Computer Vision 2
WS 2018/19

Part 5 – Tracking by Online Classification
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Course Outline

- Single-Object Tracking
  - Background modeling
  - Template based tracking
  - Tracking by online classification
  - Tracking-by-detection
- Bayesian Filtering
- Multi-Object Tracking
- Visual Odometry
- Visual SLAM & 3D Reconstruction
- Deep Learning for Video Analysis

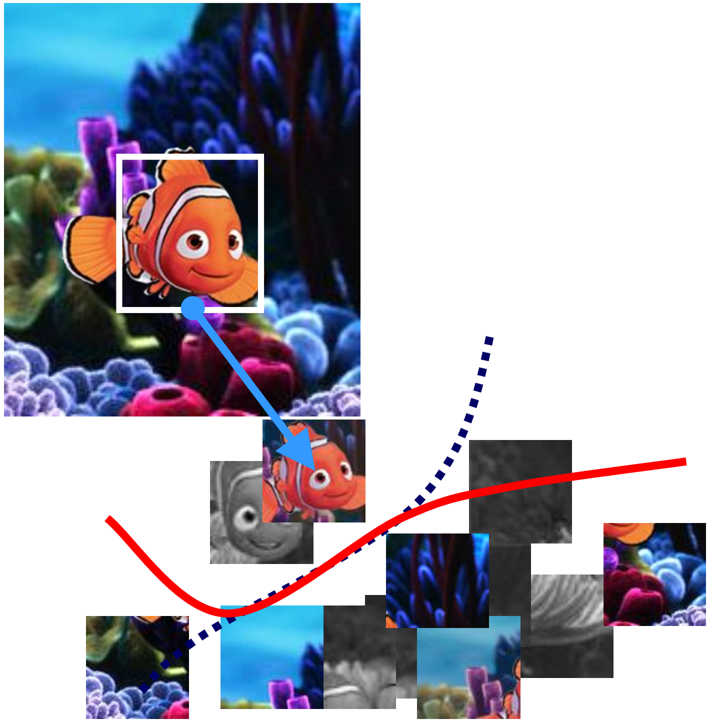


Image source: Robert Collins

Recap: General LK Image Registration

- Goal
  - Find the warping parameters $\mathbf{p}$ that minimize the sum-of-squares intensity difference between the template image $T(\mathbf{x})$ and the warped input image $I(\mathbf{W}(\mathbf{x};\mathbf{p}))$.

- LK formulation
  - Formulate this as an optimization problem

$$\arg\min_{\mathbf{p}} \sum_{\mathbf{x}} \left[I(\mathbf{W}(\mathbf{x};\mathbf{p})) - T(\mathbf{x}) \right]^2$$

  - We assume that an initial estimate of $\mathbf{p}$ is known and iteratively solve for increments to the parameters $\Delta\mathbf{p}$:

$$\arg\min_{\Delta\mathbf{p}} \sum_{\mathbf{x}} \left[I(\mathbf{W}(\mathbf{x};\mathbf{p}+\Delta\mathbf{p})) - T(\mathbf{x}) \right]^2$$

Recap: Step-by-Step Derivation

- Key to the derivation
  - Taylor expansion around $\Delta\mathbf{p}$

$$I(\mathbf{W}(\mathbf{x};\mathbf{p}+\Delta\mathbf{p})) \approx I(\mathbf{W}(\mathbf{x};\mathbf{p})) + \nabla I \frac{\partial \mathbf{W}}{\partial \mathbf{p}} \Delta\mathbf{p} + \mathcal{O}(\Delta\mathbf{p}^2)$$

$$= I(\mathbf{W}([x,y];p_1,\dots,p_n))$$

$$+ \begin{bmatrix} \frac{\partial I}{\partial x} & \frac{\partial I}{\partial y} \end{bmatrix} \begin{bmatrix} \frac{\partial W_x}{\partial p_1} & \frac{\partial W_x}{\partial p_2} & \cdots & \frac{\partial W_x}{\partial p_n} \\ \frac{\partial W_y}{\partial p_1} & \frac{\partial W_y}{\partial p_2} & \cdots & \frac{\partial W_y}{\partial p_n} \end{bmatrix} \begin{bmatrix} \Delta p_1 \\ \Delta p_2 \\ \vdots \\ \Delta p_n \end{bmatrix}$$

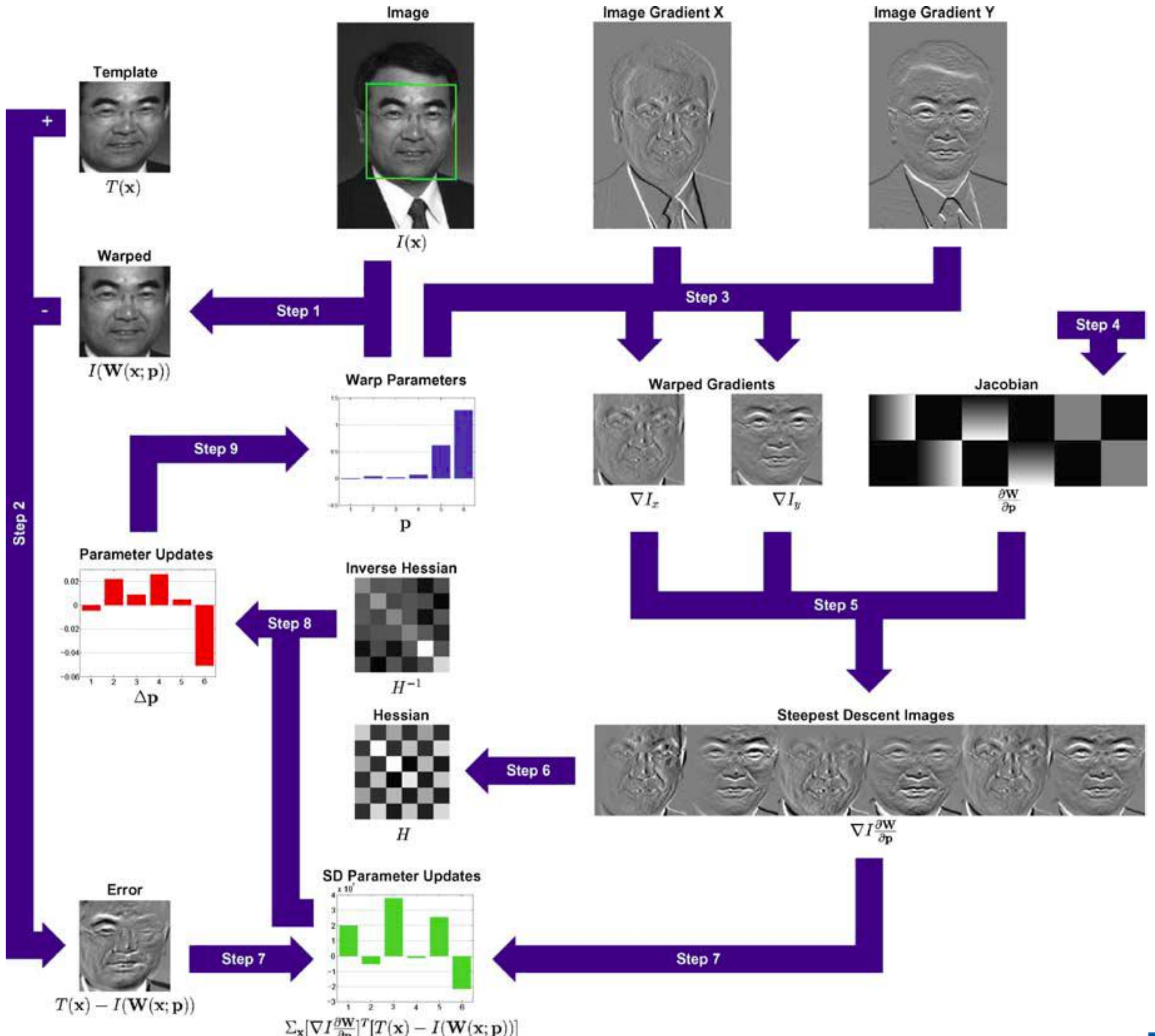
Gradient	Jacobian	Increment parameters to solve for
∇I	$\frac{\partial \mathbf{W}}{\partial \mathbf{p}}$	$\Delta\mathbf{p}$

Slide credit: Robert Collins

Recap: Inverse Compositional LK Algorithm

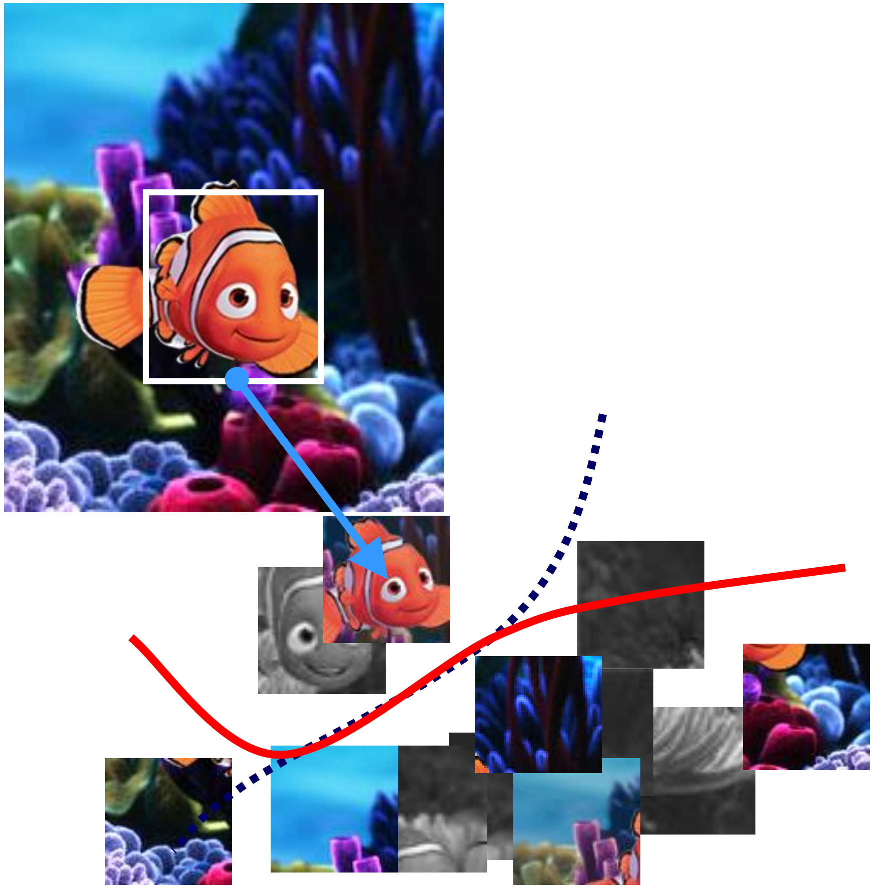
- Iterate
  - Warp I to obtain $I(\mathbf{W}([x,\ y];\ \mathbf{p}))$
  - Compute the error image $T([x,\ y])$ – $I(\mathbf{W}([x,\ y];\ \mathbf{p}))$
  - Warp the gradient ∇I with $\mathbf{W}([x,\ y];\ \mathbf{p})$
  - Evaluate $\frac{\partial \mathbf{W}}{\partial \mathbf{p}}$ at $([x,\ y];\ \mathbf{p})$ (Jacobian)
  - Compute steepest descent images $\nabla I \frac{\partial \mathbf{W}}{\partial \mathbf{p}}$
  - Compute Hessian matrix $\mathbf{H} = \sum_{\mathbf{x}} \left[\nabla I \frac{\partial \mathbf{W}}{\partial \mathbf{p}}\right]^T \left[\nabla I \frac{\partial \mathbf{W}}{\partial \mathbf{p}}\right]$
  - Compute $\sum_{\mathbf{x}} \left[\nabla I \frac{\partial \mathbf{W}}{\partial \mathbf{p}}\right]^T [T([x,y]) - I(\mathbf{W}([x,y];\mathbf{p}))]$
  - Compute $\Delta\mathbf{p} = \mathbf{H}^{-1} \sum_{\mathbf{x}} \left[\nabla I \frac{\partial \mathbf{W}}{\partial \mathbf{p}}\right]^T [T([x,y]) - I(\mathbf{W}([x,y];\mathbf{p}))]$
  - Update the parameters $\mathbf{p} \leftarrow \mathbf{p} + \Delta\mathbf{p}$
- Until $\Delta\mathbf{p}$ magnitude is negligible

Recap: Inverse Compositional LK Algorithm



[S. Baker, I. Matthews, IJCV'04]

Today: Tracking by Online Classification



Can Machine Learning solve the problem for us?

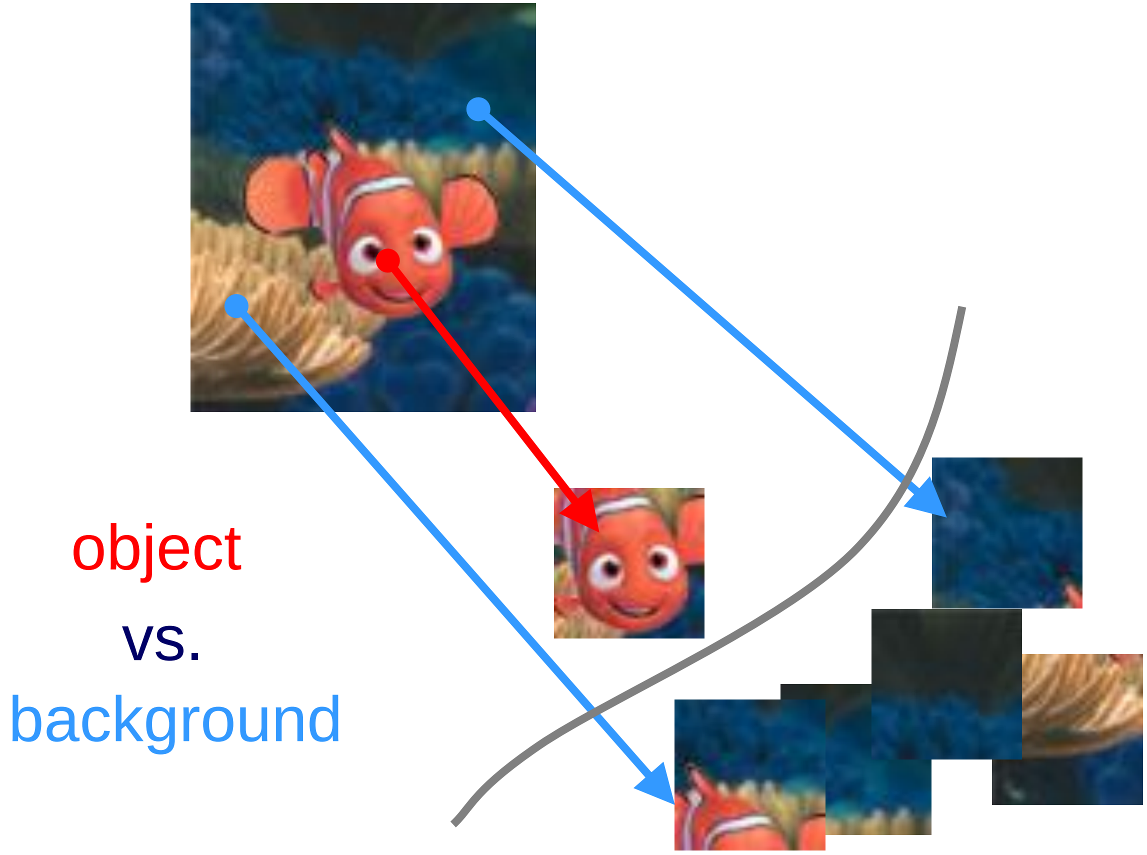
Image source: Helmut Grabner, Disney/Pixar

Topics of This Lecture

- Tracking by Online Classification
  - Motivation
- Recap: Boosting for Detection
  - AdaBoost
  - Viola-Jones Detector
- Extension to Online Classification
  - Online Boosting
  - Online Feature Selection
  - Results
- Extensions
  - Problem: Drift
  - Drift-compensation strategies

