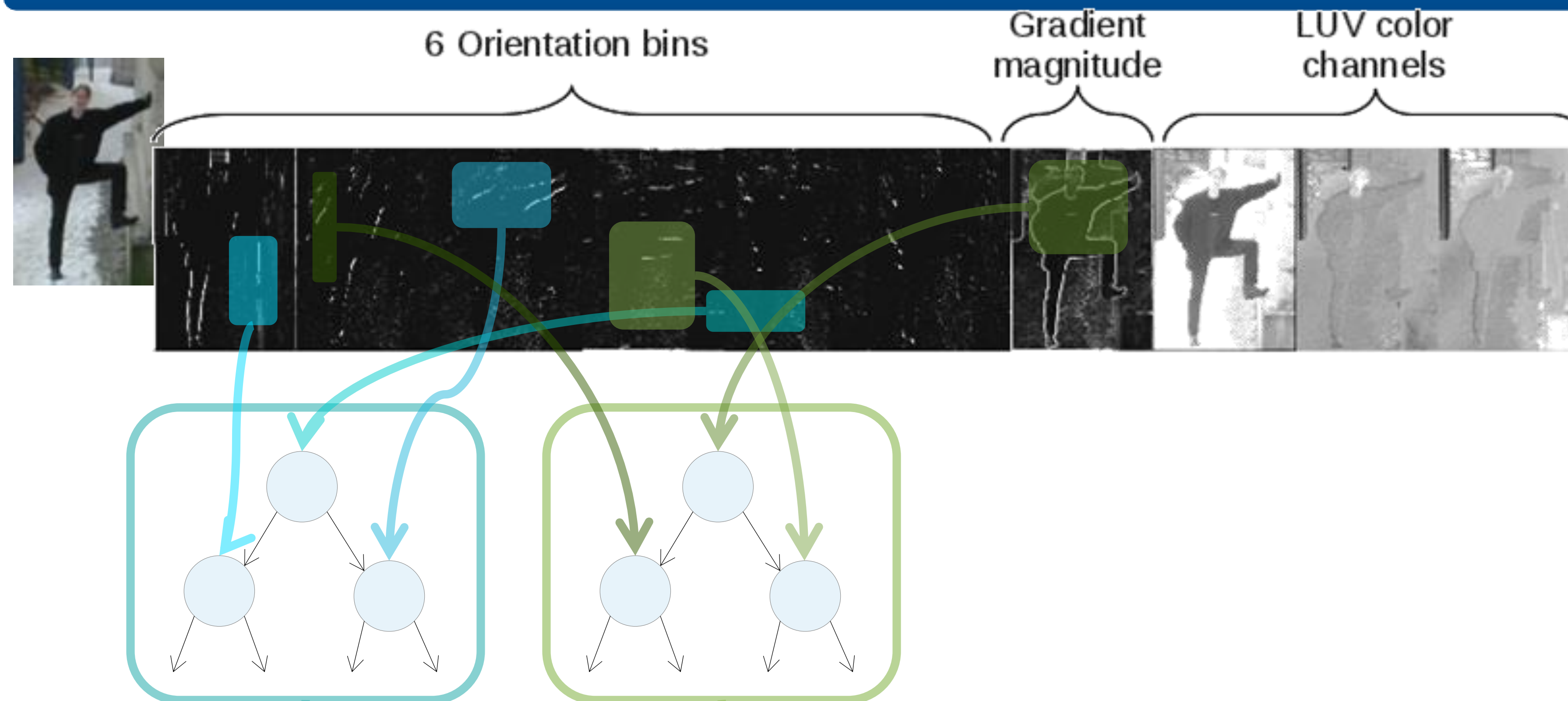


$$score = w_1 \cdot h_1 +$$

- Ensemble of short trees, learned by AdaBoost

Slide credit: Rodrigo Benenson

VeryFast: Classifier Construction

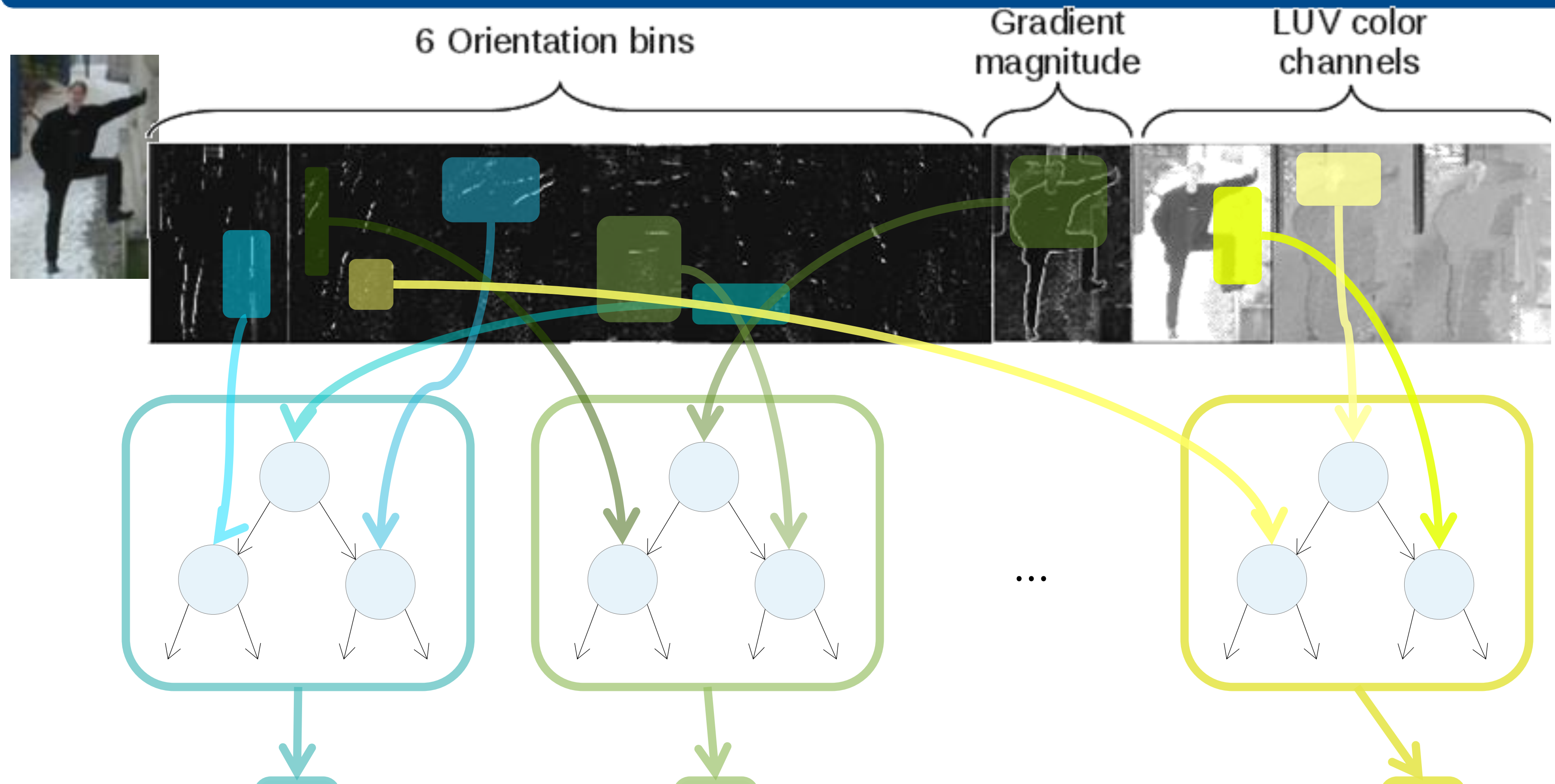


$$score = w_1 \cdot \boxed{h_1} + \quad w_2 \cdot \boxed{h_2} +$$

