Recent Developments and Tools for Image Segmentation by Mathematical Morphology

The segmentation user's guide revisited…

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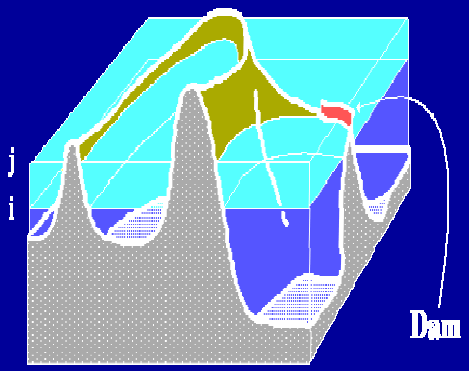
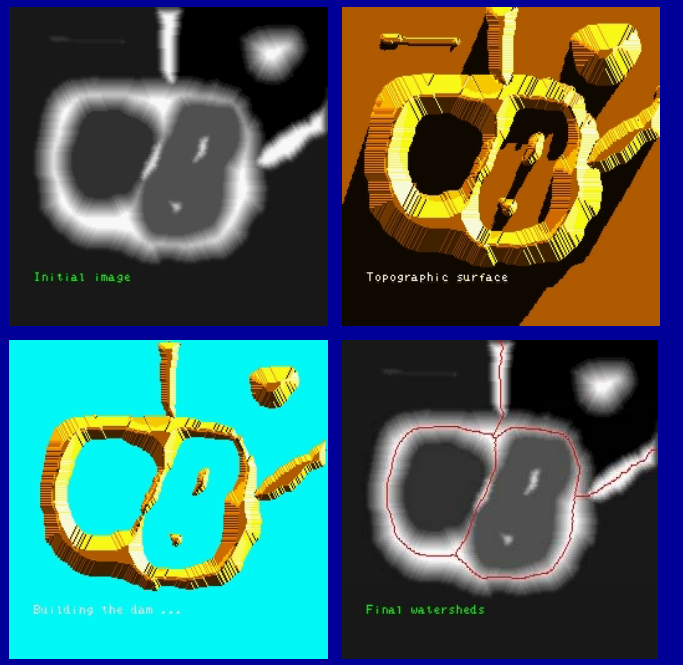
Watershed Transformation

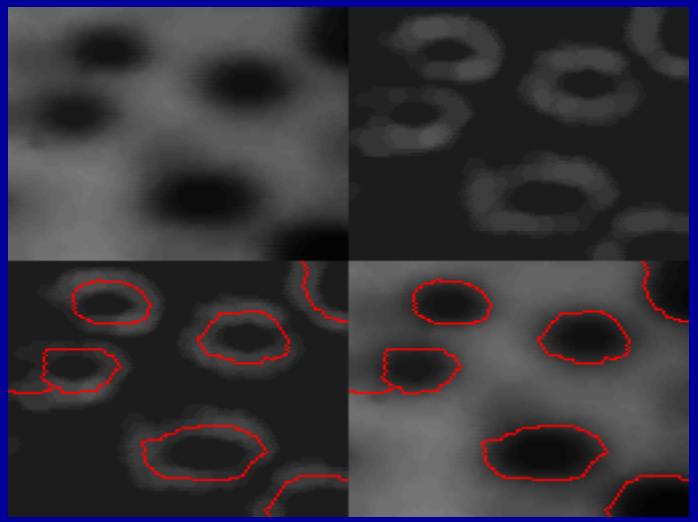
- It's a flooding process.
- Flooding sources are the minima of the function.
- The result is a partition of the image into catchment basins and watershed lines (dams).





- Efficient implementations (real time) exist
- Properties and biases are known.

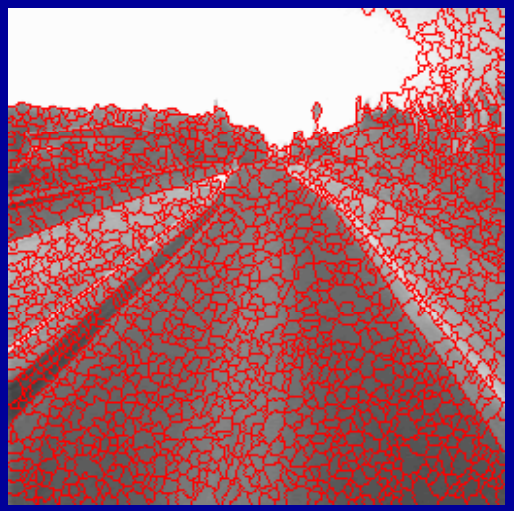
Use of the watershed transform for greyscale image segmentation (watershed of gradient)



Catchment basins correspond to homogeneous grey regions in the image.

Coping with Over-Segmentation

The gradient watershed is over-segmented.



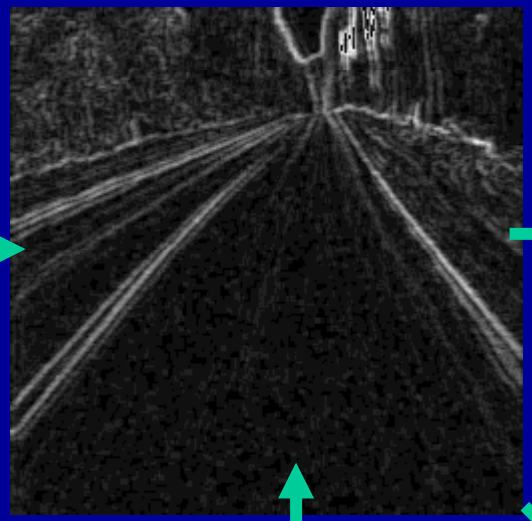
Gradient images are noisy and contain many minima. Each minimum generates a catchment basin in the WTS.