Tracking as Classification

- Tracking as binary classification problem

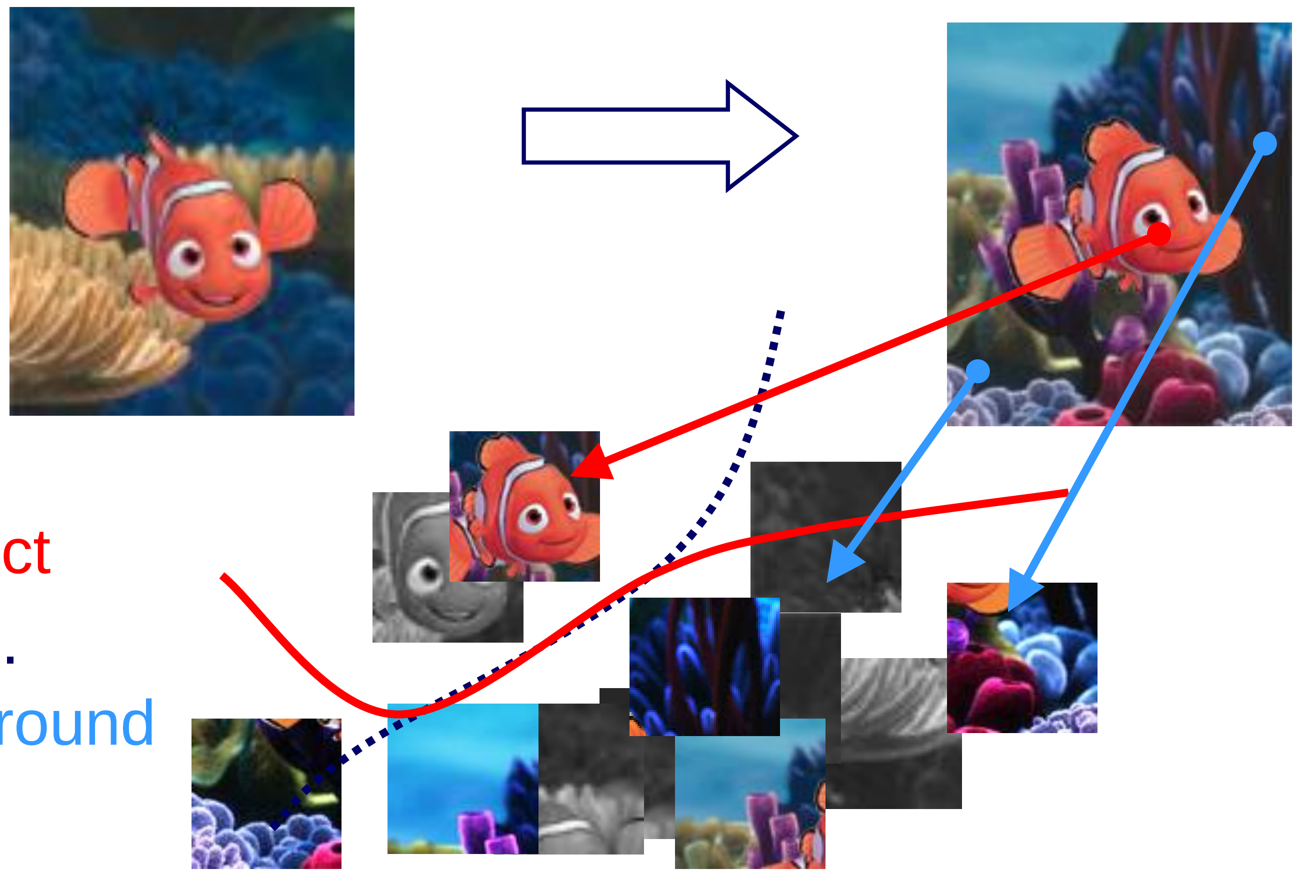


Slide credit: Helmut Grabner

Image source: Disney/Pixar

Tracking as Classification

- Tracking as binary classification problem



object

vs.

background

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

Slide credit: Helmut Grabner

Image source: Disney/Pixar

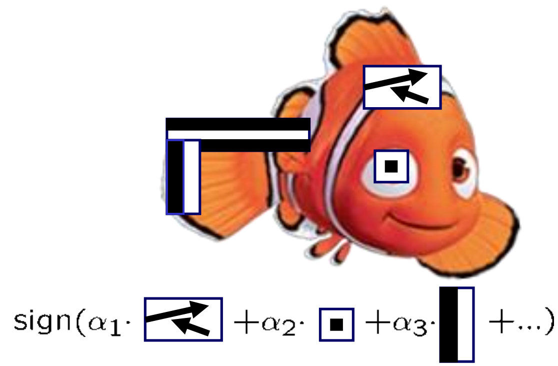
Idea: Use Boosting for Feature Selection

Object Detector

Fixed training set
General object detector

Object Tracker

On-line update
Object vs. Background



Boosting for Feature Selection

P. Viola, M. Jones. Rapid Object Detection using a Boosted Cascade of Simple Features. CVPR'01.

On-Line Boosting for Feature Selection

H. Grabner, H. Bischof. On-line Boosting and Vision. CVPR'06.

Slide credit: Helmut Grabner

Image source: Disney/Pixar

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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:

$$w_n^{(m+1)} = w_n^{(m)} \exp\left\{\alpha_m I(h_m(\mathbf{x}_n) \neq t_n)\right\}$$

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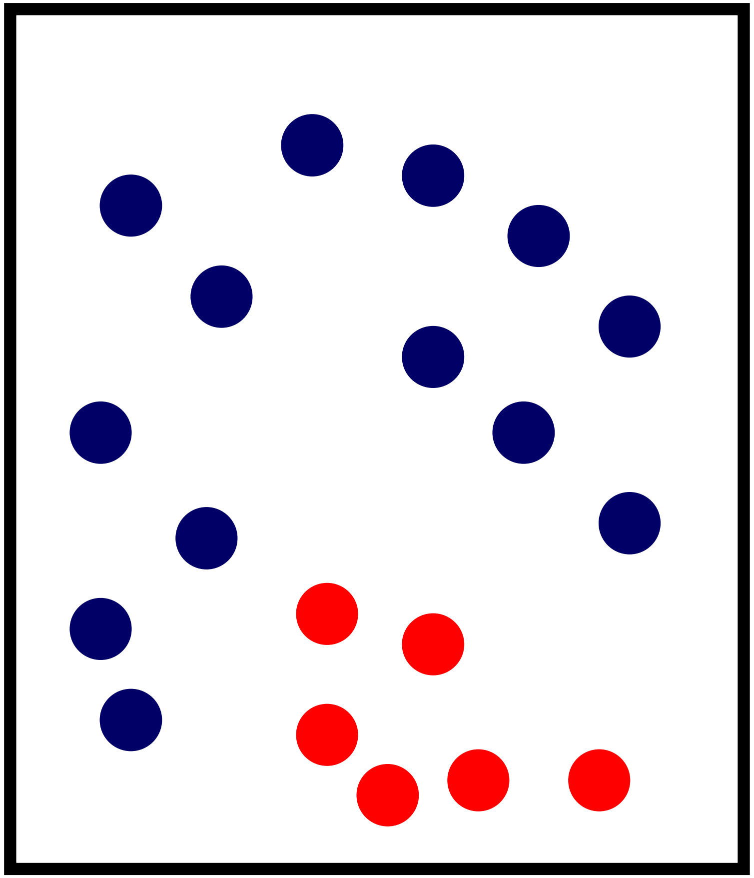
Offline Boosting



Given:

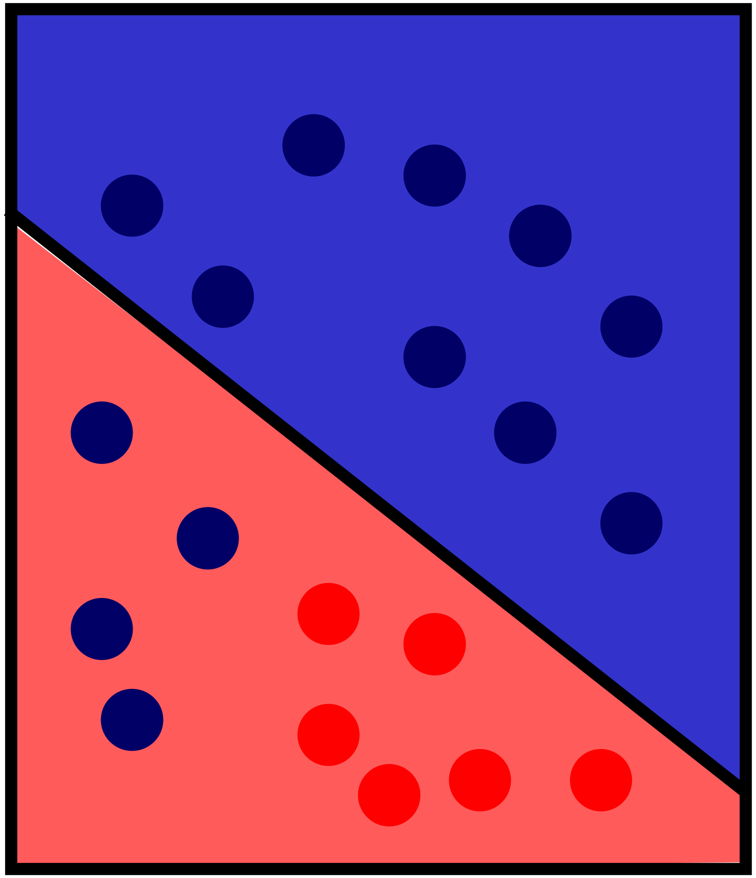
- set of labeled training samples
- weight distribution over them

Algorithm:

```
for n = 1 to N
    - train a weak classifier using
      samples and weight dist.
    - calculate error
    - calculate weight
    - update weight dist.
next
```


Slide credit: Helmut Grabner

Offline Boosting



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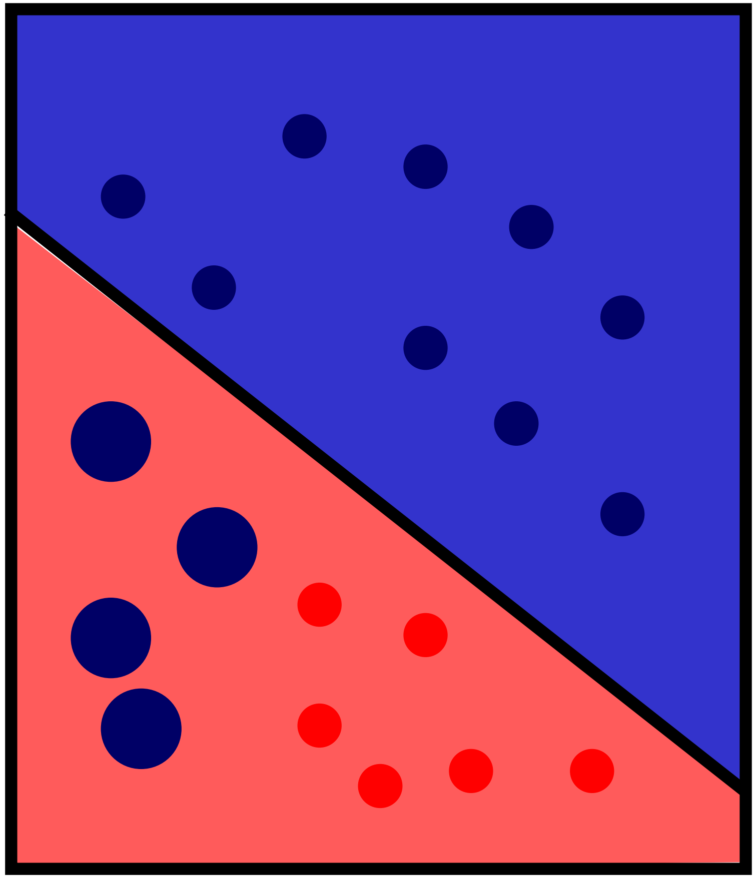
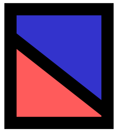


$\alpha_1 \cdot$



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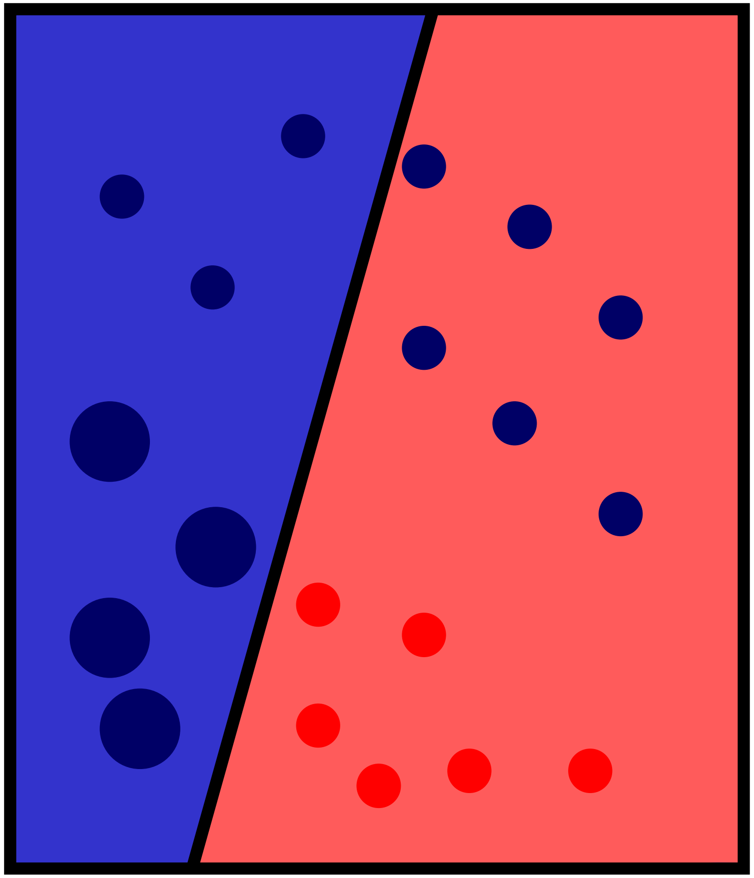

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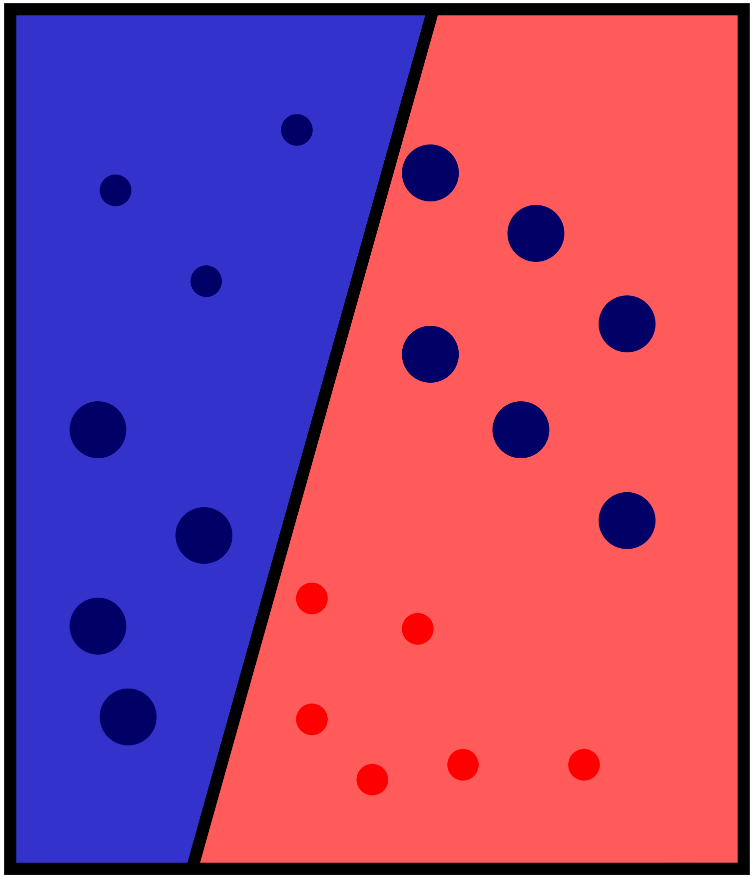