- Ensemble of short trees, learned by AdaBoost

Slide credit: Rodrigo Benenson

VeryFast: Classifier Construction

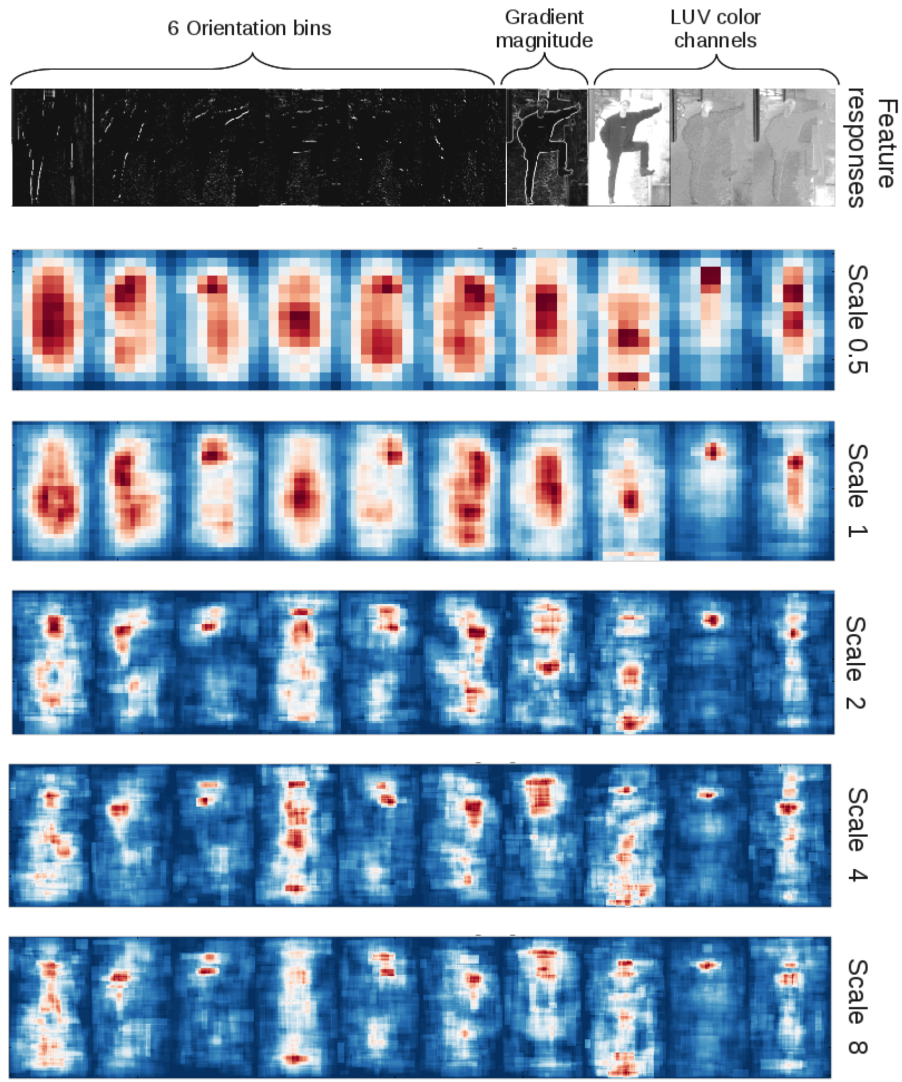


$$score = w_1 \cdot \boxed{h_1} + \quad w_2 \cdot \boxed{h_2} + \quad \ldots \quad + w_N \cdot \boxed{h_N}$$