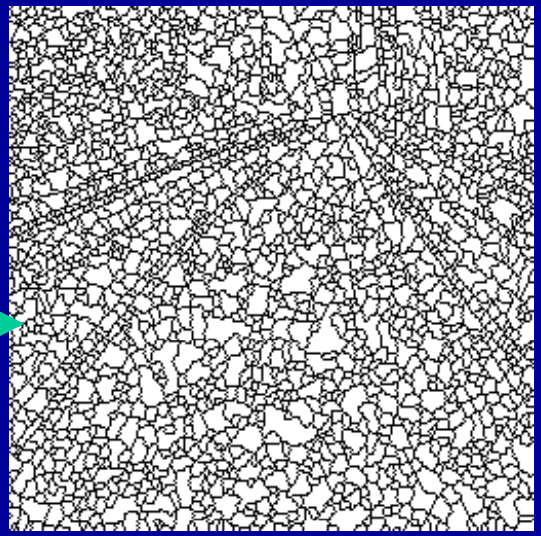
To avoid this over-segmentation due to numerous sources of flooding, one can select some of them (the markers) and perform *a marker-controlled watershed transform*.

Advantages of the Marker-Controlled Watershed

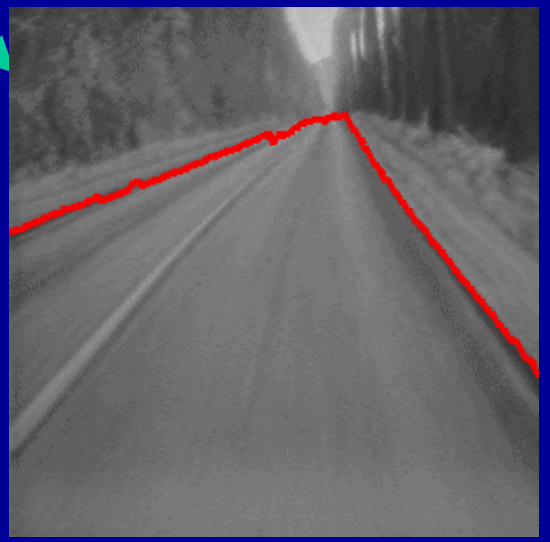
original image

gradient



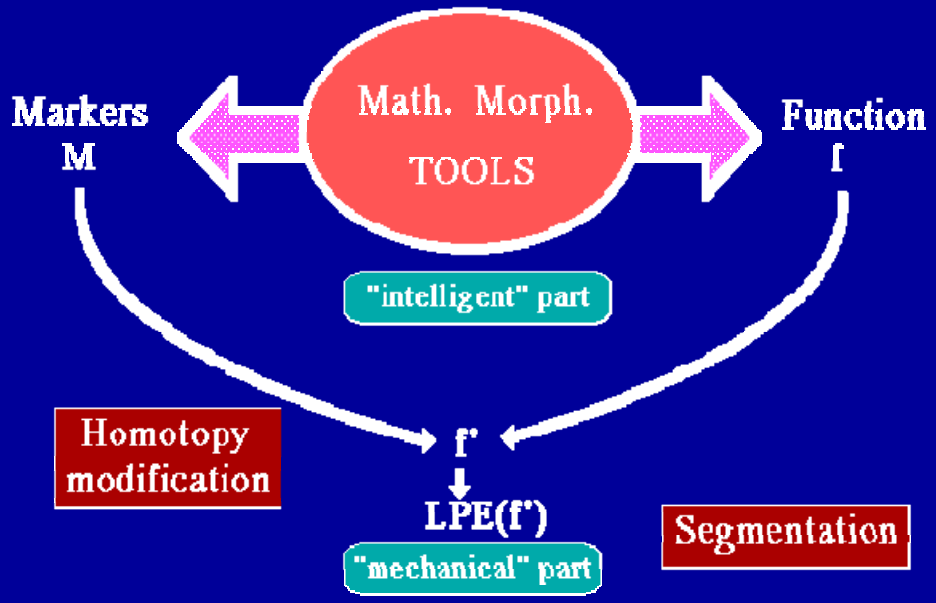


gradient watersheds



Markers corresponding to the two regions to be segmented (drawn by hand actually)

A Simple User's Guide



A morphological segmentation process is performed in two steps

- **The function f quantifies the criterion which is used by the segmentation**
- **The markers indicate the regions/objects to be extracted**

This scheme (segmentation paradigm) has the advantage to be generic and to be applicable to many segmentation problems (2D, 3D, greytone, color, multi-spectral, interactive segmentation, etc.).

It's, however, a simplistic user's guide…

Which Criteria? Which Markers?