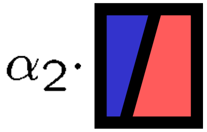

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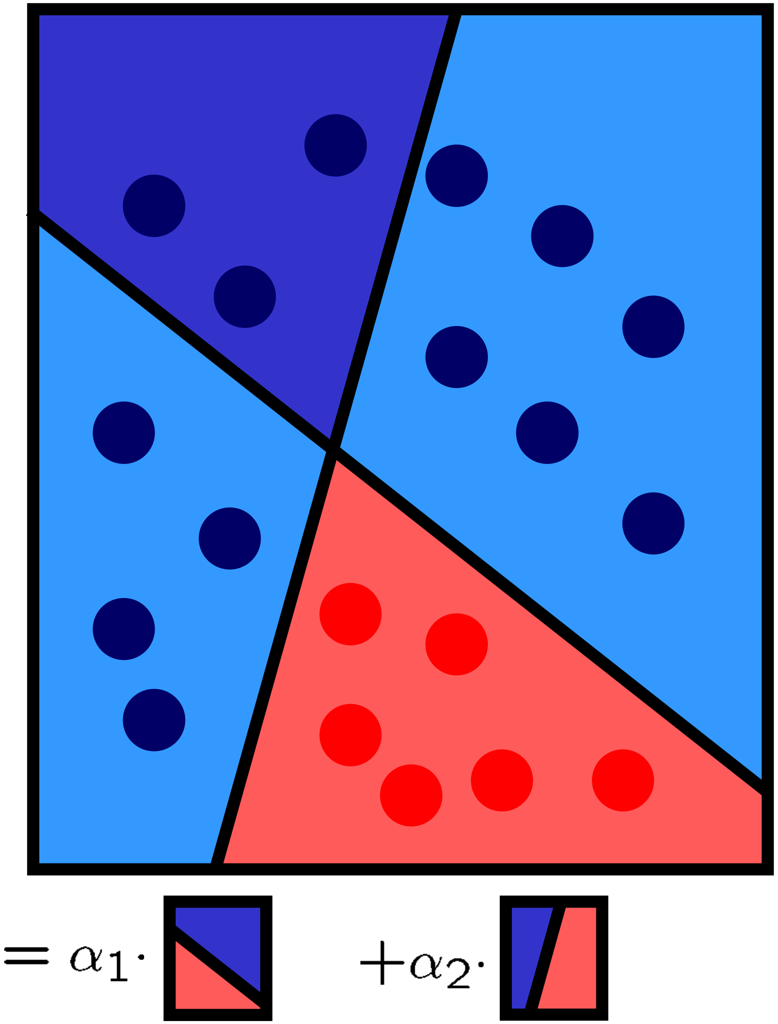

Given:

- set of labeled training samples
- weight distribution over them

Algorithm:

for n = 1 to N

- train a weak classifier using samples and weight dist.
- calculate error
- calculate weight
- update weight dist.

next

Result:

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

Slide credit: Helmut Grabner

From Offline to Online Boosting

- Goal
  - Formulate the algorithm such that we can present only 1 training sample at a time (and then forget about it).

  $\Rightarrow$ Dual problem: instead of keeping all samples and adding weak classifiers, keep a fixed set of weak classifiers and add samples.

- What changes?
  - Updating the classifiers online can be done easily.
    - Many classification approaches can use online updates.
  - Computing the classifier weights is also straightforward if we know the estimated error (which we can compute).

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 $N \rightarrow \infty$ iterations.

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

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

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

on-line

Slide credit: Helmut Grabner

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

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

on-line

Given:

for n = 1 to N

next

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

Slide credit: Helmut Grabner

From Offline to Online Boosting

Only one training example to update the classifier

off-line	on-line

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
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- update weight dist. D_n

next

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

on-line

Given:

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

for n = 1 to N

next

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

Slide credit: Helmut Grabner

From Offline to Online Boosting

Update importance for the current sample

off-line

Given:

- set of labeled training samples

$\mathcal{X} = \{\langle \mathbf{x}_1, y_1 \rangle, ..., \langle \mathbf{x}_\mathbf{L}, y_L \rangle \mid y_i \pm 1\}$

- 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
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- update weight dist. D_n

next

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

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 importance weight λ

next

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

Slide credit: Helmut Grabner

From Offline to Online Boosting

Online update the weak classifier

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.

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

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

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 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

From Offline to Online Boosting

Update errors and weights

off-line	on-line
Given:	**Given**:
- set of labeled training samples $\mathcal{X} = \{\langle \mathbf{x_1}, y_1 \rangle, ..., \langle \mathbf{x_L}, y_L \rangle \mid y_i \pm 1\}$	- ONE labeled training sample $\langle \mathbf{x}, y \rangle \mid y \pm 1$
- weight distribution over them $D_0 = 1/L$	- strong classifier to update
	- initial importance $\lambda = 1$
for n = 1 to N	for n = 1 to N
- train a weak classifier using samples and weight dist. $h_n^{weak}(\mathbf{x}) = \mathcal{L}(\mathcal{X}, D_{n-1})$	- update the weak classifier using samples and importance $h_n^{weak}(\mathbf{x}) = \mathcal{L}(h_n^{weak}, \langle x, y \rangle, \lambda)$
- calculate error e_n	- update error estimation $\widehat{e_n}$
- calculate weight $\alpha_n = f(e_n)$	- update weight $\alpha_n = f(\widehat{e}_n)$
- update weight dist. D_n	- update importance weight λ
next	next
$h^{strong}(\mathbf{x}) = \text{sign}(\sum_{n=1}^{N} \alpha_n \cdot h_n^{weak}(\mathbf{x}))$	$h^{strong}(\mathbf{x}) = \text{sign}(\sum_{n=1}^{N} \alpha_n \cdot h_n^{weak}(\mathbf{x}))$

Slide credit: Helmut Grabner

From Offline to Online Boosting

off-line

Given:

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on-line

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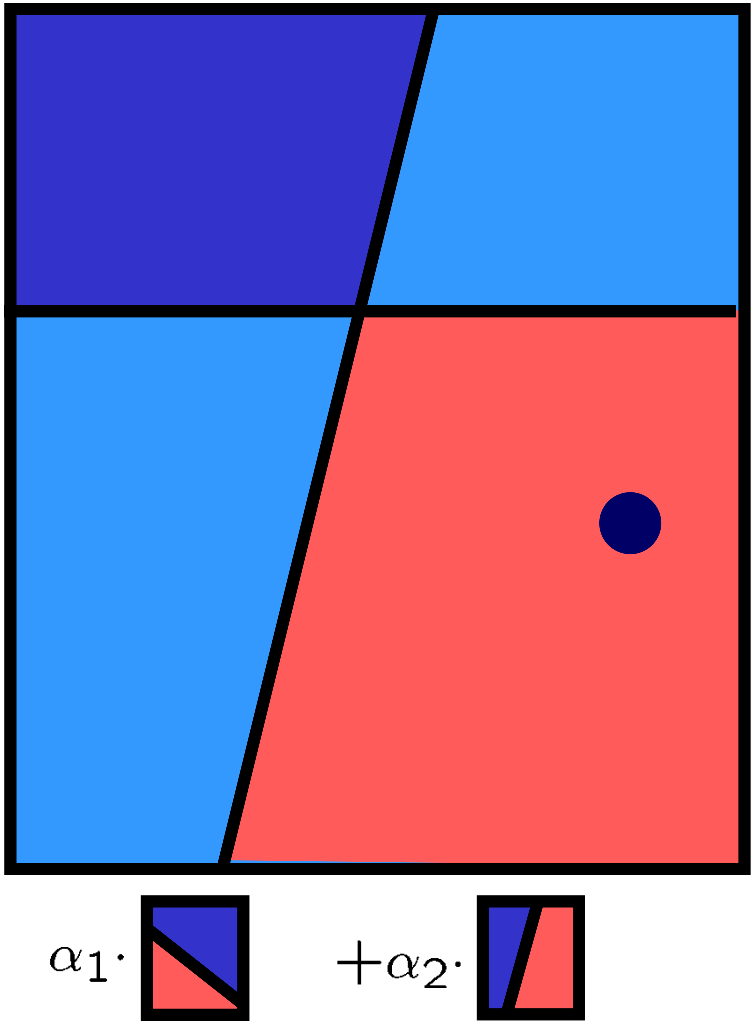
Online Boosting



Given:

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Algorithm:

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- initial importance
for n = 1 to N
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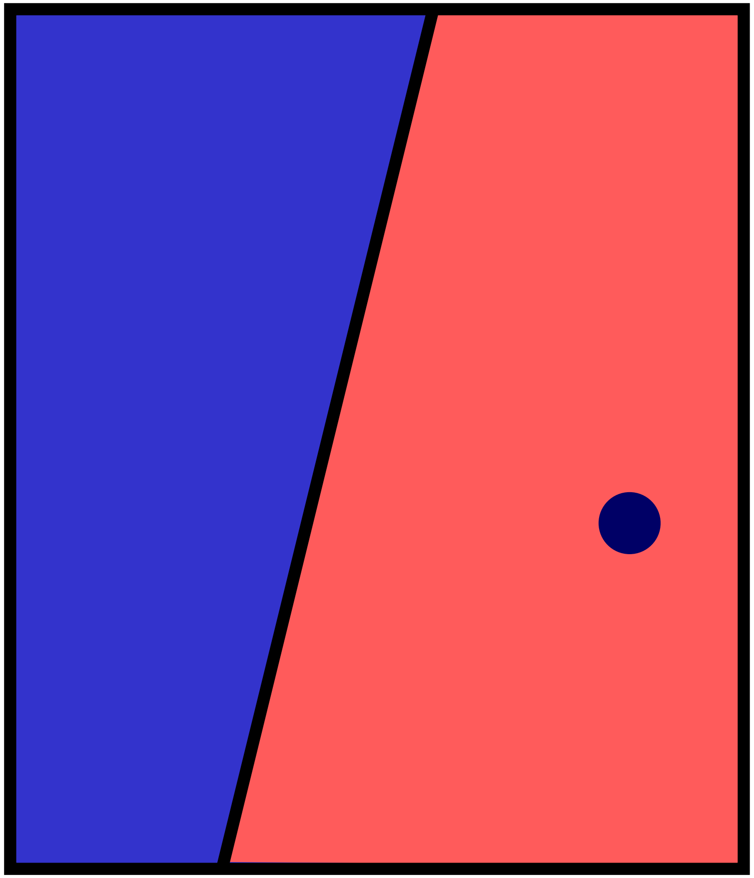
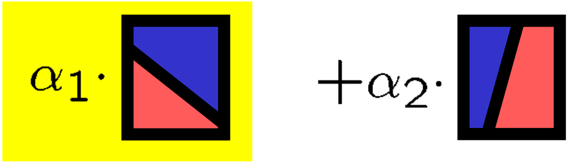
Online Boosting





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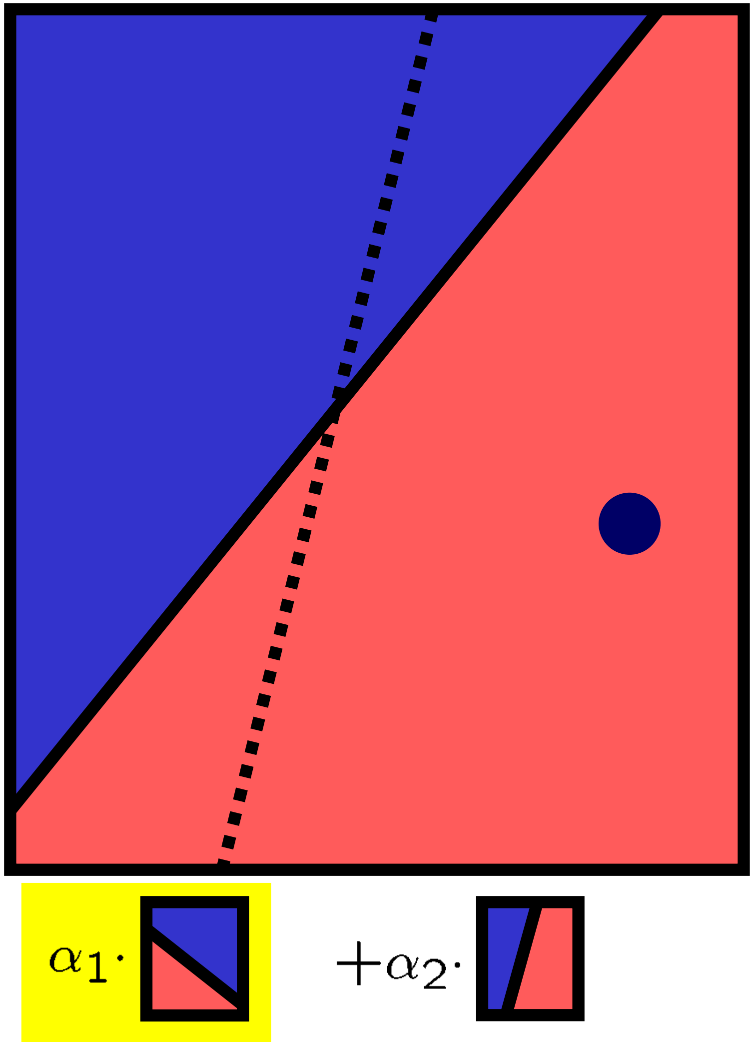

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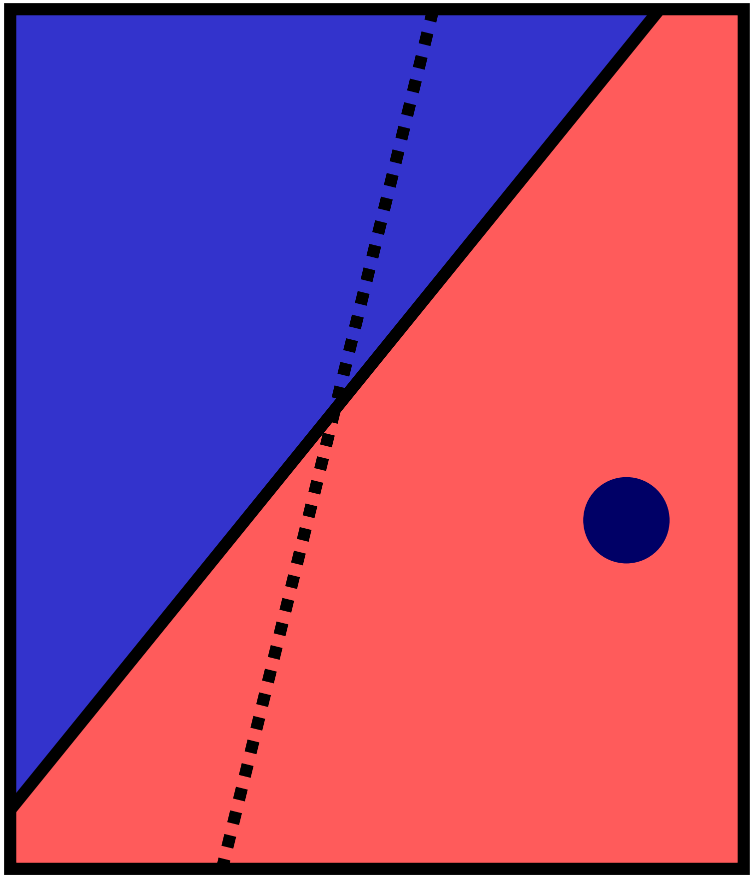

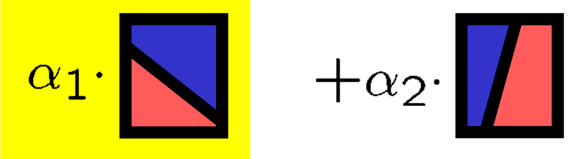

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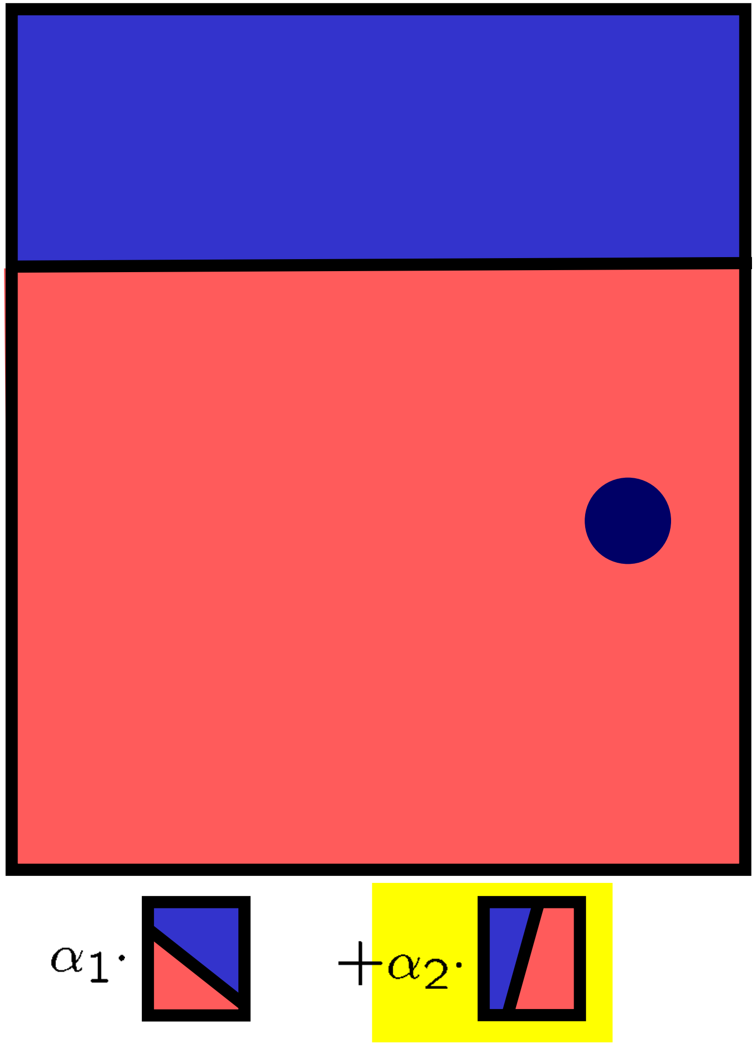
Slide credit: Helmut Grabner