- Ensemble of short trees, learned by AdaBoost

Slide credit: Rodrigo Benenson

Learned Models



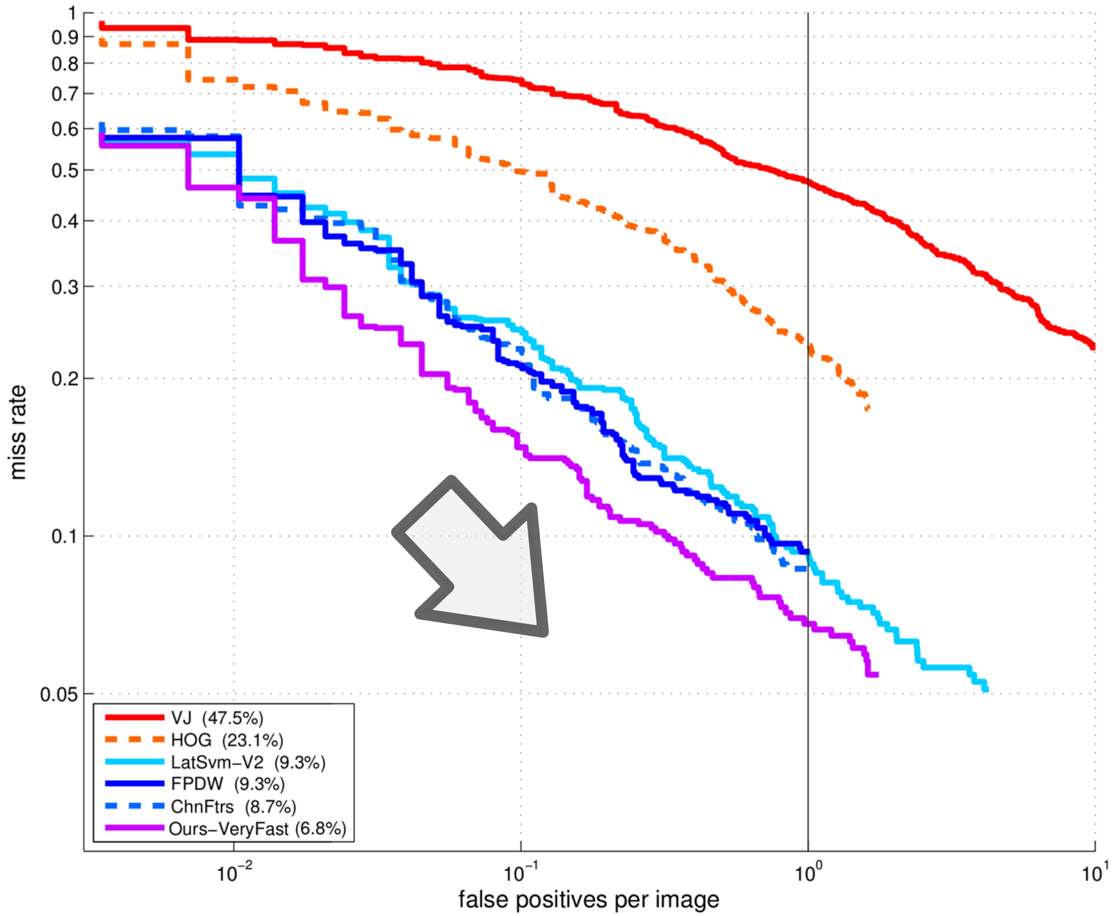
Integral Channel features

Models

⋮

Slide credit: Rodrigo Benenson

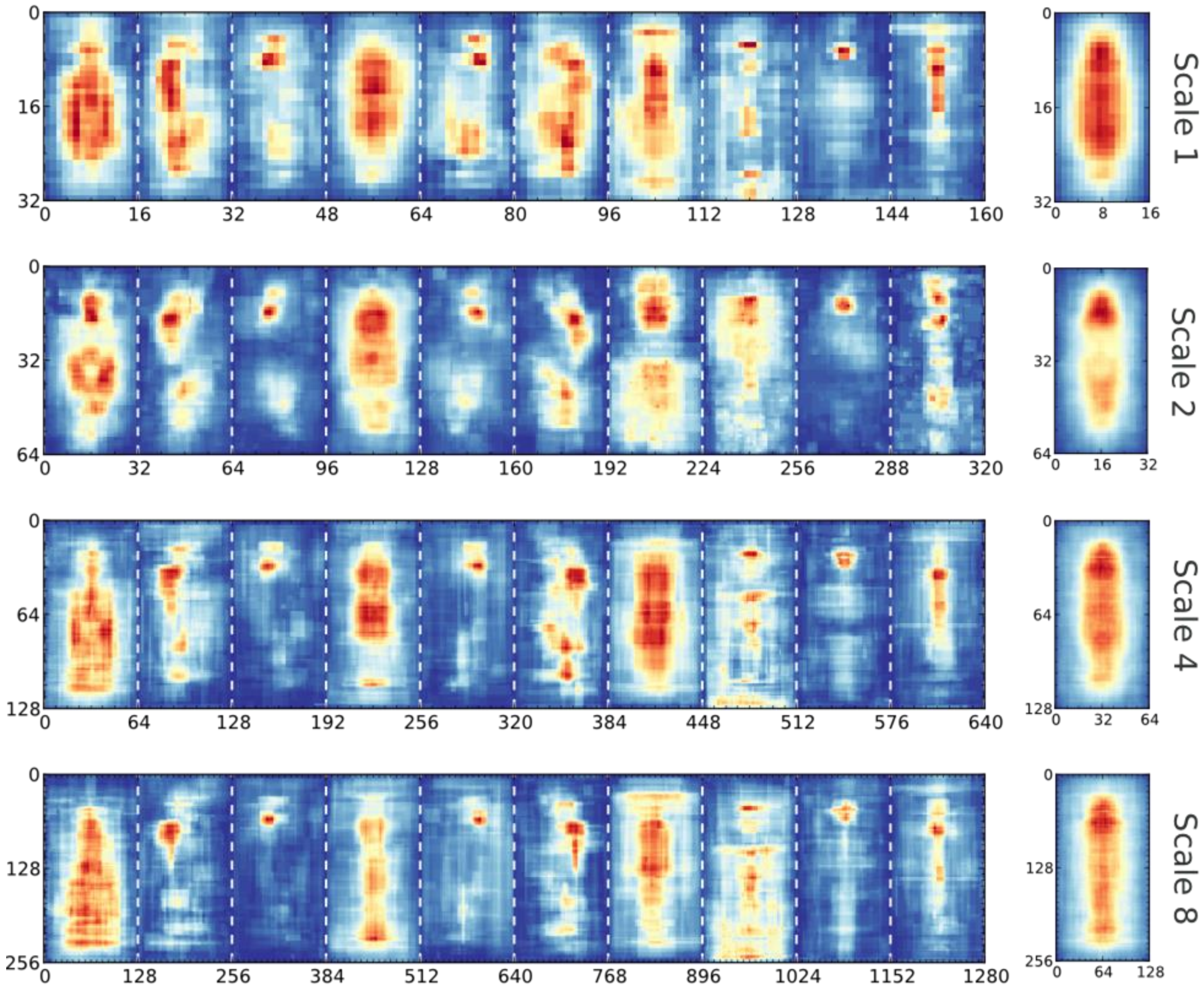
Results



- Detection without resizing improves quality of results

Slide credit: Rodrigo Benenson