- **Regarding greyscale (or color) images, contrast criteria are used and therefore functions quantifying differences between adjacent pixels and/or regions:**

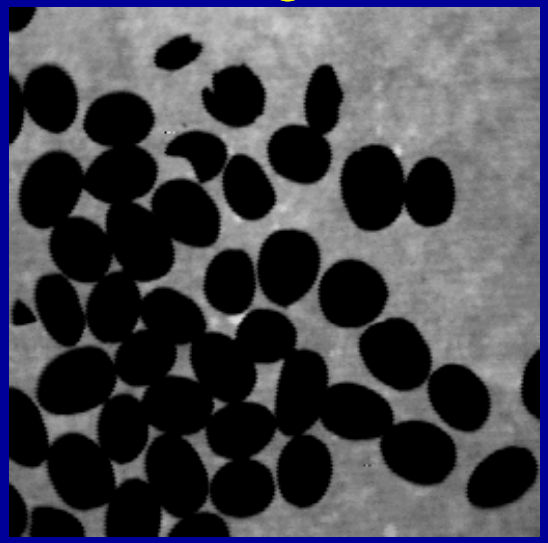
  Gradient
  Top-hat transform
  Various combinations

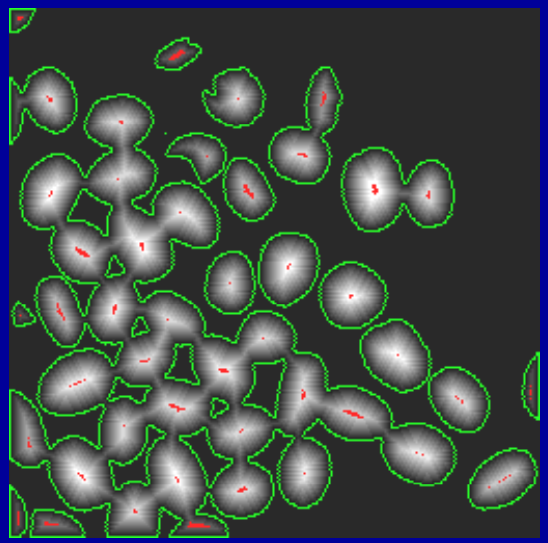
- **The watershed approach can also be used to segment sets according to their shapes and sizes. In this case, the *Distance function* is widely used.**

- **Markers are built by various means. They are often obtained from extrema (minima or maxima) of the criteria functions or by more sophifisticated approaches using a wide range of morphological tools (filters, geodesic operators).**

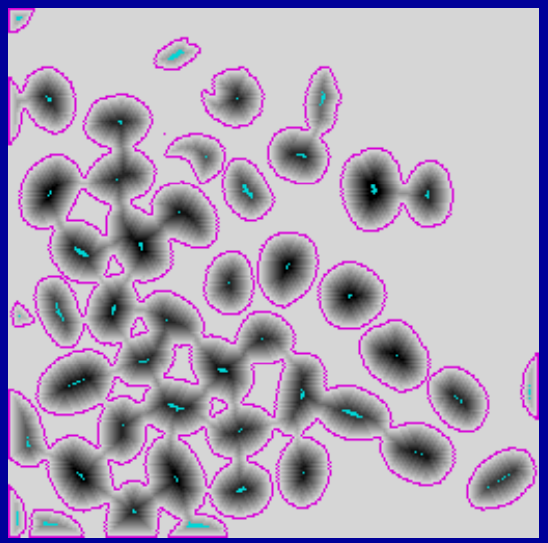
Set Segmentation, an Example

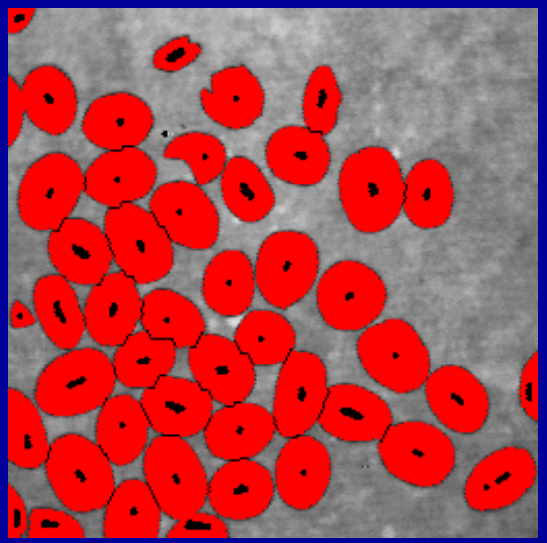
Coffee grains





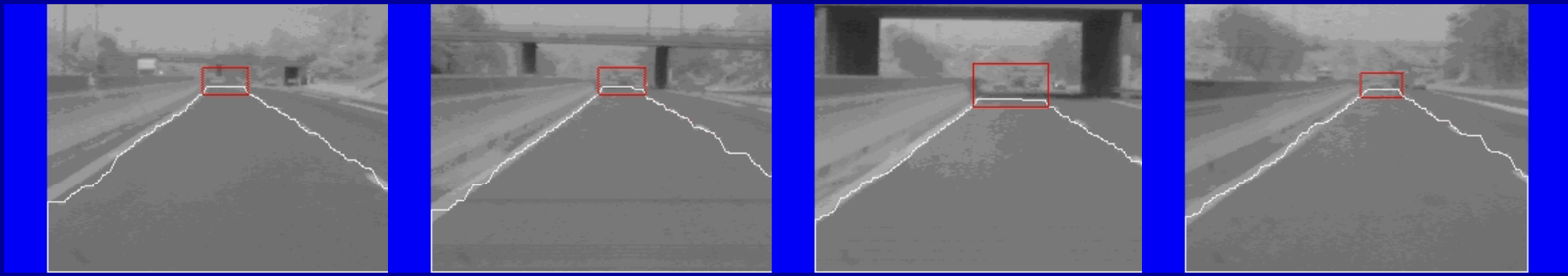
The *distance function* of the set is computed. This distance function is inverted and its watershed is performed. The marker set is made of the maxima of the distance function.