Online Boosting



Given:

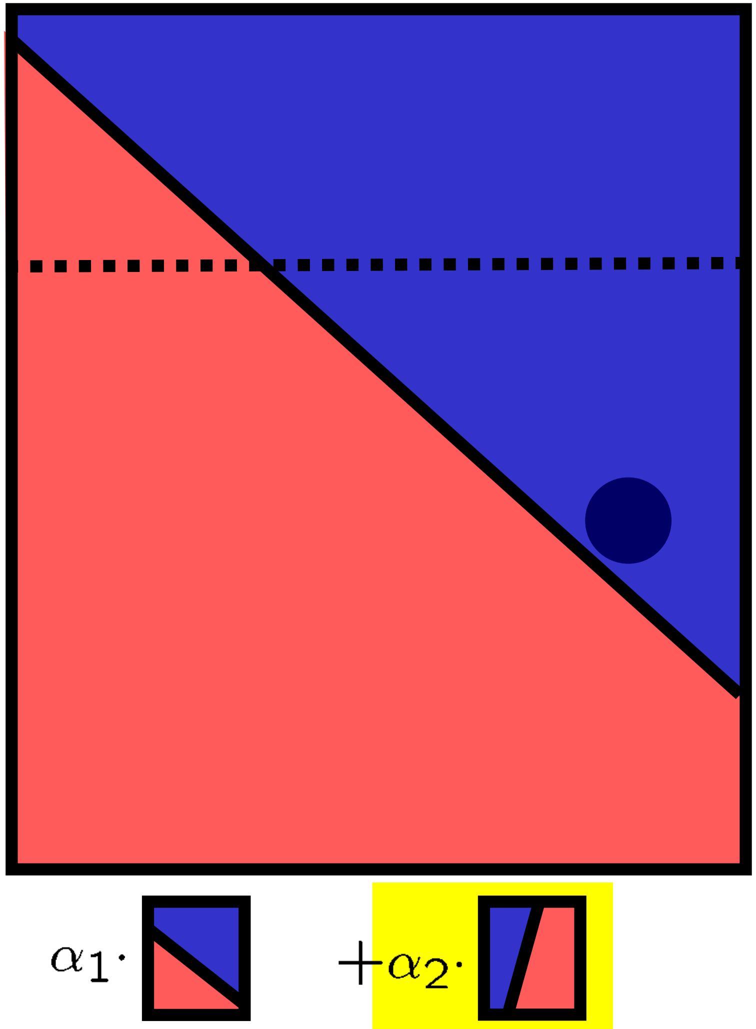
- ONE labeled training sample
- strong classifier to update

Algorithm:

```
- initial importance
for n = 1 to N
    - update the weak classifier using
      sample and importance
    - update error estimation
    - update weight
    - update importance weight
next
```


Slide credit: Helmut Grabner

Online Boosting



Given:

- ONE labeled training sample
- strong classifier to update

Algorithm:

- initial importance

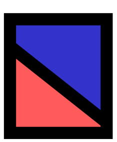
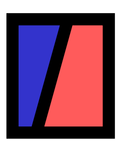
for n = 1 to N

- update the weak classifier using sample and importance
- update error estimation
- update weight
- update importance weight

next

Slide credit: Helmut Grabner

Online Boosting

$= \alpha_1 \cdot$  $+\alpha_2 \cdot$ 

Given:

- ONE labeled training sample
- strong classifier to update

Algorithm:

ier using

- update importance weight

next

Converges to the off-line results...

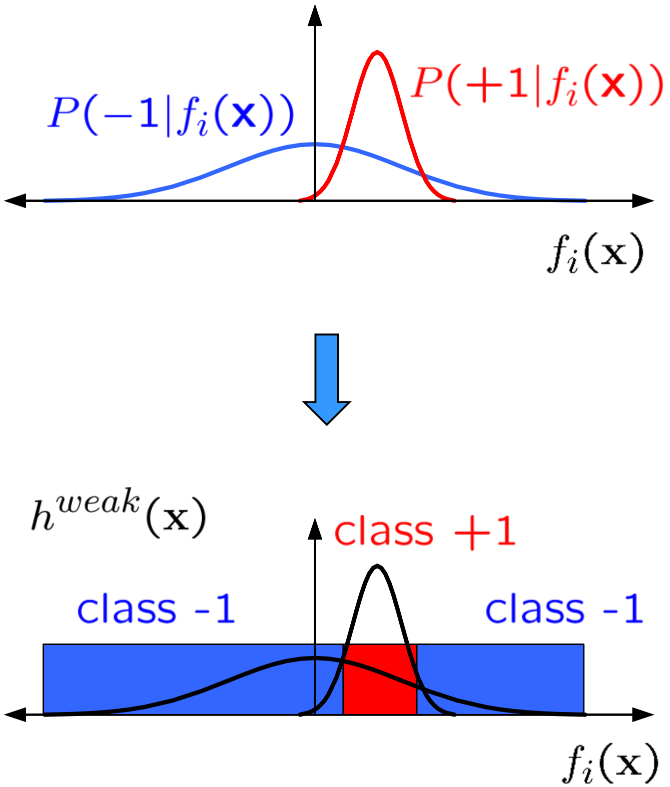
N. Oza and S. Russell. Online Bagging and Boosting. Artificial Intelligence and Statistics, 2001.

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

Slide credit: Helmut Grabner

Online Boosting for Feature Selection

- Each feature corresponds to a weak classifier.
- Features
  - Haar-like wavelets
  - Orientation histograms
  - Locally binary patterns (LBP)
- Fast computation using efficient data structures
  - integral images
  - integral histograms



F. Porikli. Integral histogram: A fast way to extract histograms in cartesian spaces. CVPR'05.

Slide credit: Helmut Grabner

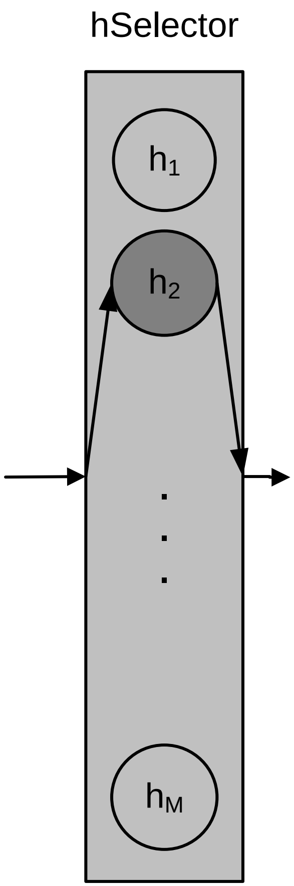
Online Boosting for Feature Selection

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

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

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

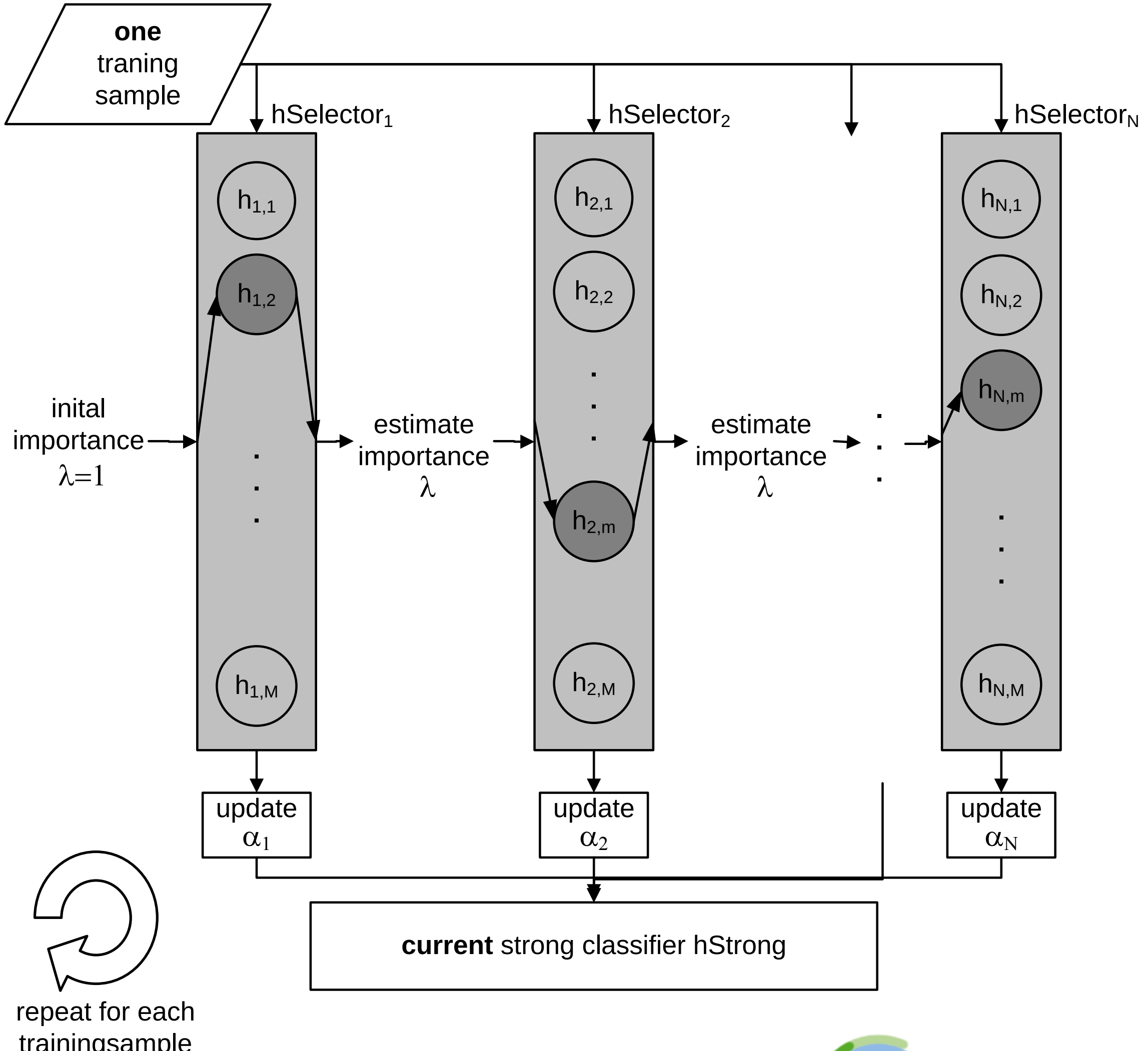
On-line boosting is performed on the Selectors and not on the weak classifiers directly.



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

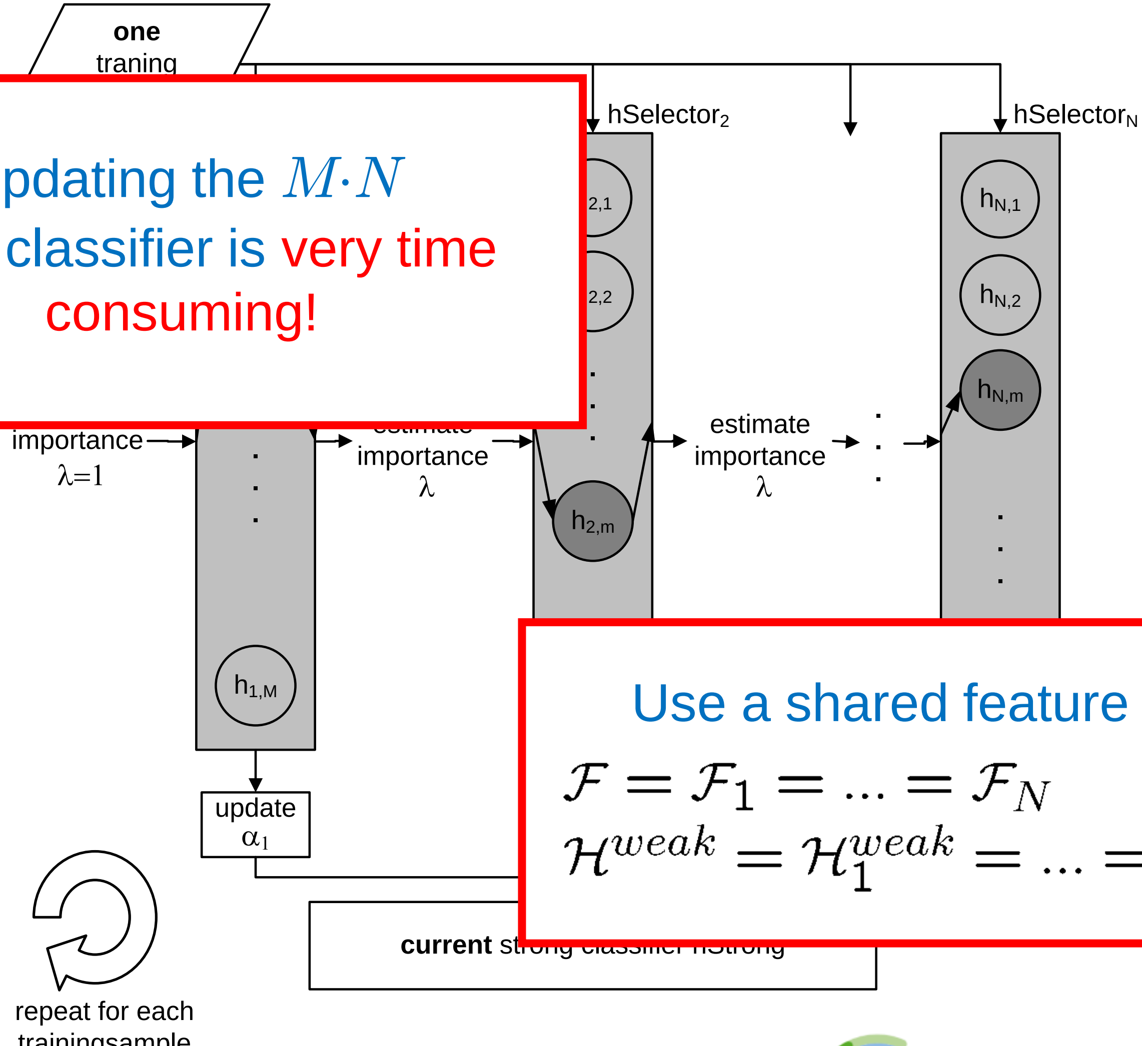
Slide credit: Helmut Grabner

Online Boosting for Feature Selection



Slide credit: Helmut Grabner

Online Boosting for Feature Selection



Updating the $M \cdot N$ weak classifier is very time consuming!