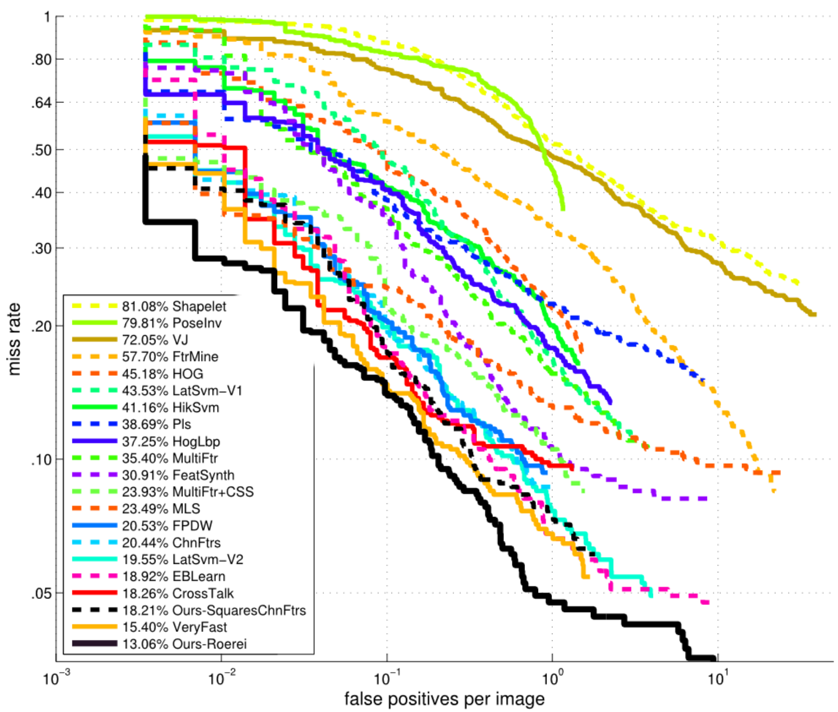
Multi-Scale Models > Single-Scale Model



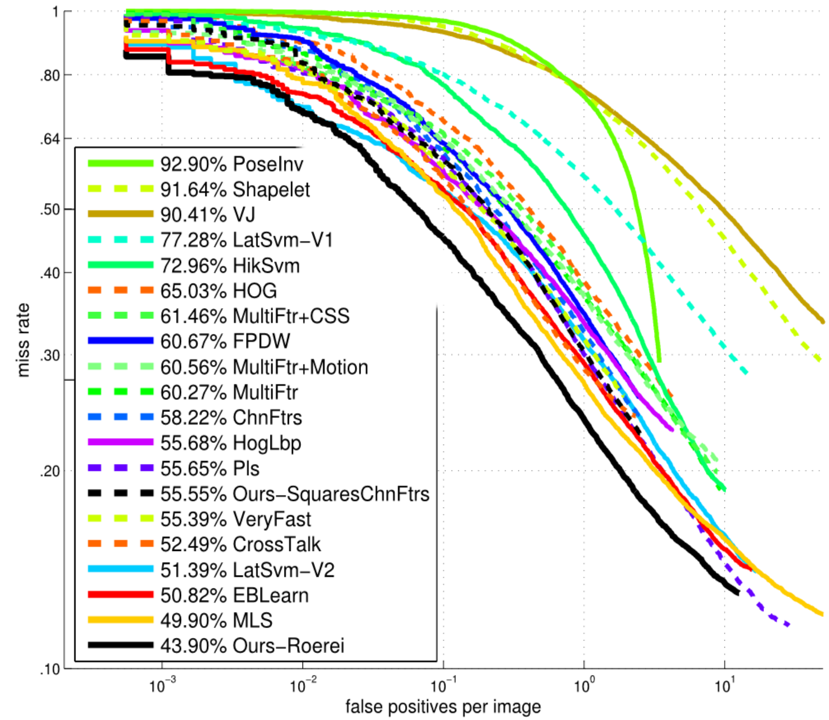
Slide adapted from Rodrigo Benenson

Comparison to State-of-the-Art

INRIA dataset



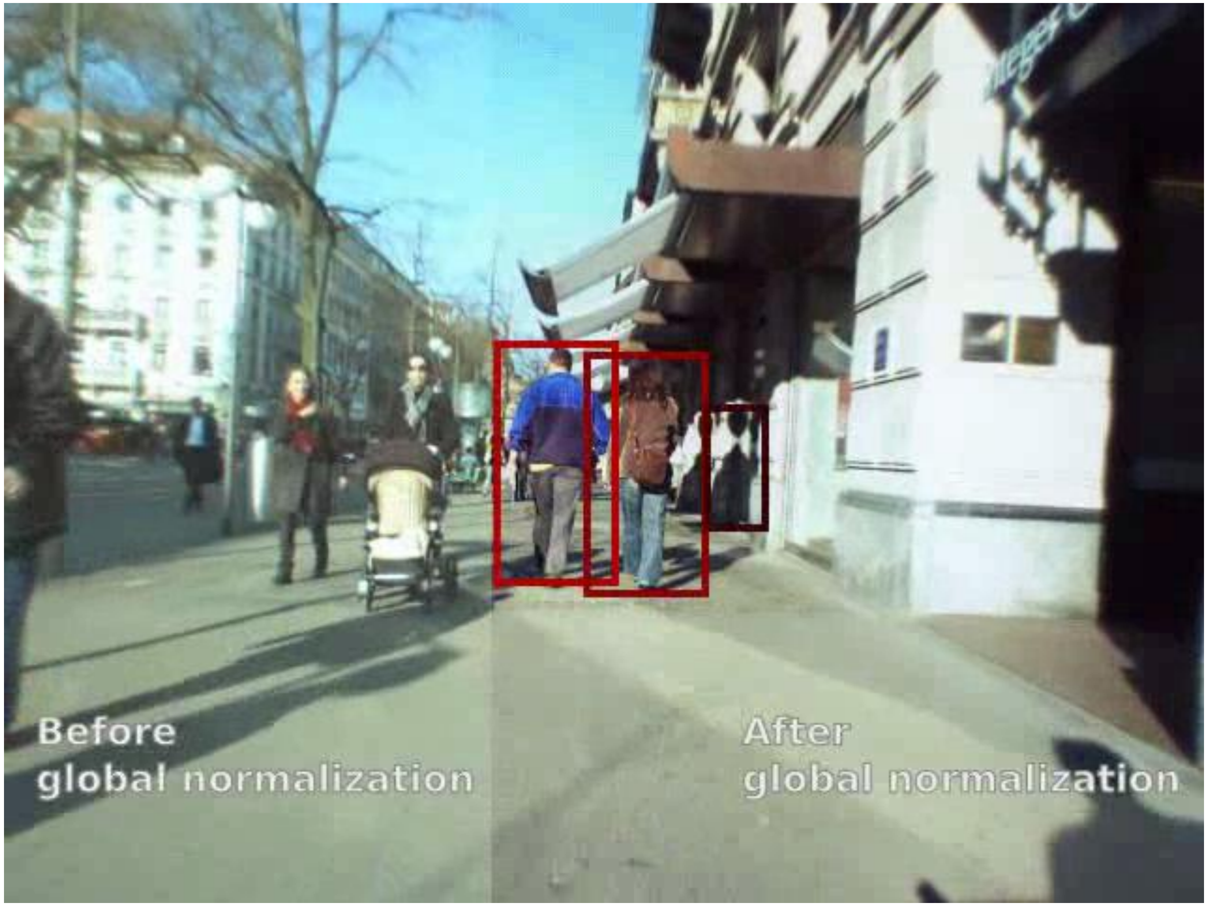
ETH dataset



- Extension: Roerei detector
  - Detailed evaluation of design space