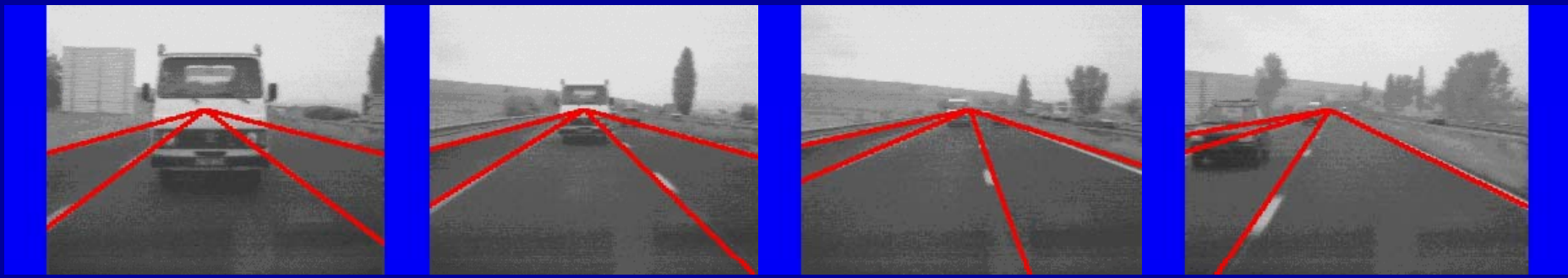


… And With Animated Images

The PROMETHEUS project: road segmentation and obstacle detection



Lane detection based on a watershed segmentation applied on each image of the sequence



Lanes detection with re-use of the previous result as markers in the current image

Extending Shape Criteria to Greyscale Images, Is It Possible?

Until recently, it was difficult to apply shape and size criteria to greyscale image segmentation.

Example of traffic lanes segmentation: the lanes are not separated by a significant difference in grey levels. Therefore, using contrast criteria is irrelevant. Conversely, to use shape or size criteria, we need to work on the set corresponding to the road, which must be obtained by a… segmentation.

New operators allow to bridge the gap between these two kinds of criteria.

A Deeper Insight into the Tools

- Limited toolbox
- Which class of tools?
- Is it possible to expand it?

All the operators used with the watershed transformation are residues.
A residual operator is the difference of two operators called primitive functions:

- **Morphological gradient** $\longrightarrow \delta - \varepsilon$ **(dilation, erosion)**
- **Top-Hat transform** $\longrightarrow I - \gamma$ **(identity, opening)**
- **Distance function/ultimate erosion** $\longrightarrow \varepsilon_i \setminus \gamma(\varepsilon_i)$ **(erosion, opening of erosion)**

New residues can be defined and used

Numerical Residues, Short Introduction

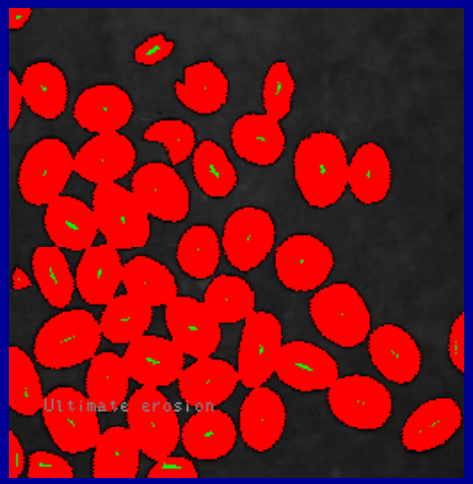
An elementary residual operator is defined by the difference of two operators.

General definition

Starting from two sequences of transformations ψ_i **and** ζ_i **with** $\psi_i \geq \zeta_i$ **, we define a doublet of operators:**

- **The residual transformation** $\theta = \sup_{i \in I}(\psi_i - \zeta_i)$
- **Its associated function** $q = \arg\max(\psi_i - \zeta_i) + 1$

A residual transform is made of a couple of operators: the first one provides locally (at every point of the image) the maximum value of the residue, the second one indicates the value of the index i (it often corresponds to a size) which produces this maximum.
Both operators are important!