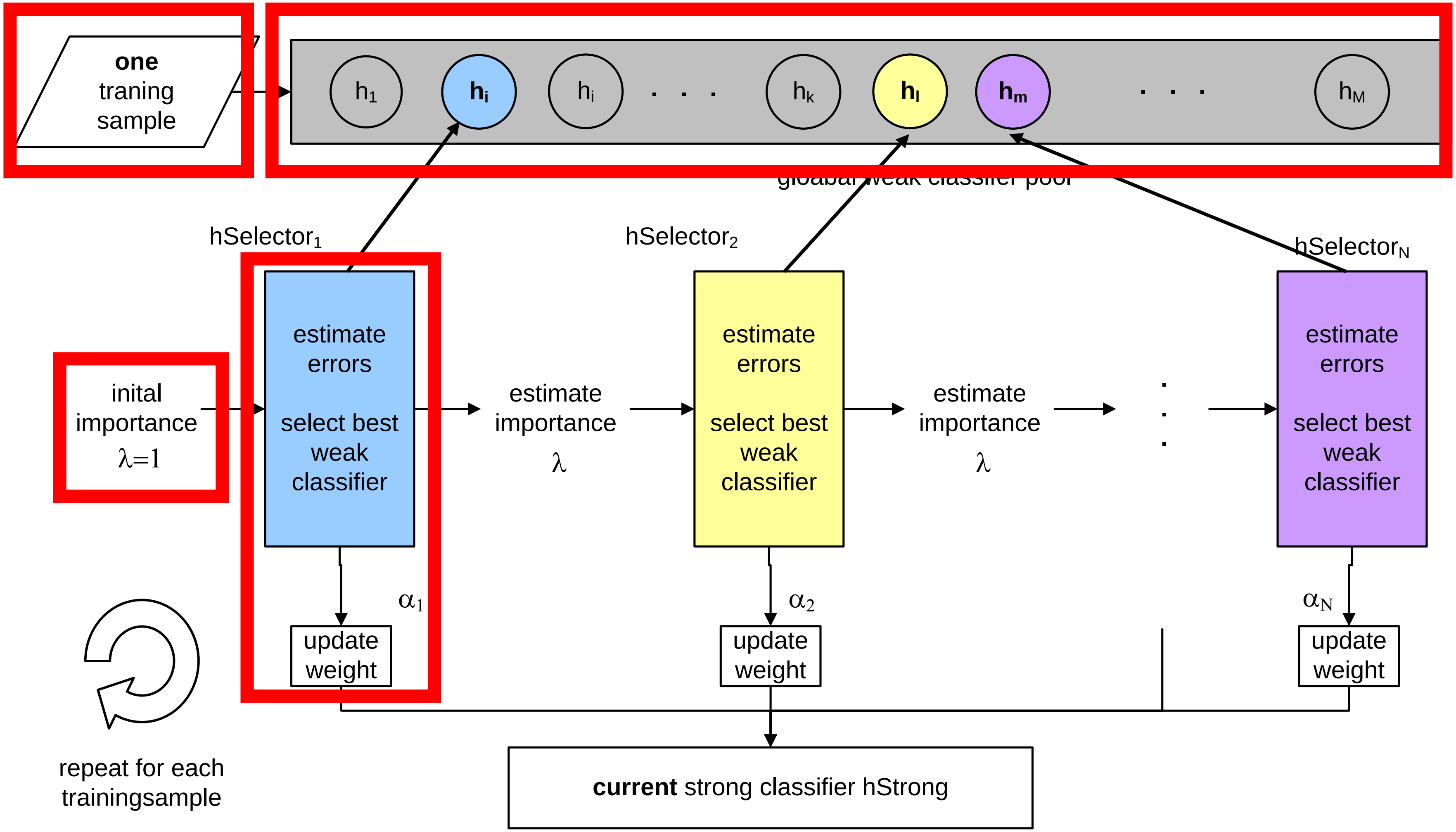
Use a shared feature pool

$$\mathcal{F} = \mathcal{F}_1 = \ldots = \mathcal{F}_N$$

$$\mathcal{H}^{weak} = \mathcal{H}_1^{weak} = \ldots = \mathcal{H}_N^{weak}$$

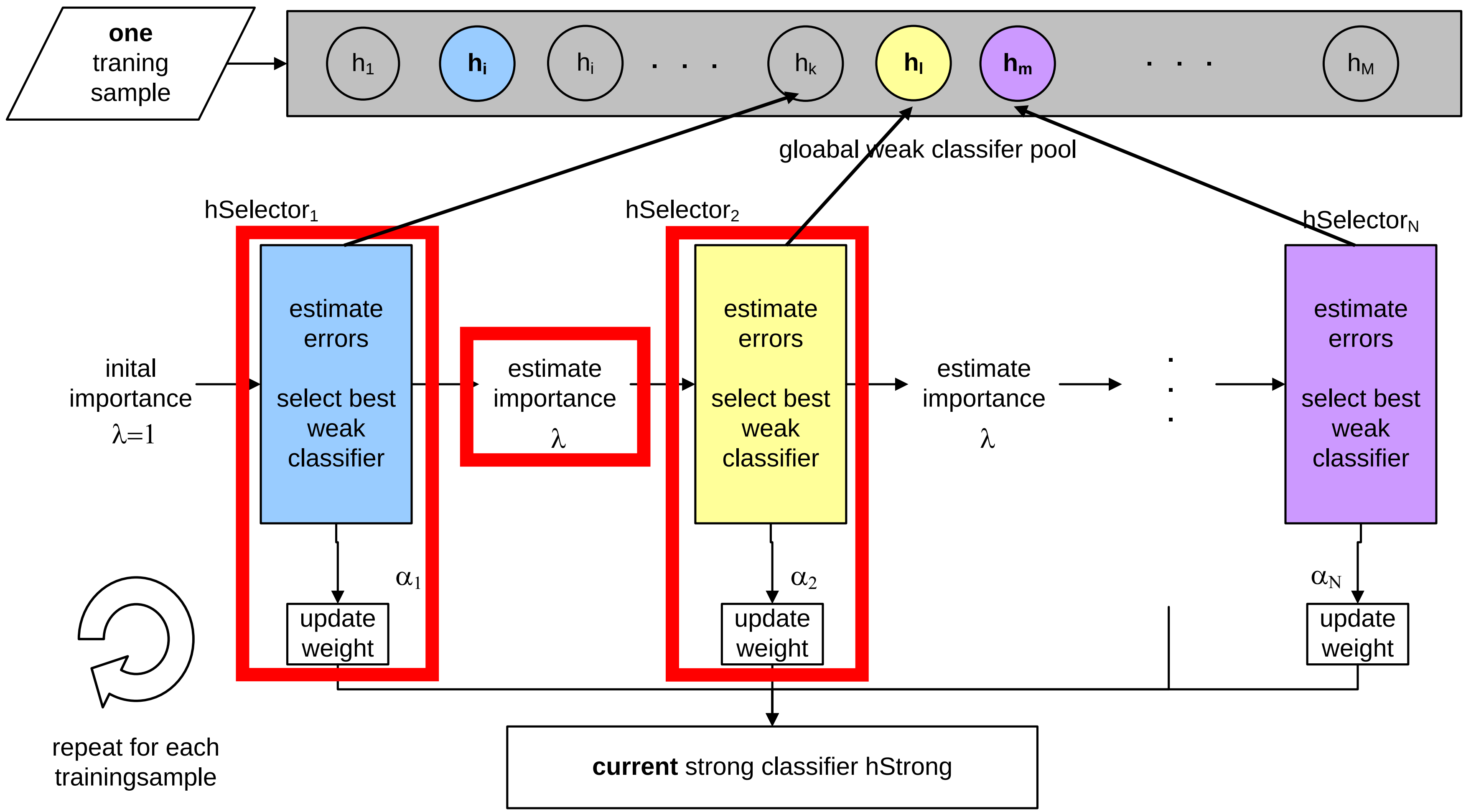
Slide credit: Helmut Grabner

Direct Feature Selection



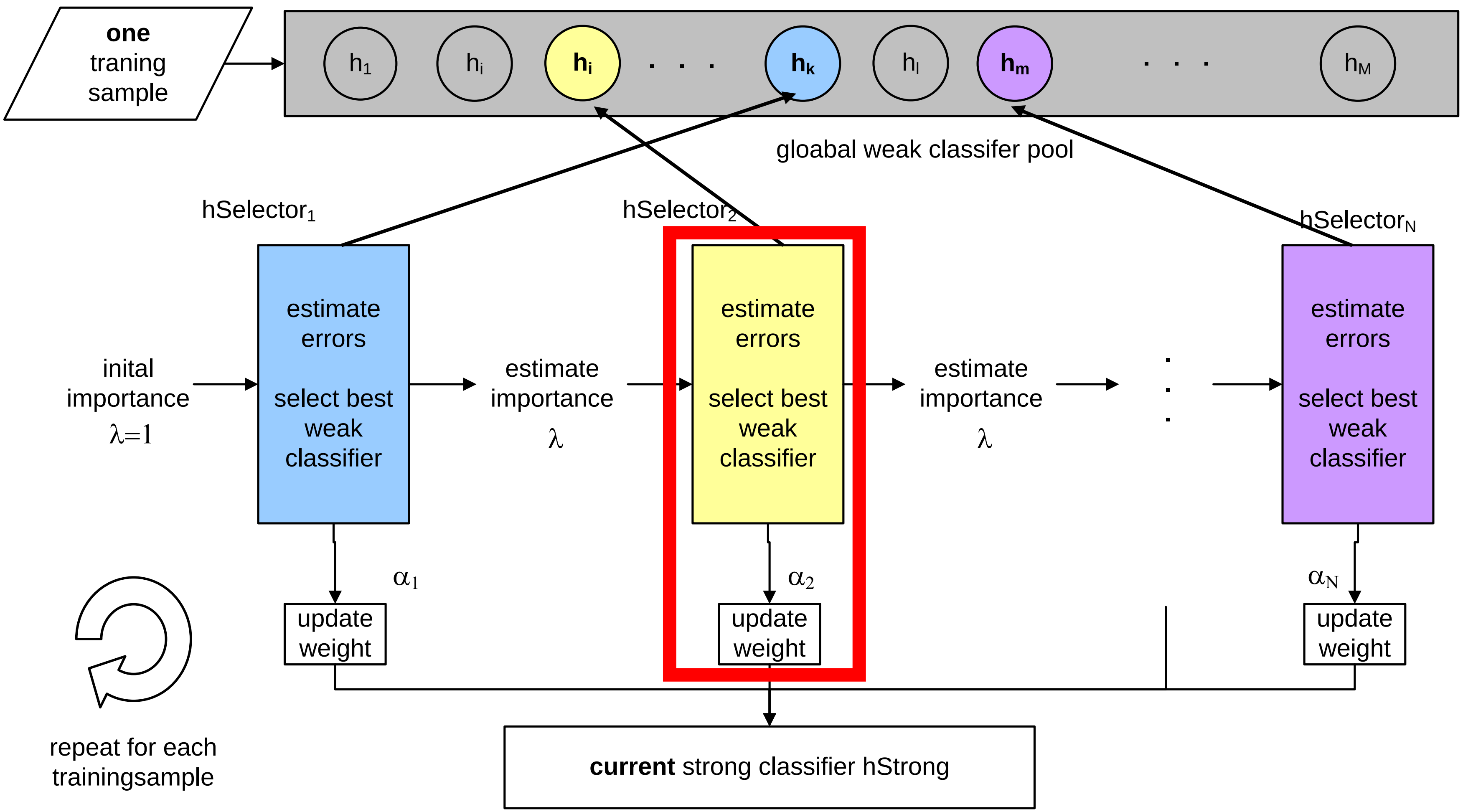
Slide credit: Helmut Grabner

Direct Feature Selection



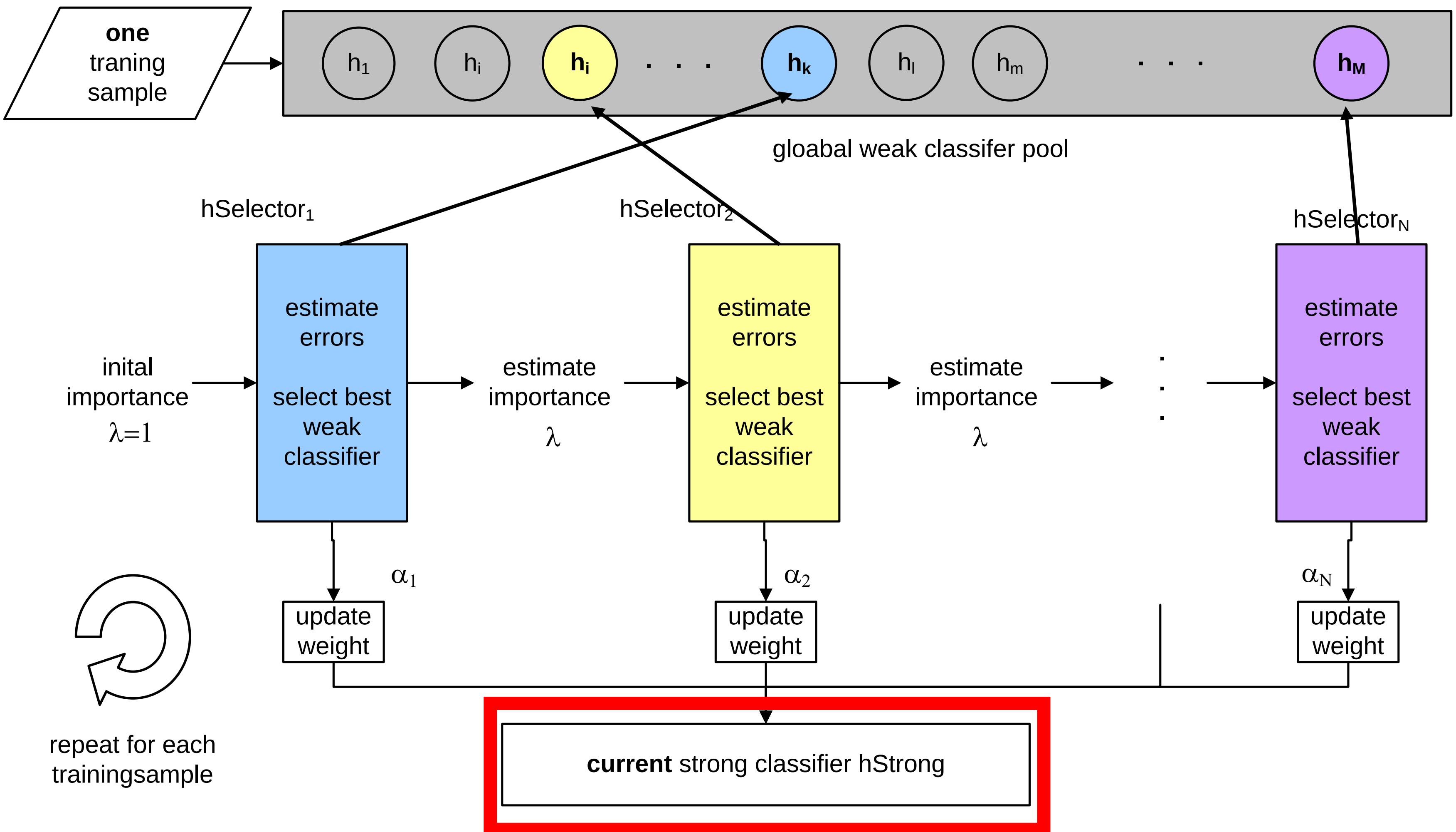
Slide credit: Helmut Grabner

Direct Feature Selection



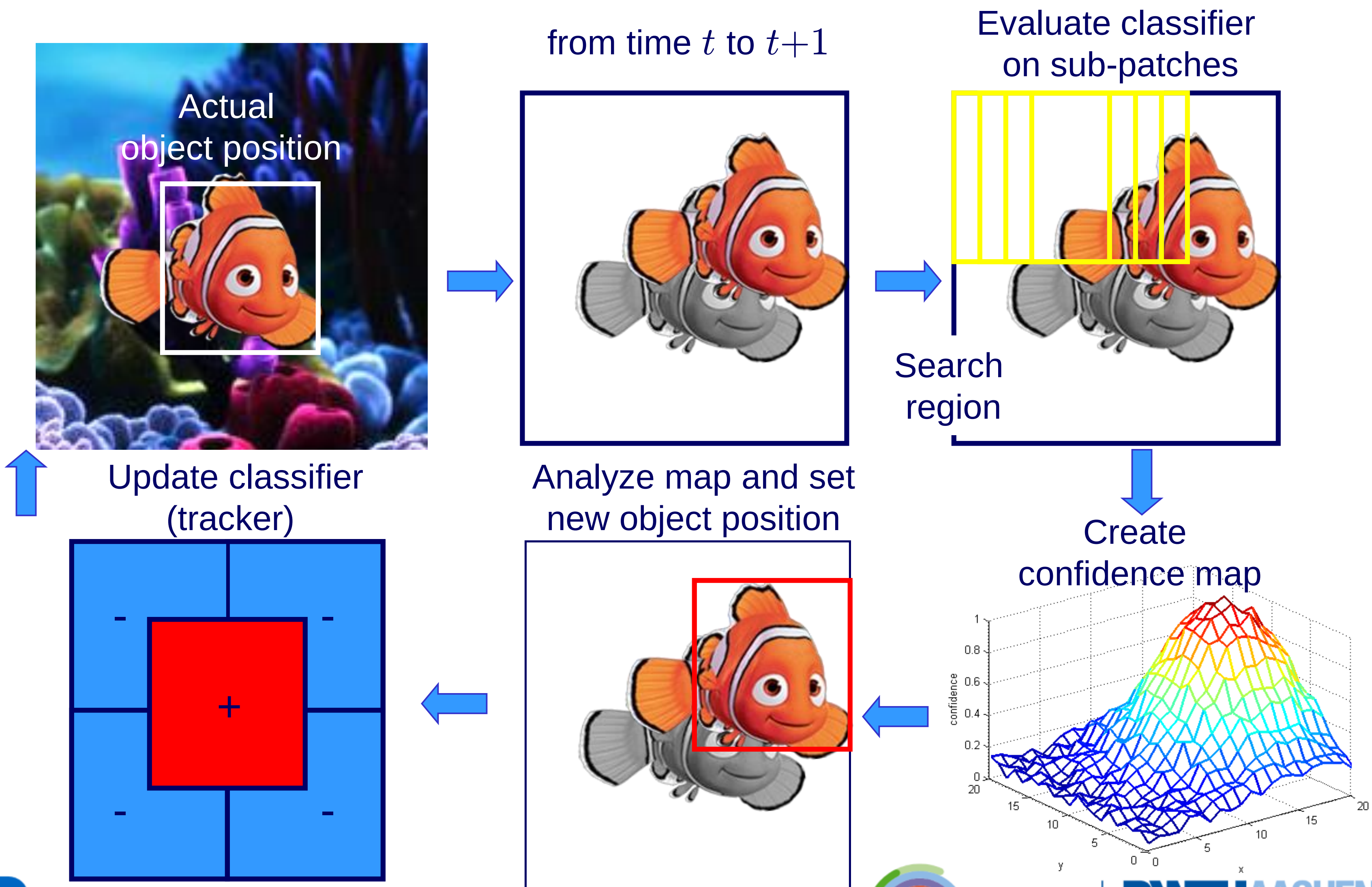
Slide credit: Helmut Grabner

Direct Feature Selection



Slide credit: Helmut Grabner