  - Non-regular pooling regions found to work best.

Slide adapted from Rodrigo Benenson

Roerei Results



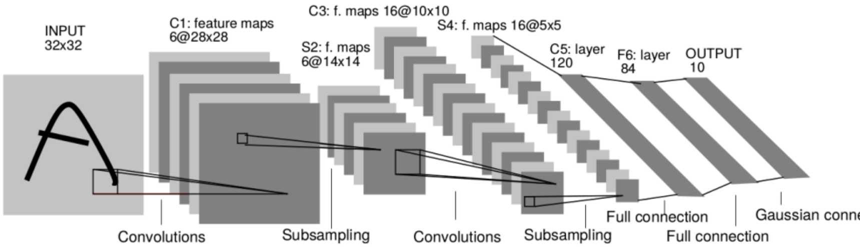
R. Benenson, M. Mathias, R. Timofte, L. Van Gool. [Seeking the Strongest Rigid Detector](). CVPR'13.

Applications: Mobile Robot Navigation

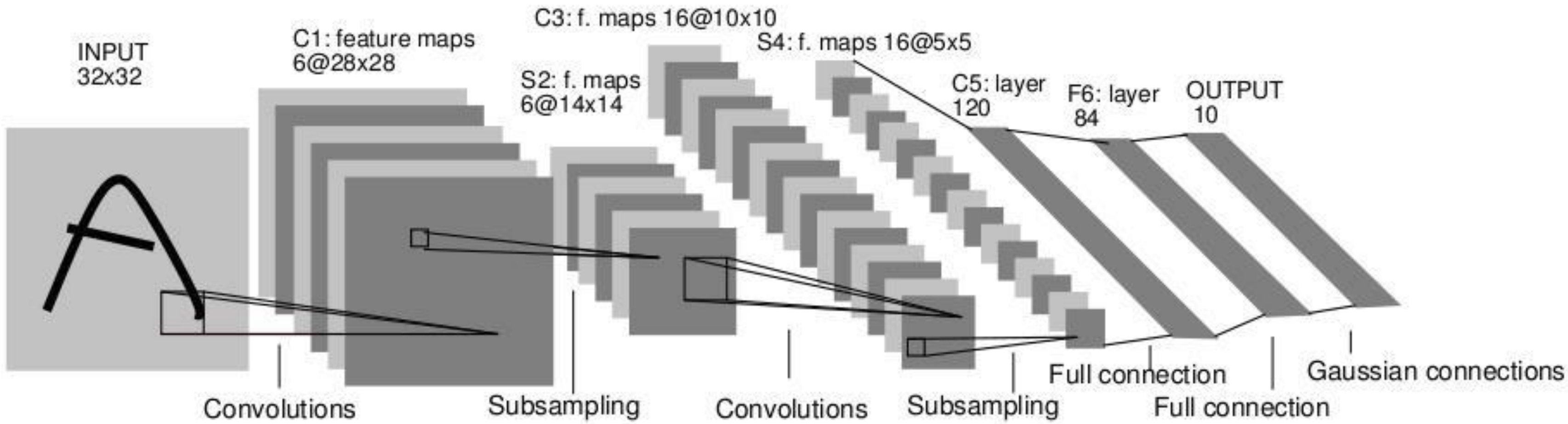
[link to the video]