Ultimate erosion

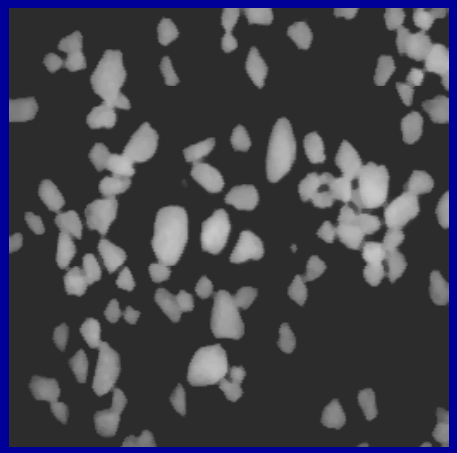
New Residues

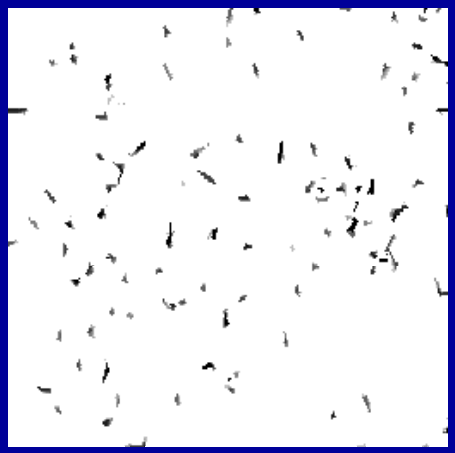
Thanks to this general definition of a residual transform, it is possible to extend to functions residues defined for sets:

$$\psi_i = \varepsilon_i$$

$$\zeta_i = \gamma_{rec}(\varepsilon_i)$$

Ultimate Erosion





It is also possible to define new transformations:

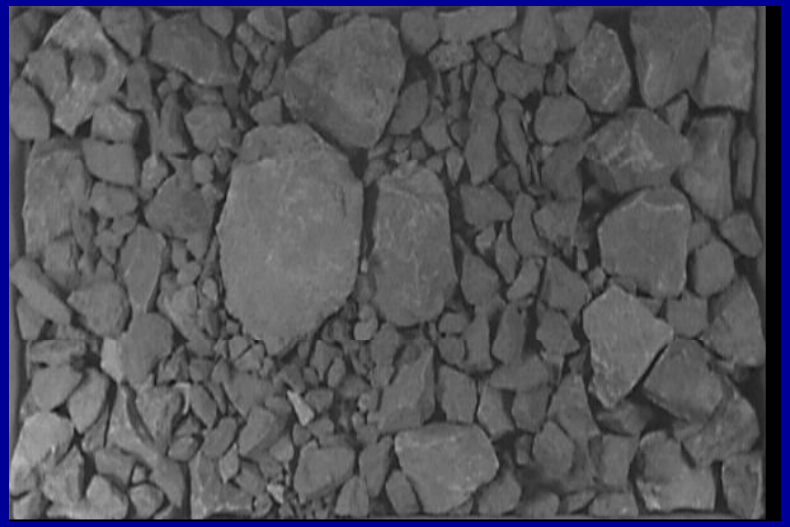
$$\left.\begin{aligned}\psi_i &= \gamma_i \\ \zeta_i &= \gamma_{i+1}\end{aligned}\right\} \rightarrow$$

θ is named *Ultimate Opening*
q is the *Granulometric function*

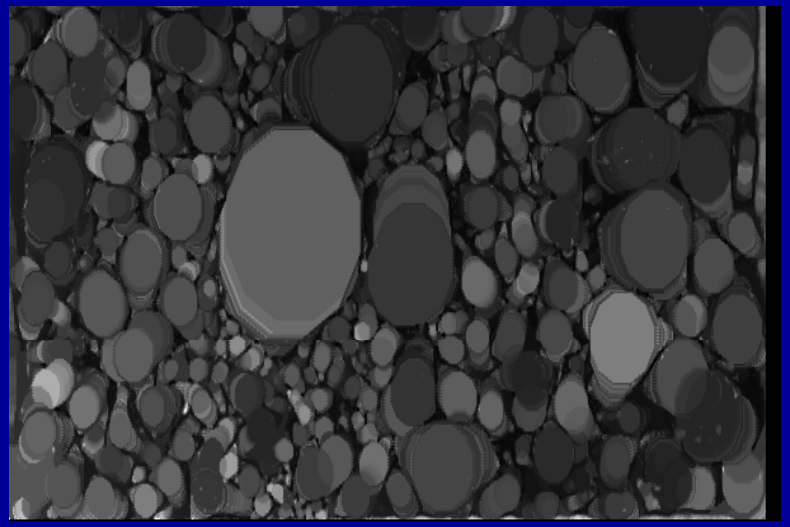
$$\left.\begin{aligned}\psi_i &= \varepsilon_i \\ \zeta_i &= \varepsilon_{i+1}\end{aligned}\right\} \rightarrow$$

q is called *Quasi- Distance*.