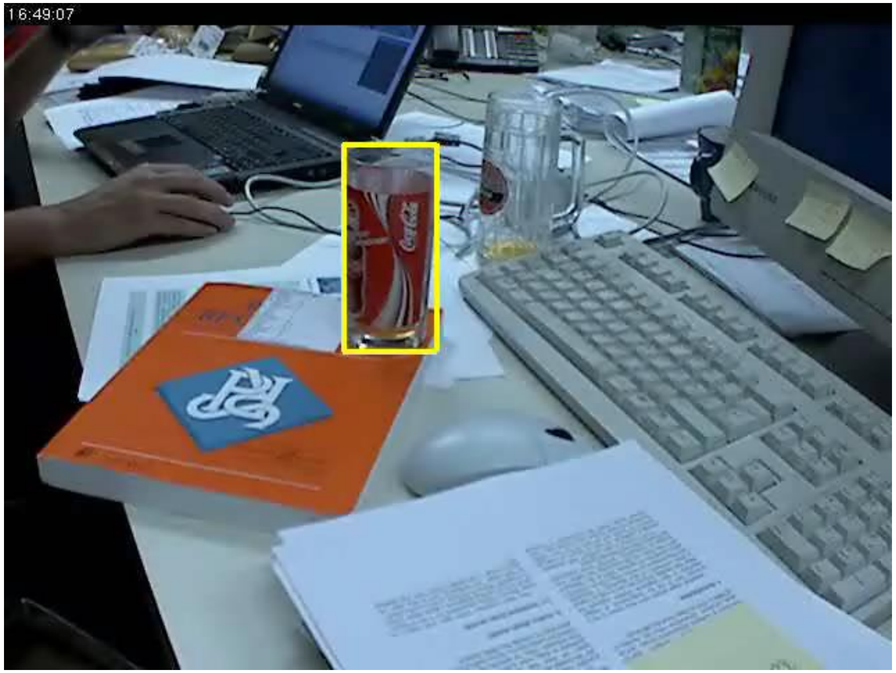
Tracking by Online Classification

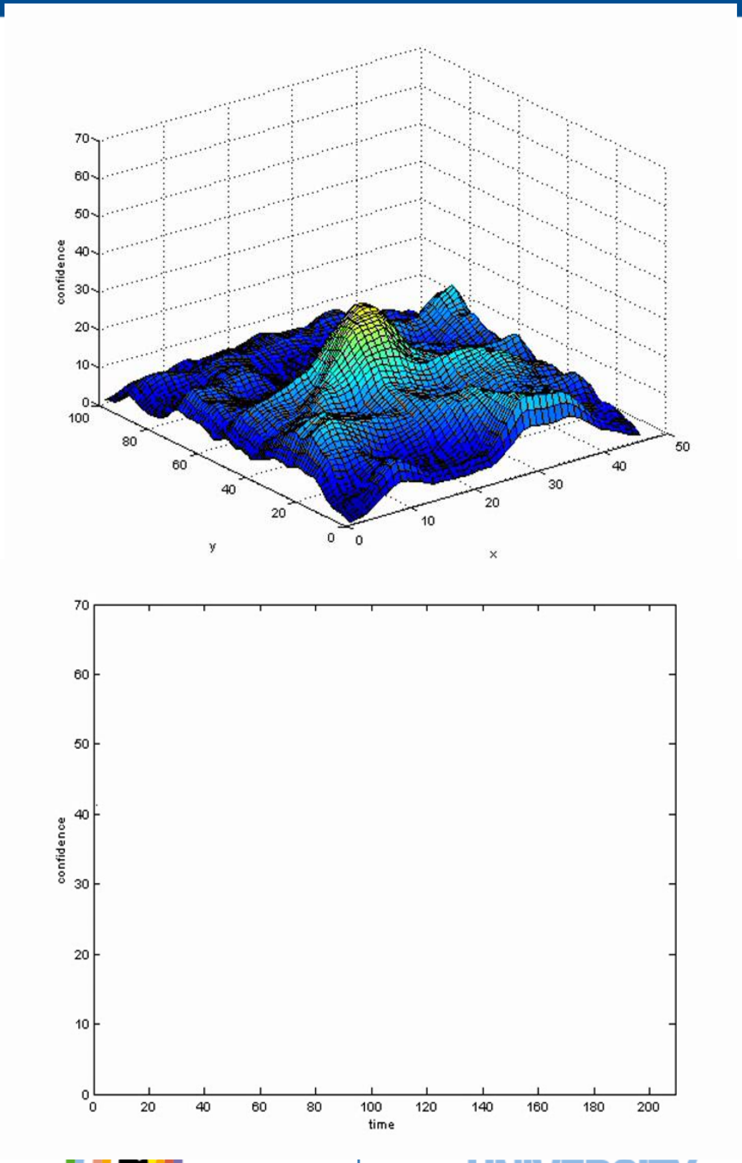


Slide credit: Helmut Grabner

Image source: Disney/Pixar

Tracking Results

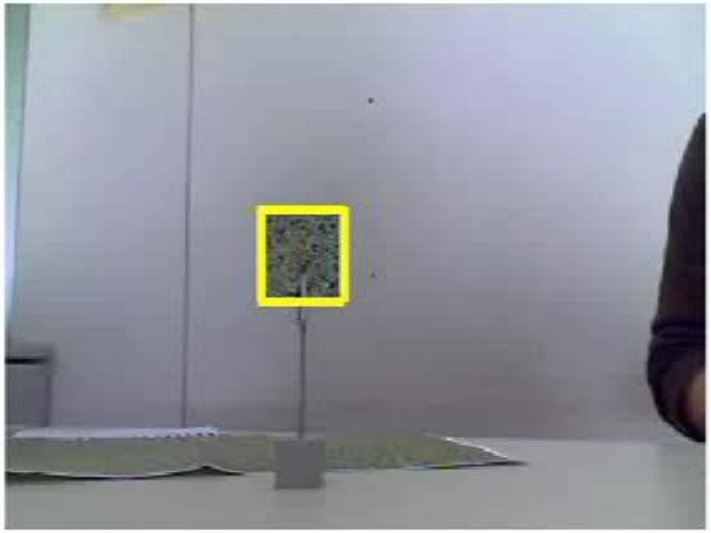


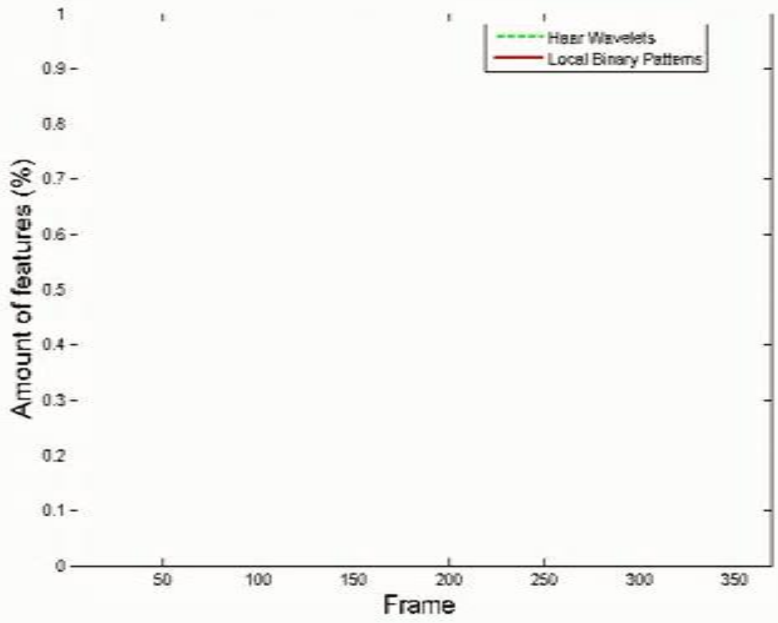


Slide credit: Helmut Grabner

Video source: Grabner et al., BMVC'06

Online Feature Exchange

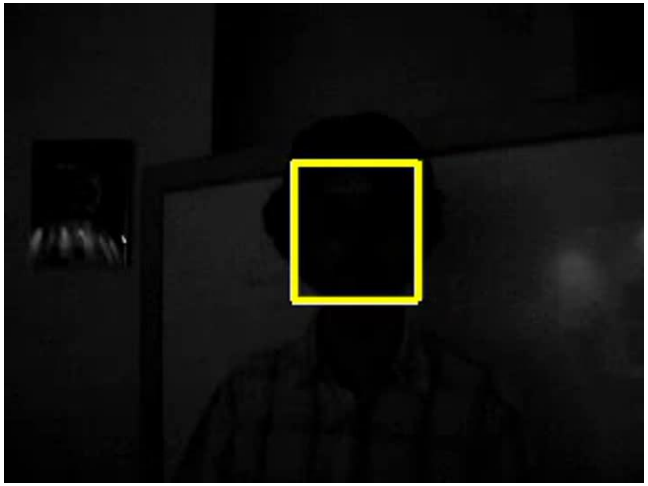




Slide credit: Helmut Grabner

Video source: Grabner et al., BMVC'06

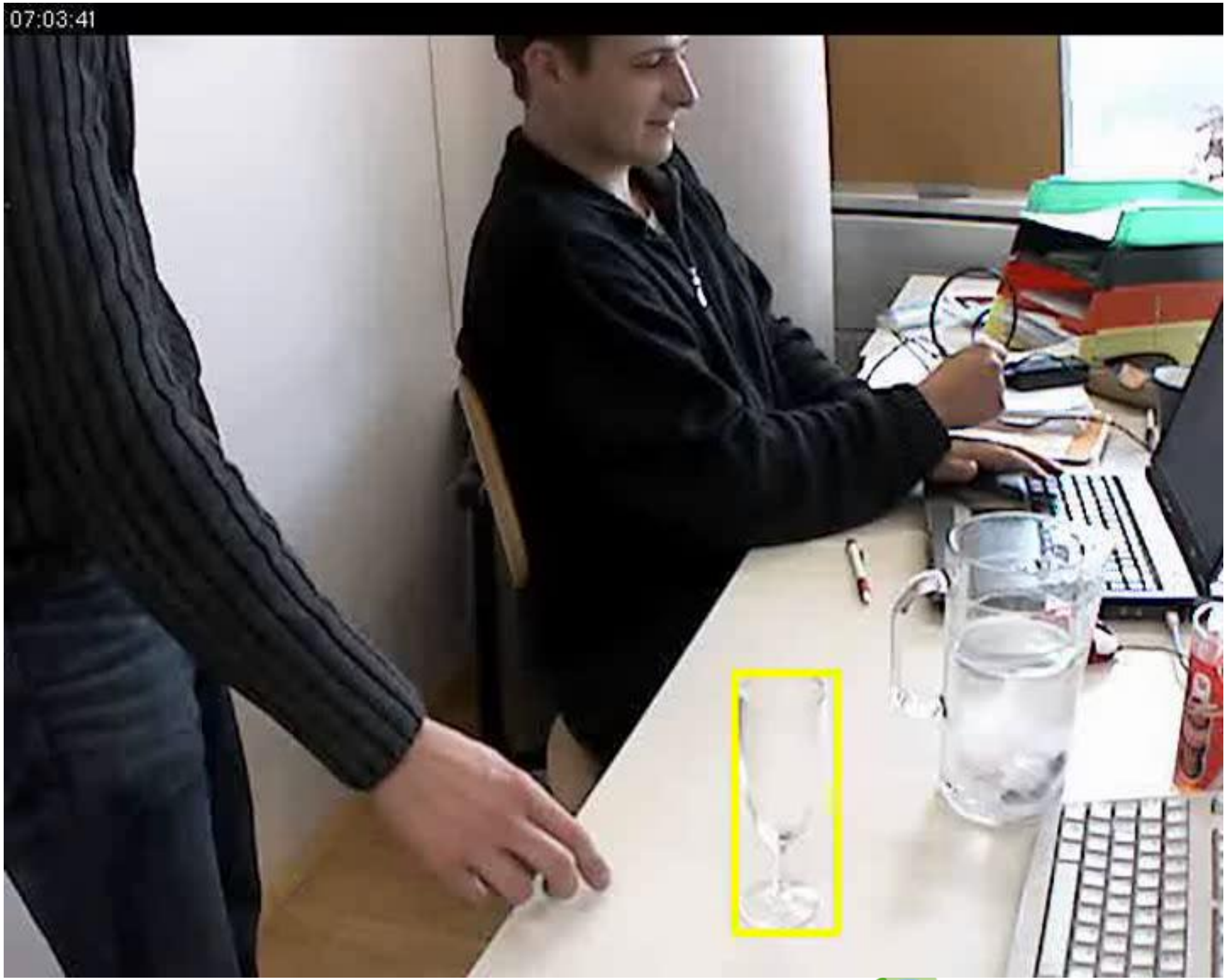
Additional Tracking Results



Slide credit: Helmut Grabner

Video source: Grabner et al., BMVC'06

"Tracking the Invisible"