Topics of This Lecture

- Tracking by Detection
  – Motivation
  – Recap: Object detection
- SVM based Detectors
  – Recap: HOG
  – DPM
- AdaBoost based Detectors
  – Recap: Viola-Jones
  – Integral Channel features
  – VeryFast/Roerei
- CNN-based Detectors
  – Recap: CNNs
  – R-CNN



Recap: Convolutional Neural Networks

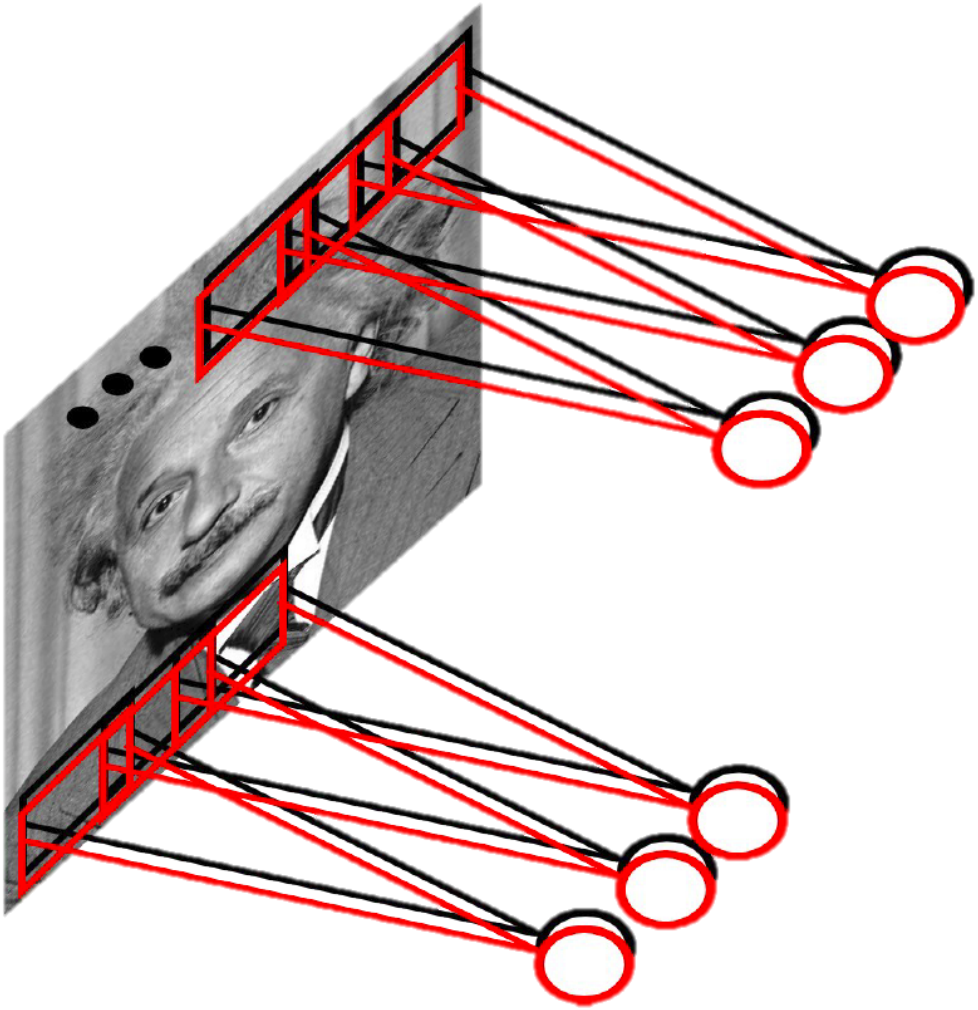


- Neural network with specialized connectivity structure
  - Stack multiple stages of feature extractors
  - Higher stages compute more global, more invariant features
  - Classification layer at the end

Y. LeCun, L. Bottou, Y. Bengio, and P. Haffner, Gradient-based learning applied to document recognition, Proceedings of the IEEE 86(11): 2278–2324, 1998.