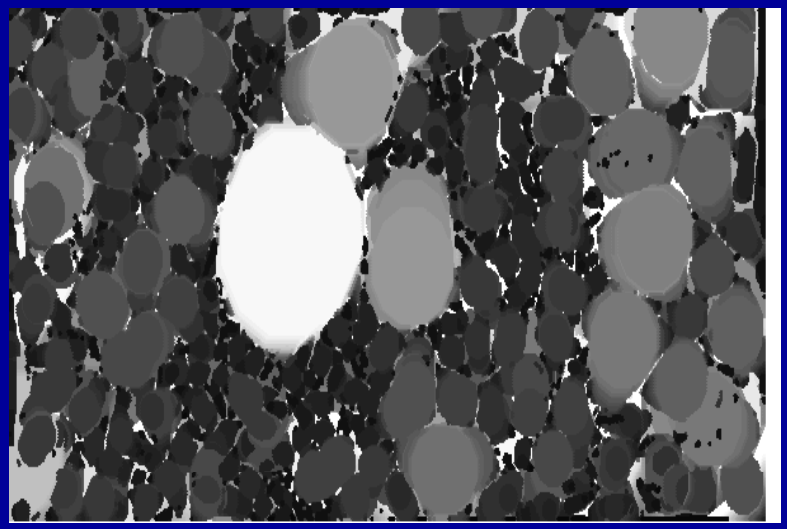
Ultimate Opening
Granulometic Function

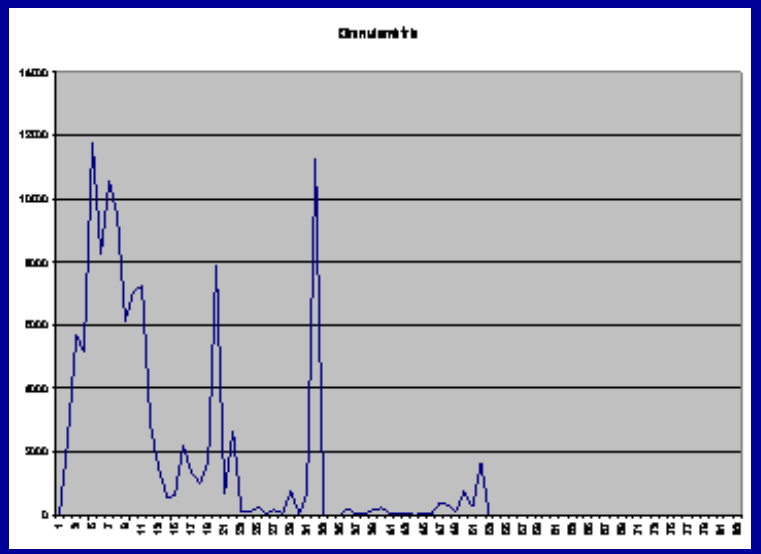


Heap of rocks



Ultimate Opening



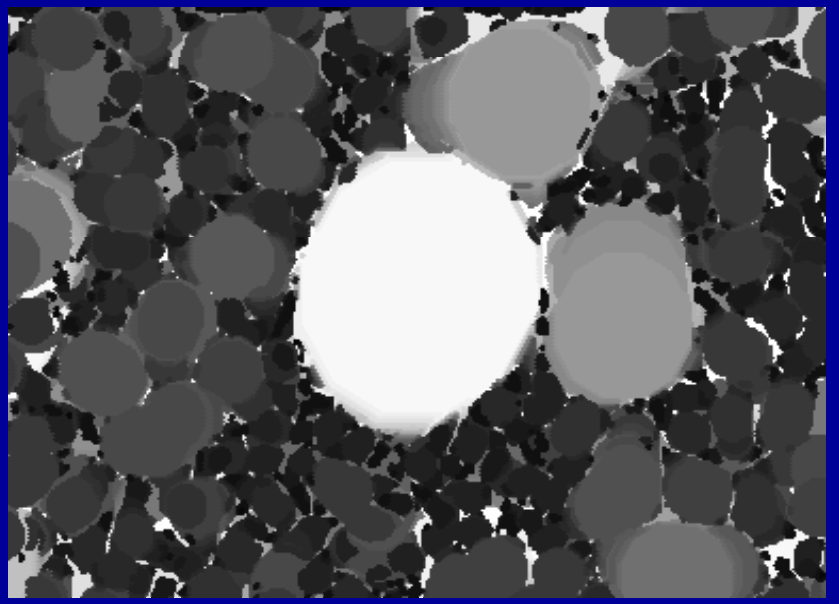


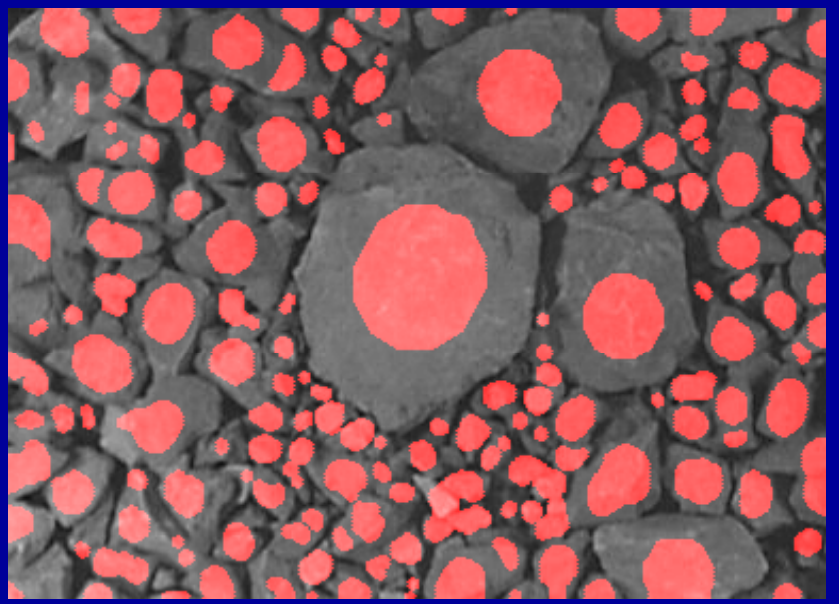
Granulometric function

Markers Generation

The granulometric function can be used to produce efficient markers for the watershed segmentation.