Slide credit: Helmut Grabner

Video source: Grabner et al., BMVC'06

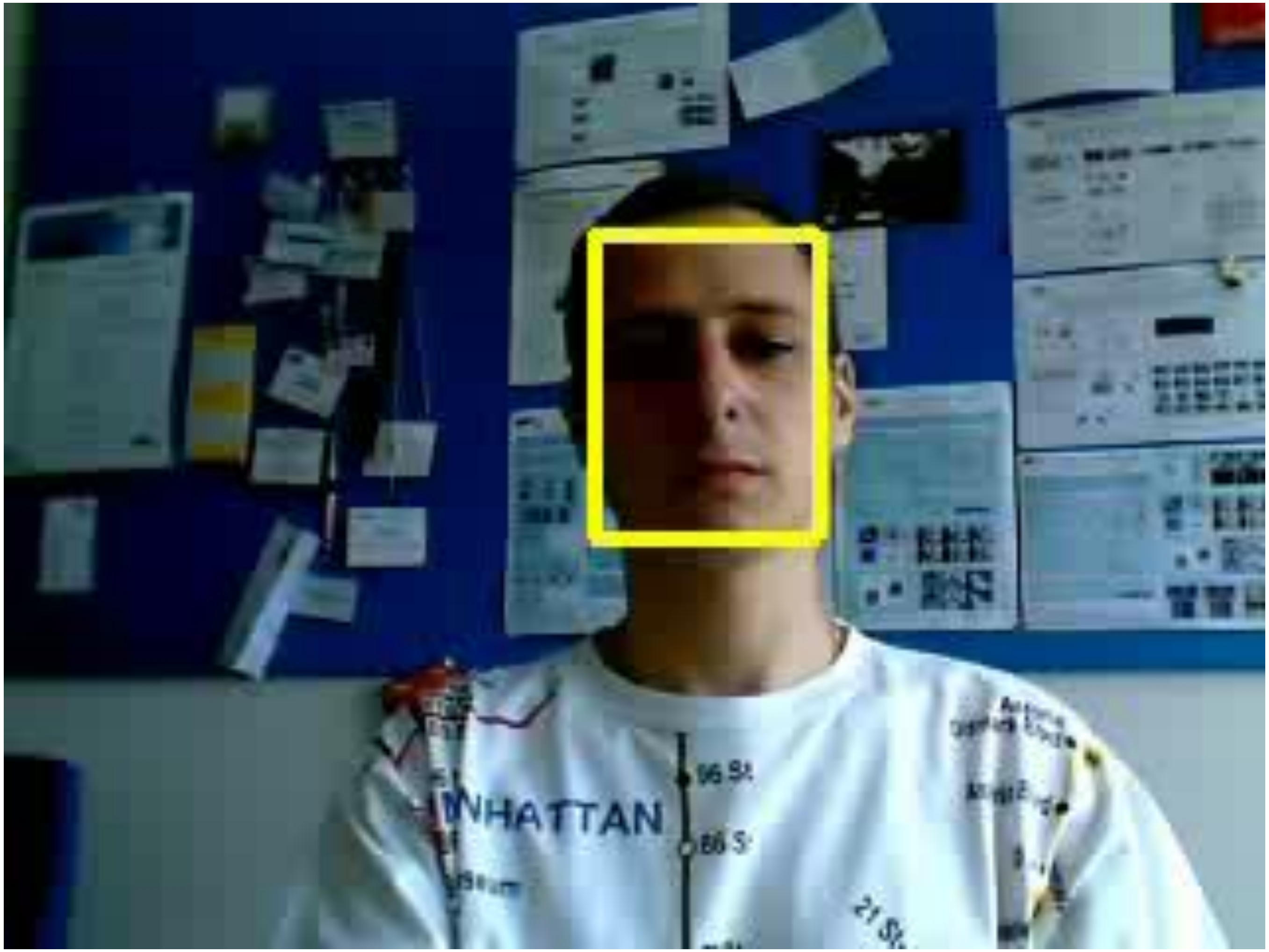
Summary: Tracking by Online Classification

- Interpret tracking as a classification problem
  - Continuously updating a classifier which discriminates the object from the background.
- Online Boosting
  - Adaptation of AdaBoost to process 1 training sample at a time.
  - Process sample by fixed set of classifiers to compute its importance weight.
  - Converges to the same result as Offline Boosting.
- Online Boosting for Feature Selection
  - Perform Boosting on Selectors instead of weak classifiers.
  - Each Selector chooses from a pool of weak classifiers.
  - Selected features and voting weights change over time.
  - Shared feature pool for real-time processing.

Topics of This Lecture

- Tracking by Online Classification
  – Motivation
- Recap: Boosting for Detection
  – AdaBoost
  – Viola-Jones Detector
- Extension to Online Classification
  – Online Boosting
  – Online Feature Selection
  – Results
- Extensions
  – Problem: Drift
  – Drift-compensation strategies

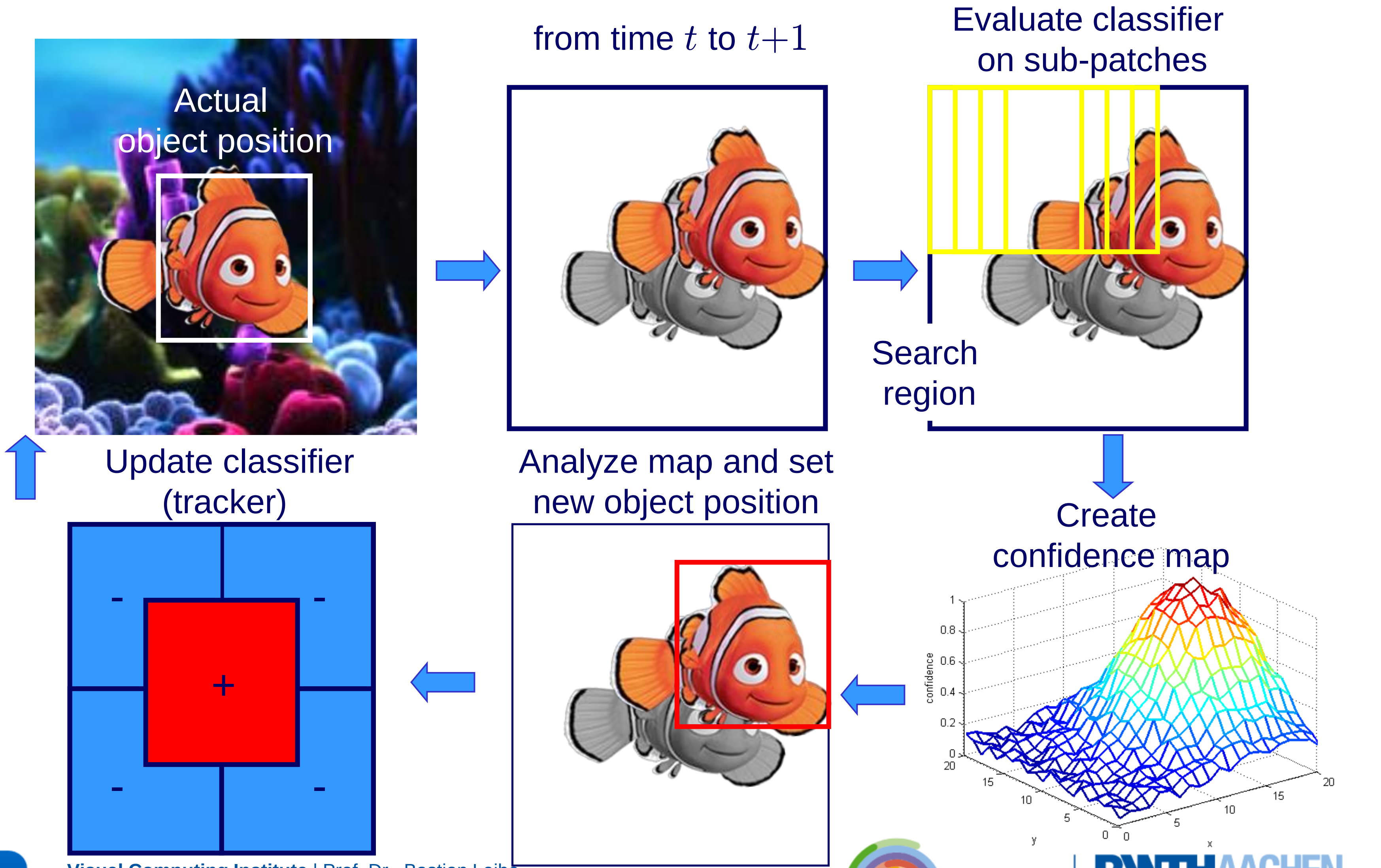
When Does It Fail...



Slide credit: Helmut Grabner

Video source: Grabner et al., ECCV'08

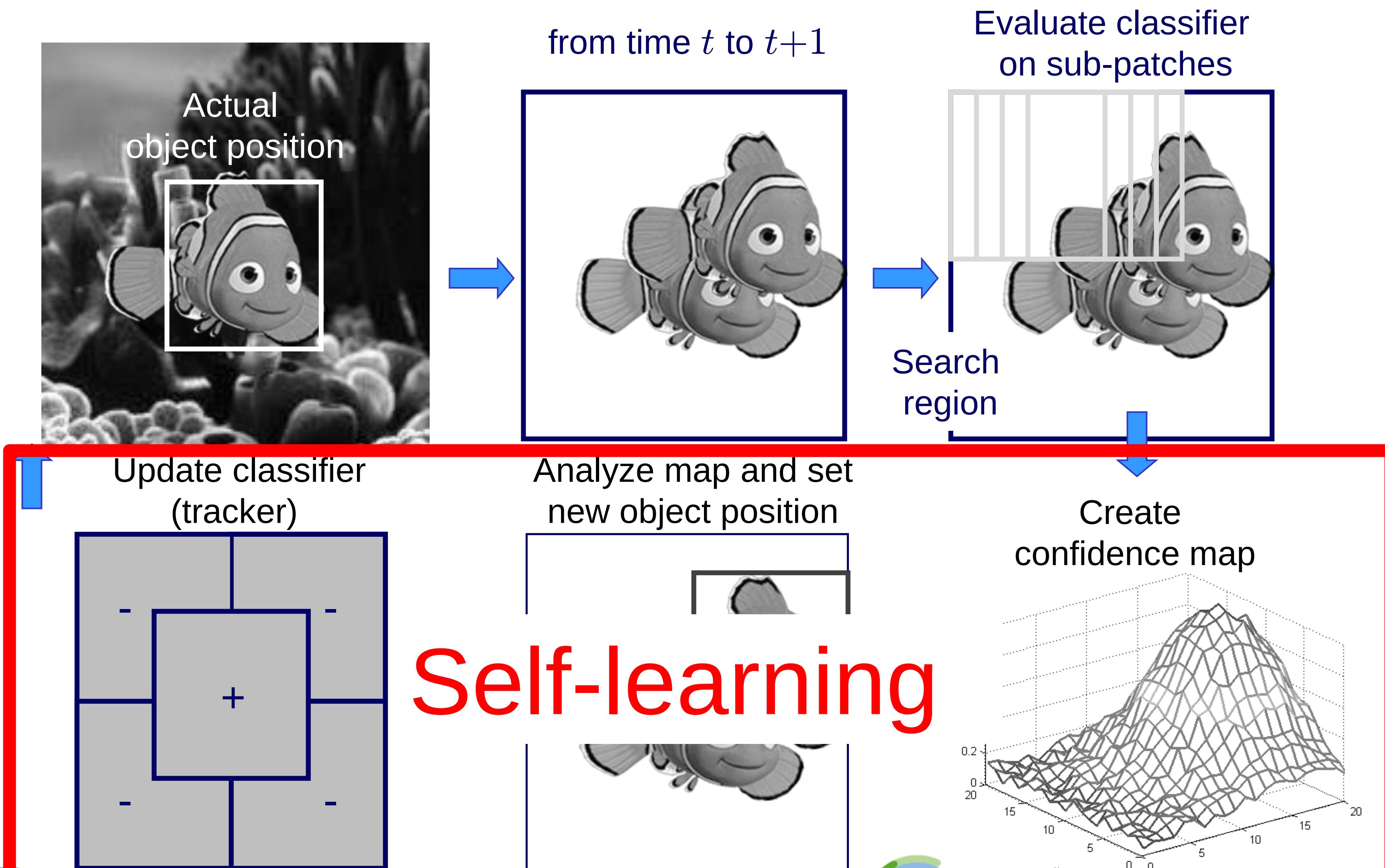
Why Does It Fail?



Slide credit: Helmut Grabner

Image source: Disney/Pixar

Why Does It Fail?