Slide credit: Svetlana Lazebnik

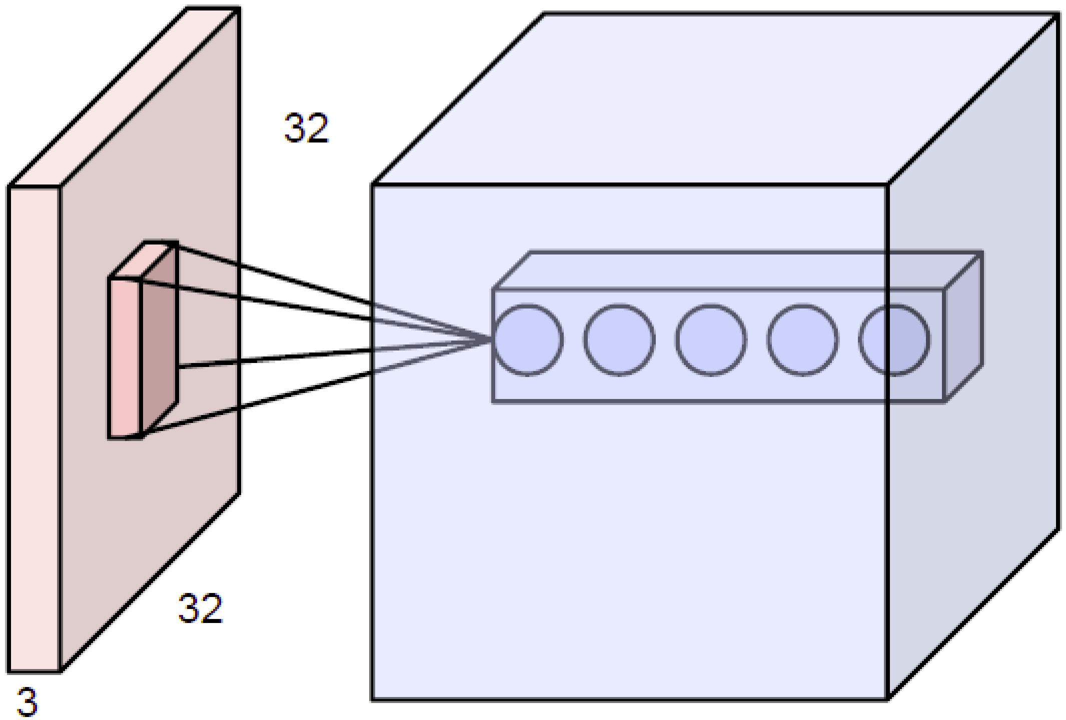
Recap: Intuition of CNNs



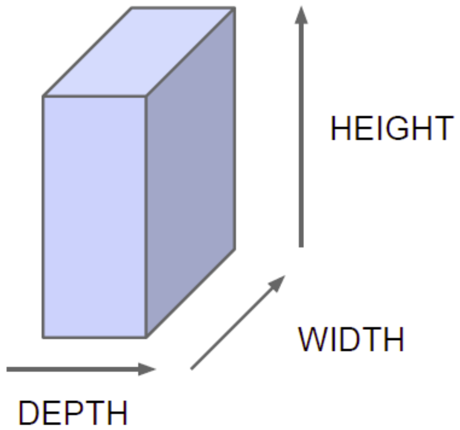
- Convolutional net
  - Share the same parameters across different locations
  - Convolutions with learned kernels
- Learn *multiple* filters
  - E.g. 1000×1000 image
    100 filters
    10×10 filter size
    $\Rightarrow$ only 10k parameters
- Result: Response map
  - size: $1000\times1000\times100$
  - Only memory, not params!

Slide adapted from Marc'Aurelio Ranzato

Recap: Convolution Layers



Naming convention:

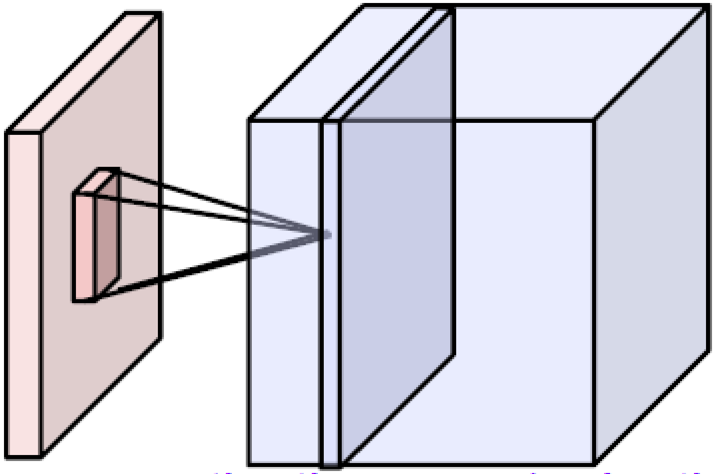


- All Neural Net activations arranged in 3 dimensions
  - Multiple neurons all looking at the same input region, stacked in depth
  - Form a single [$1\times1\times$depth] depth column in output volume.