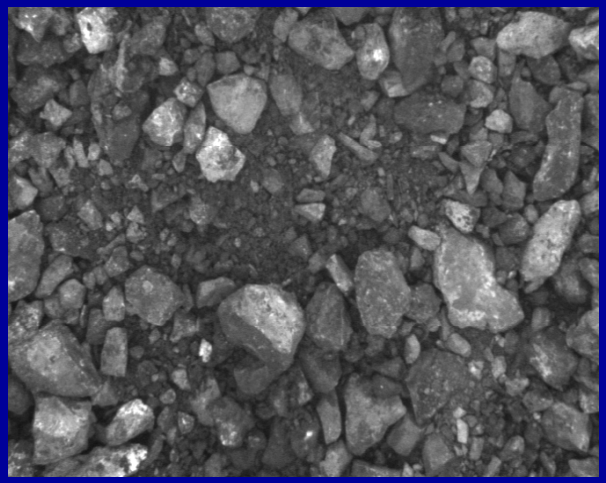
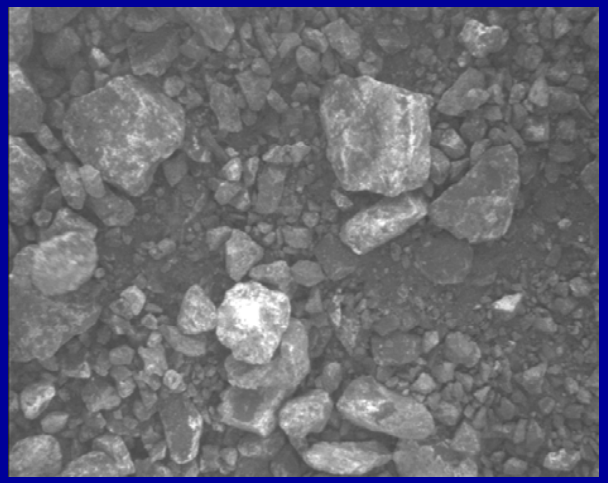
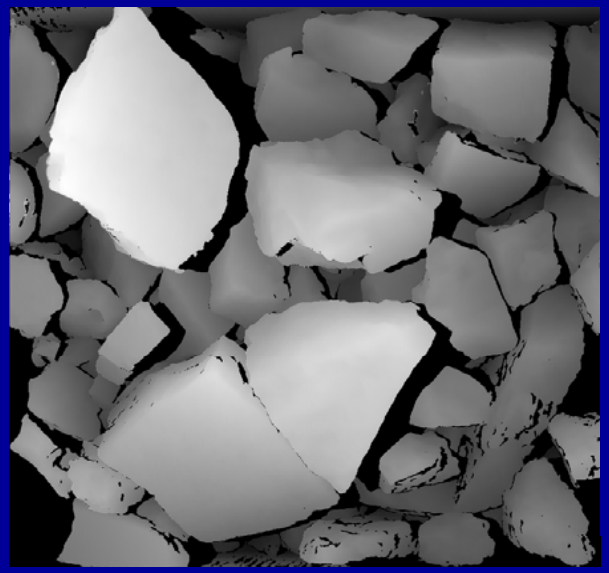
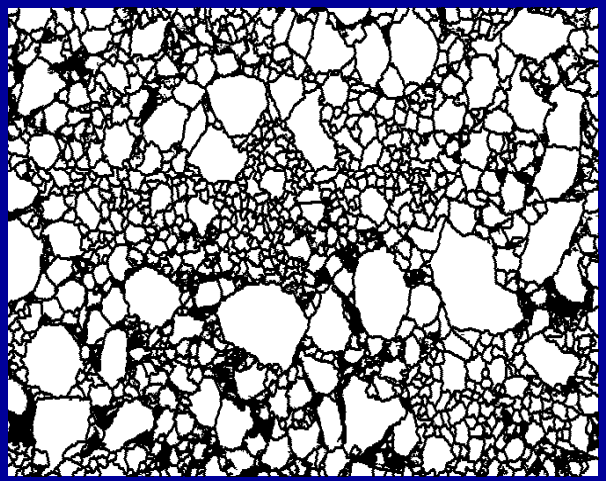
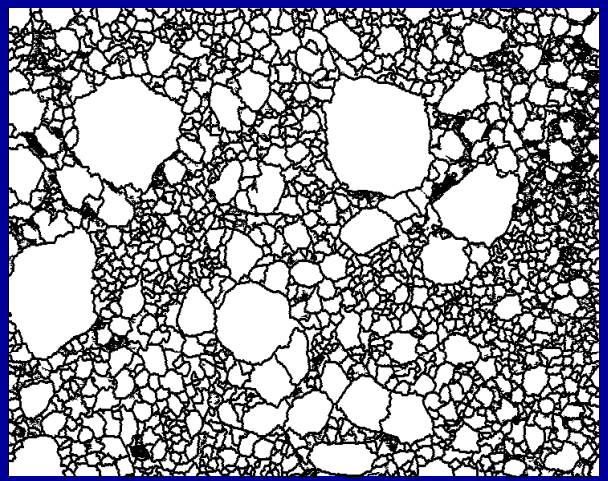
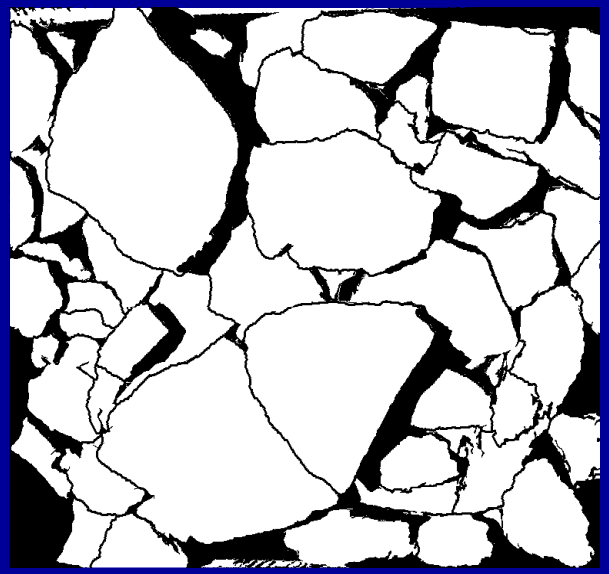
Each threshold λ of the granulometric function q is eroded by a disk of size $k\lambda$ ($k<1$)