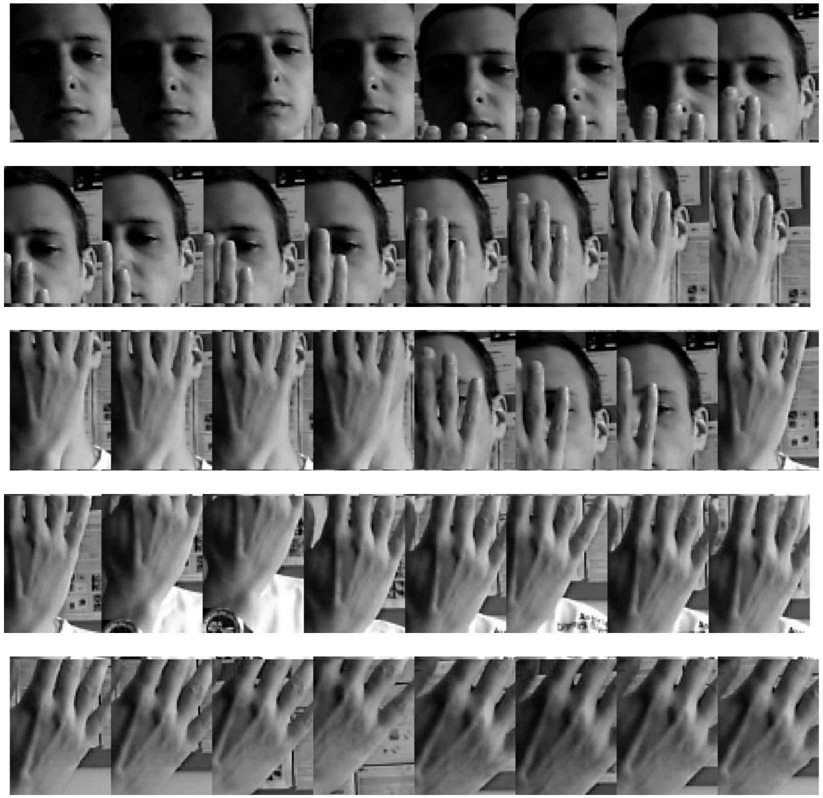


Slide credit: Helmut Grabner

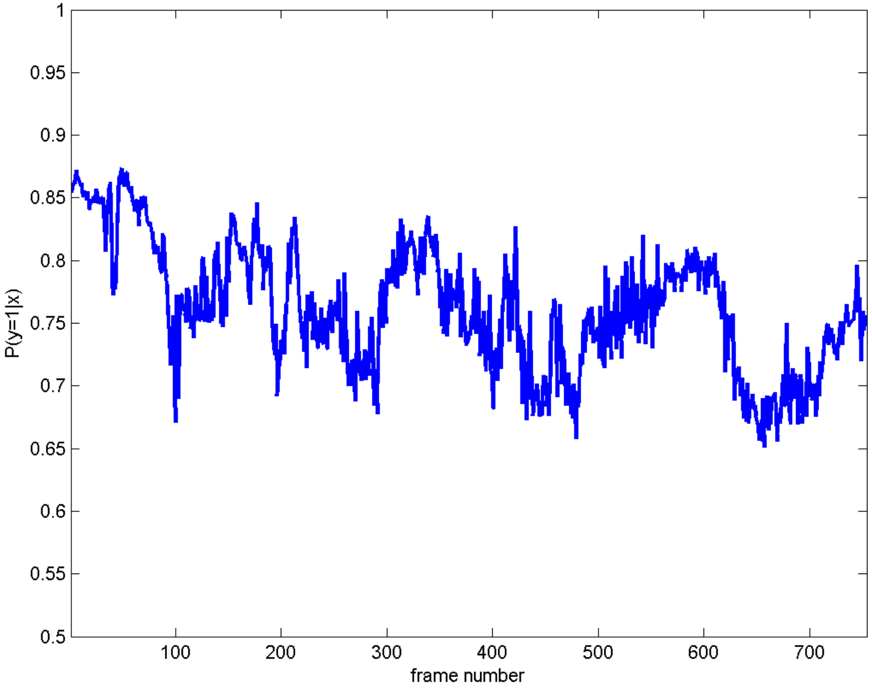
Image source: Disney/Pixar

Drifting Due to Self-Learning Policy

Tracked Patches



Confidence



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

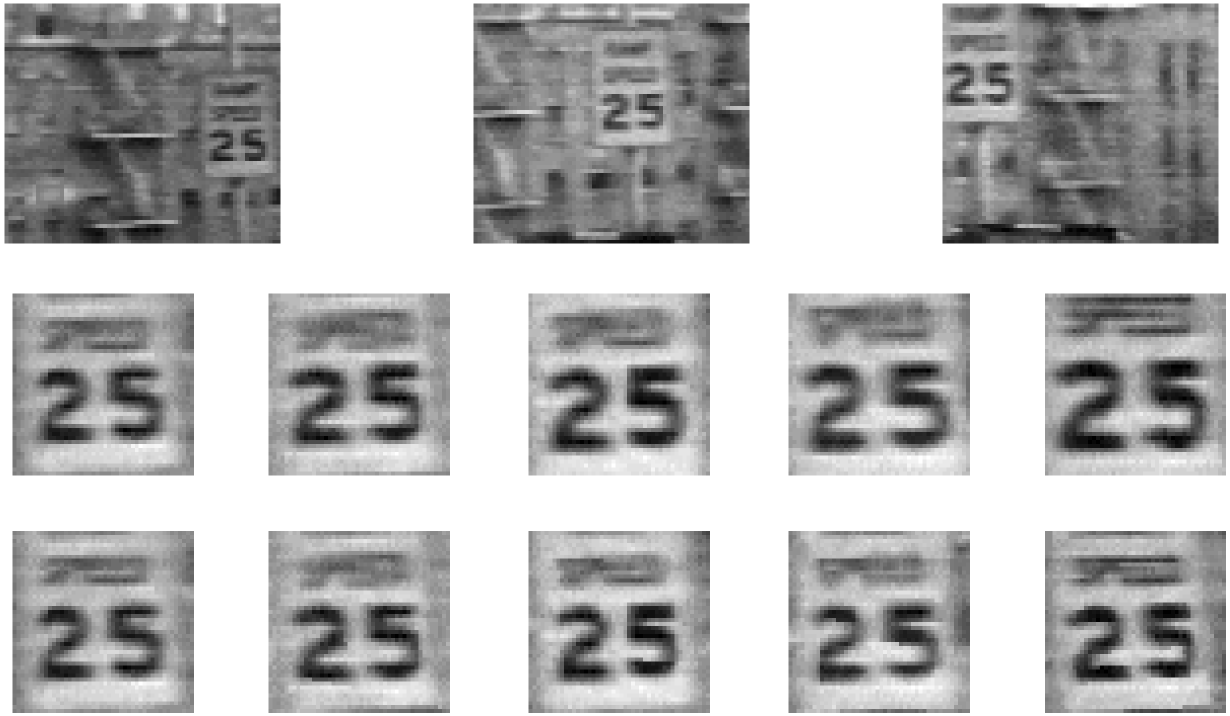
Slide credit: Helmut Grabner

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

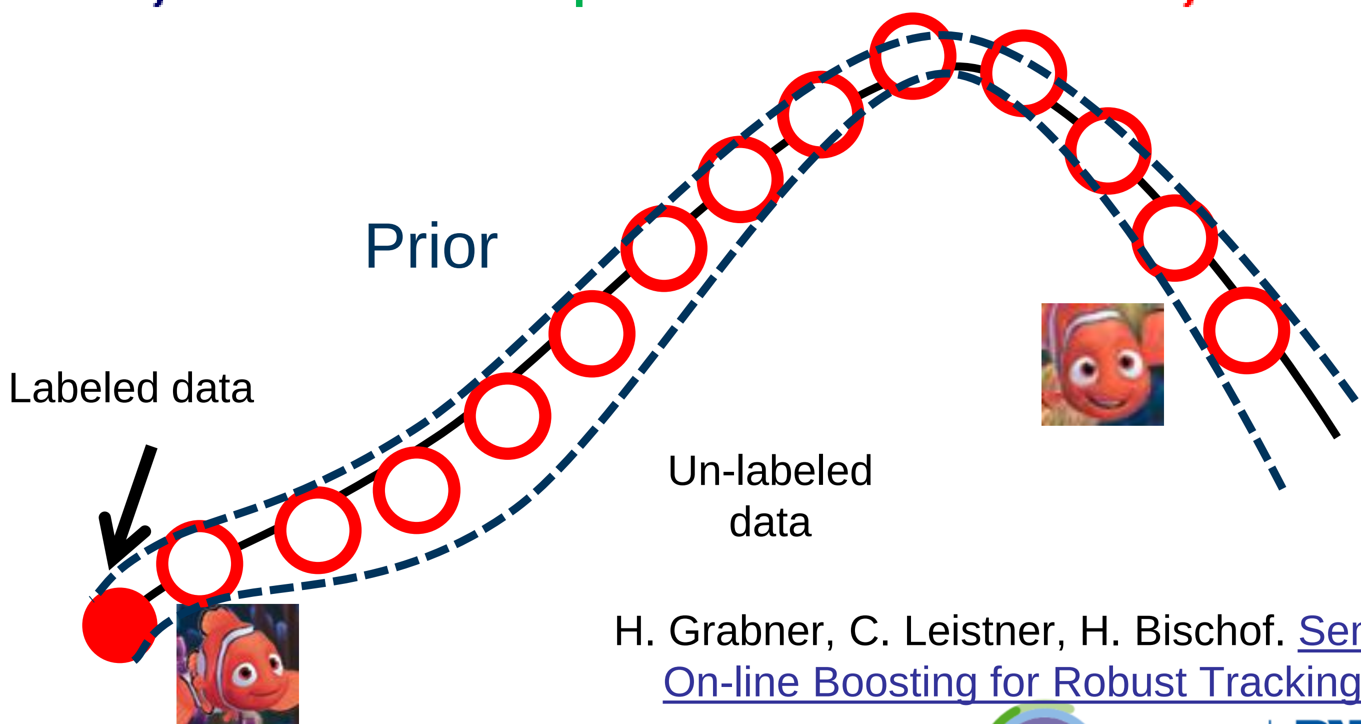


- Used mostly in low-level trackers (e.g., KLT)
  - Advantage: robustly catches drift
  - Disadvantage: cannot follow appearance changes

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



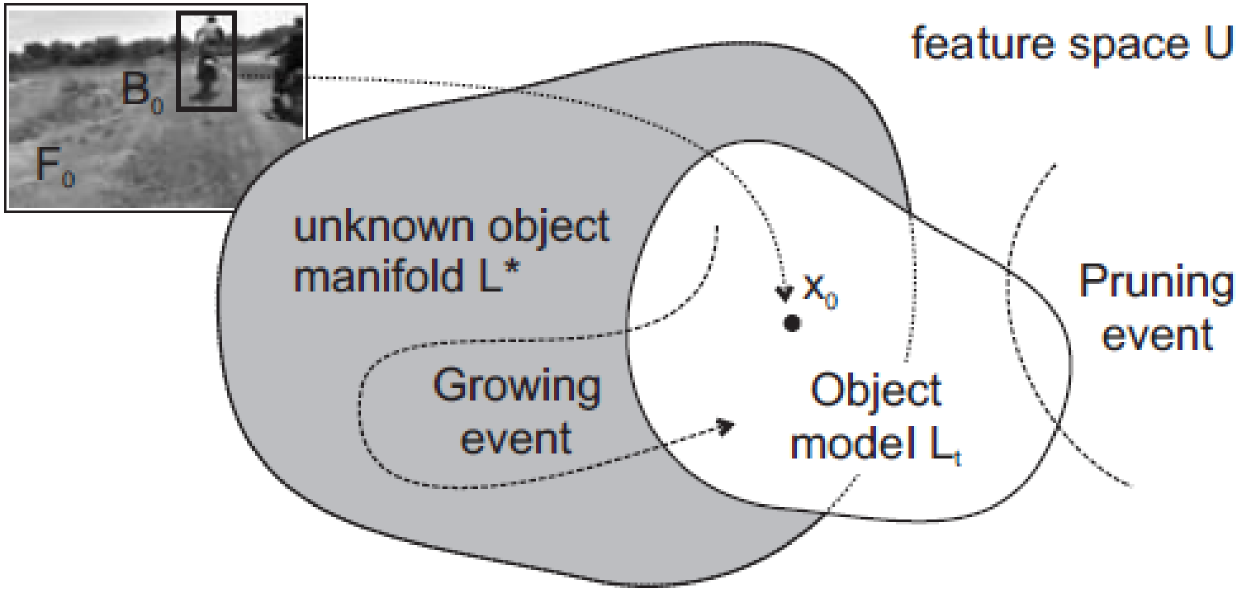
H. Grabner, C. Leistner, H. Bischof. [Semi-Supervised On-line Boosting for Robust Tracking](). ECCV'08.

Slide credit: Helmut Grabner

Tracking despite Occlusions

Video source: Grabner et al., ECCV’08

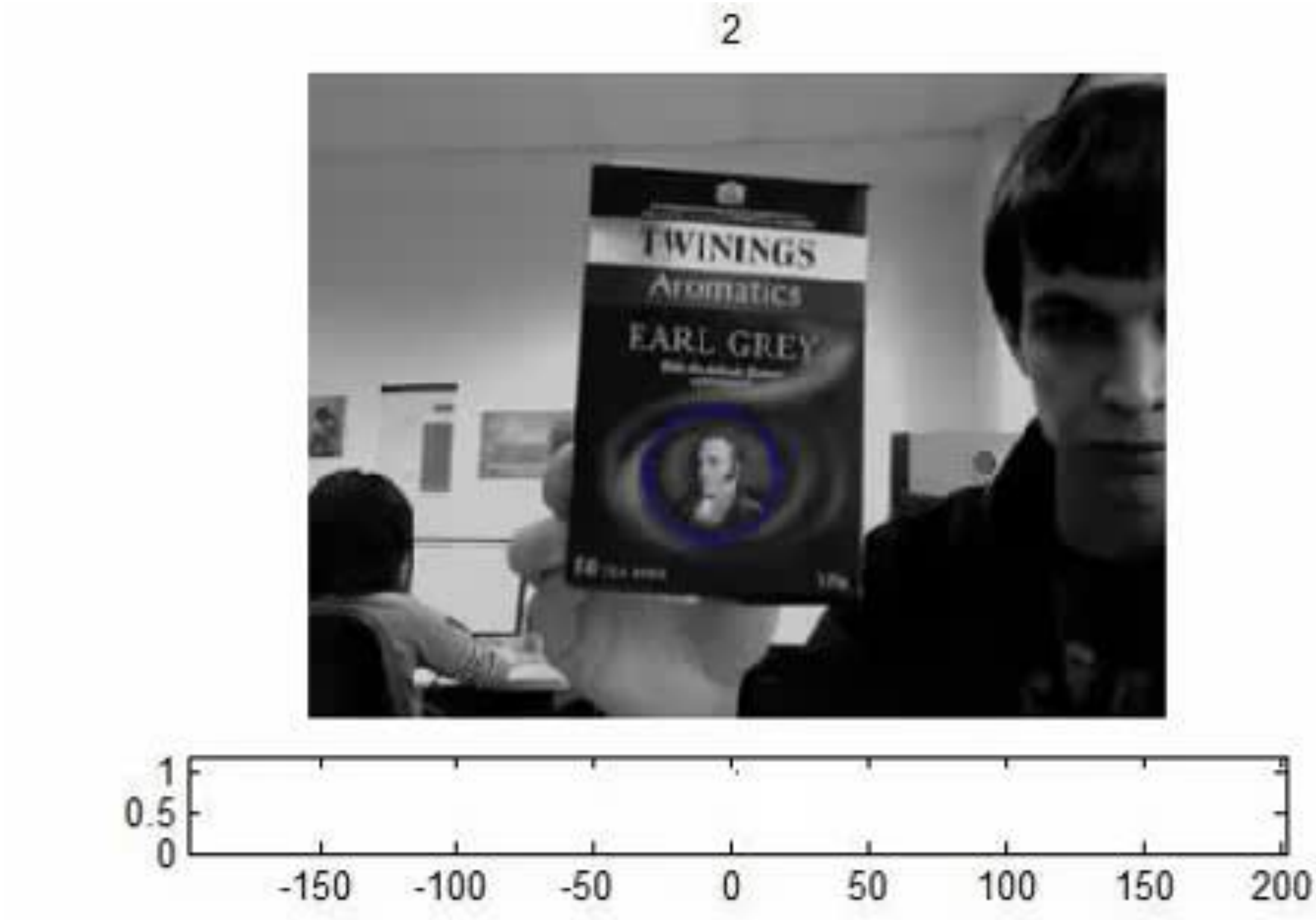
Strategy 3: Using Additional Cues



- 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

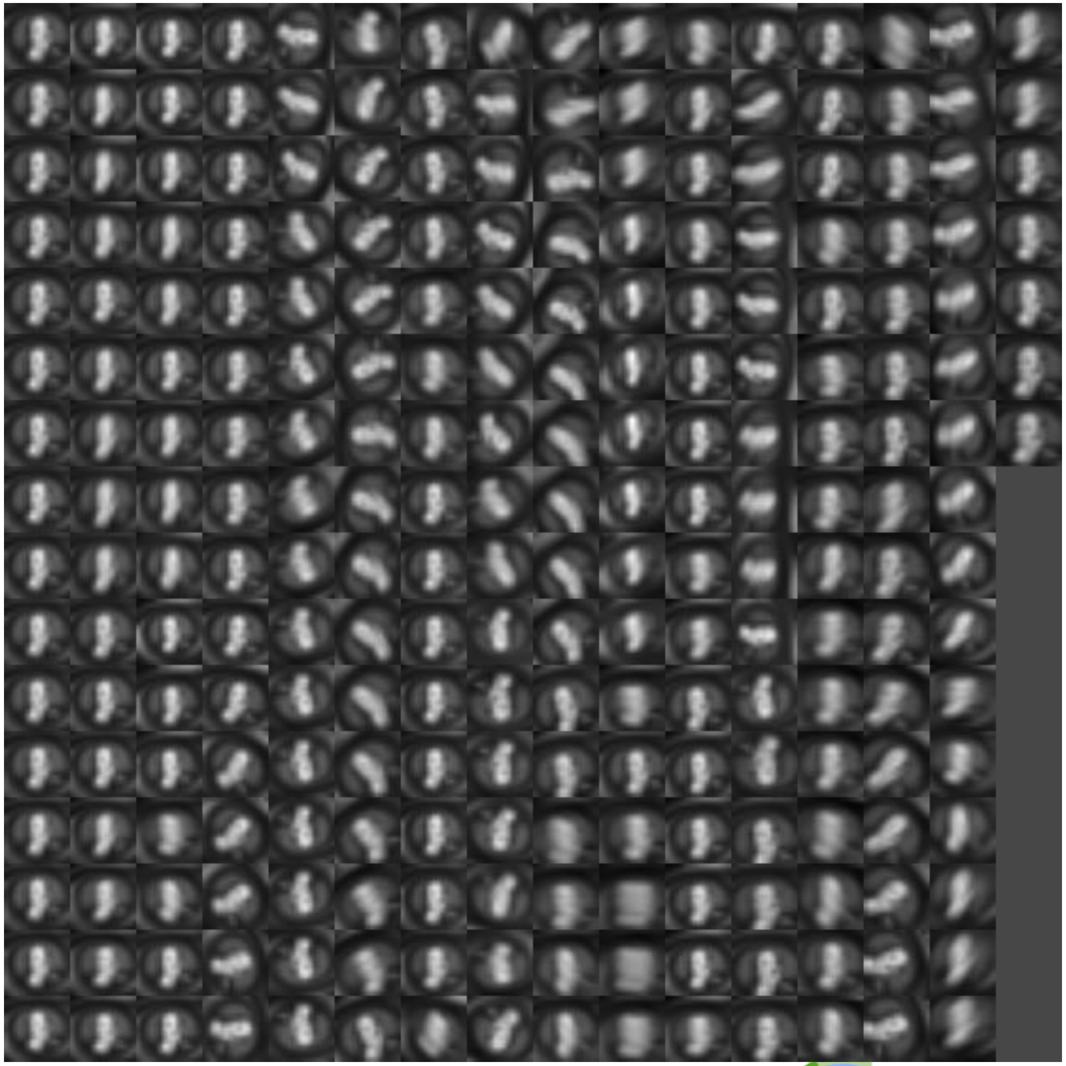


Image source: Z. Kalal

TLD Results

Video source: Z. Kalal

References and Further Reading

- The original Online AdaBoost paper
  - N. Oza and S. Russell. Online Bagging and Boosting. Artificial Intelligence and Statistics, 2001.
- Online Boosting for Tracking
  - H. Grabner, H. Bischof. On-line Boosting and Vision. CVPR'06.
- Semi-Supervised Boosting
  - H. Grabner, C. Leistner, H. Bischof. Semi-Supervised On-line Boosting for Robust Tracking. ECCV'08.
- Tracking-Learning-Detection
  - Z. Kalal, K. Mikolajczyk, J. Matas. Tracking-Learning-Detection. PAMI 2011.