Slide credit: FeiFei Li, Andrej Karpathy

Recap: Activation Maps

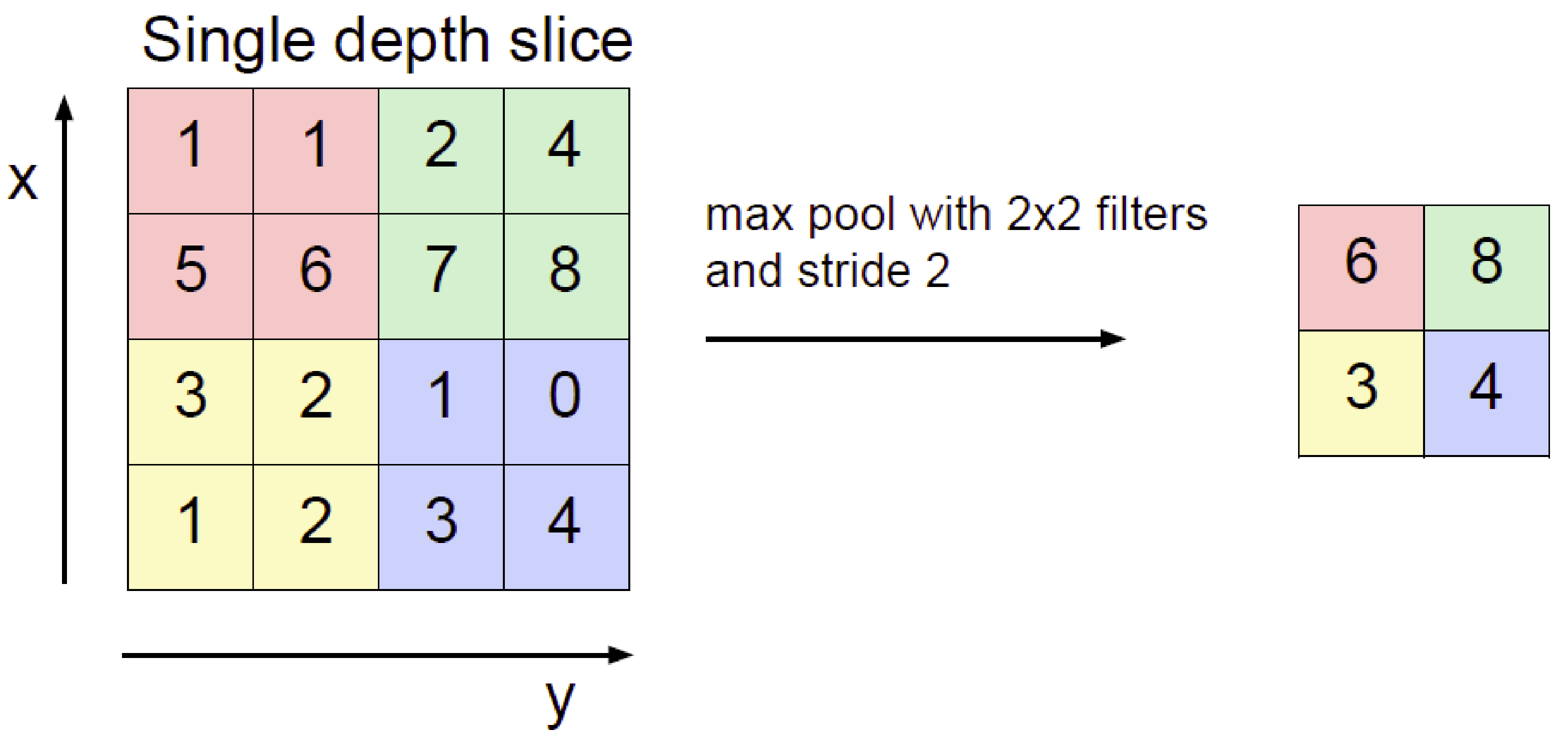
5×5 filters



Activation maps

Slide adapted from FeiFei Li, Andrej Karpathy

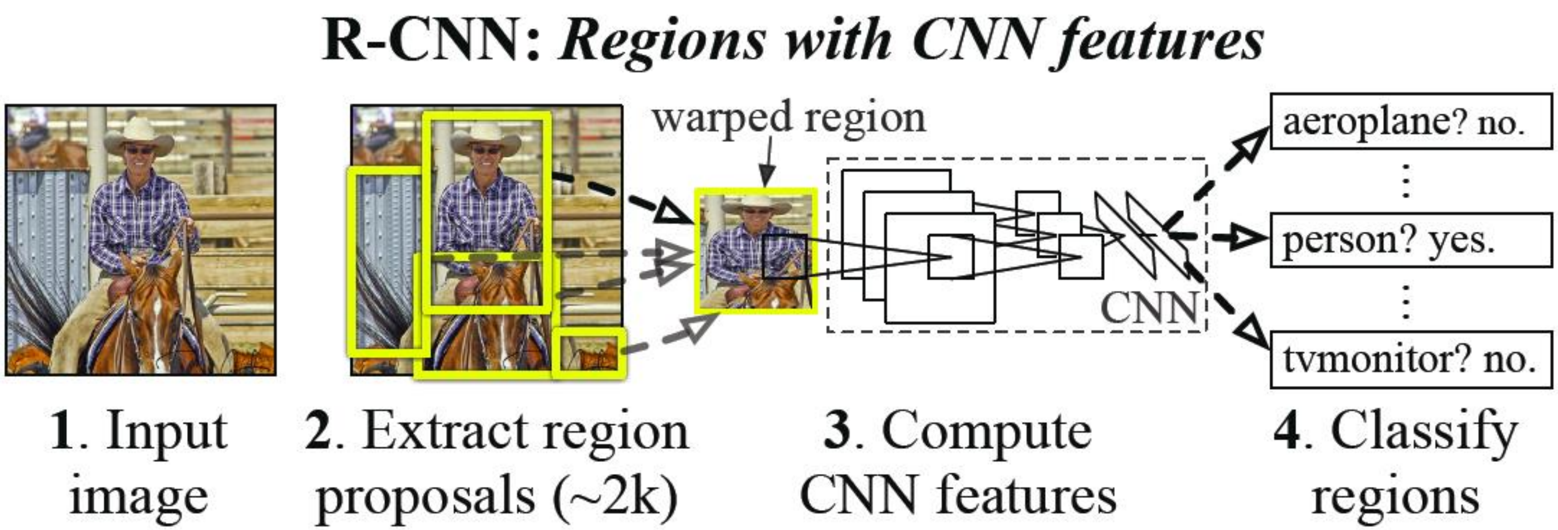
Recap: Pooling Layers



- Effect:
  - Make the representation smaller without losing too much information
  - Achieve robustness to translations

Slide adapted from FeiFei Li, Andrej Karpathy

R-CNN Detector



- Results on PASCAL VOC Detection benchmark
  - Pre-CNN state of the art: 35.1% mAP [Uijlings et al., 2013]
    33.4% mAP DPM
  - R-CNN: 53.7% mAP

R. Girshick, J. Donahue, T. Darrell, and J. Malik, Rich Feature Hierarchies for Accurate Object Detection and Semantic Segmentation, CVPR 2014

You Can Try All of This At Home…

- Detector code is publicly available
  - HOG:
    - Dalal's original implementation: http://www.navneetdalal.com/software/
    - Our CUDA-optimized *groundHOG* code (>80 fps on GTX 580) http://www.mmp.rwth-aachen.de/projects/groundhog
  - DPM:
    - Felzenswalb's original implementation: http://www.cs.uchicago.edu/~pff/latent
  - VeryFast
    - Benenson's original implementation: https://bitbucket.org/rodrigob/doppia/
  - R-CNN
    - Girshick's original implementation: https://github.com/rbgirshick/rcnn