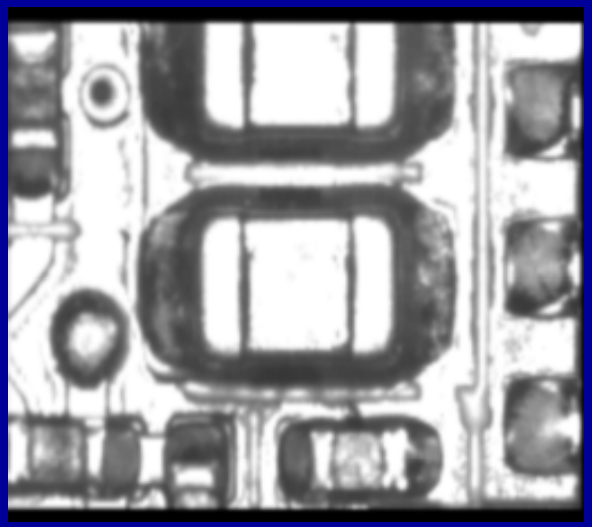
This operation produces markers of blocks whose size is proportional to the size of the block. As a result, markers are better centered, even small particles are well marked and the watershed segmentation is of better quality.

Some Results of Segmentation

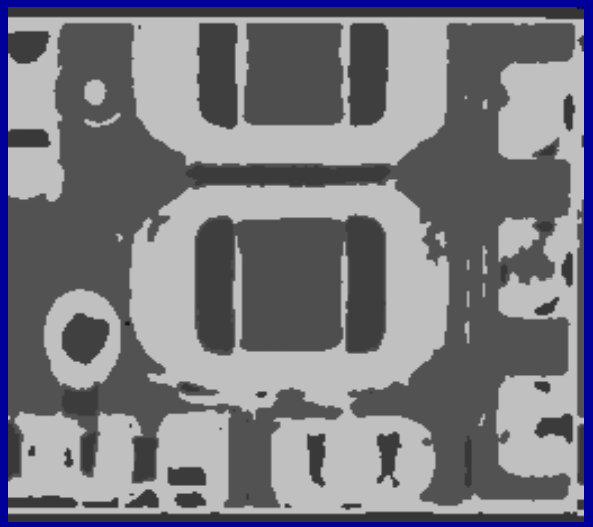
Ultimate Opening Can Be Defined From Any Opening Operator

For instance, with opening by geodesic reconstruction…
This operator emphasizes the size criterion.



Initial image

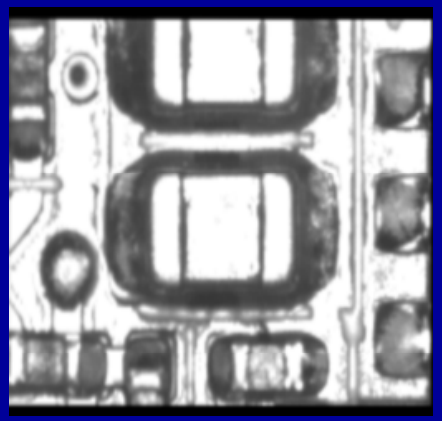
Ultimate Opening by reconstruction



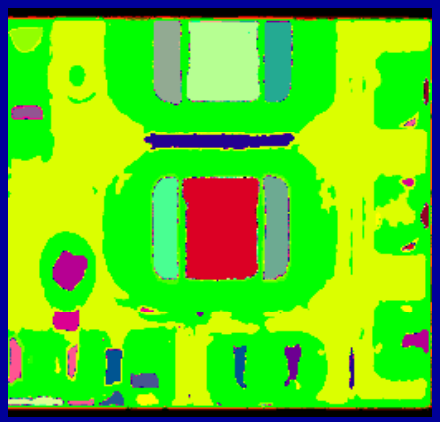
Granulometric function

Residual operators provide efficient non parametric filters. The Ultimate Opening is a remarkable tool for marking and extracting salient features from an image.

Segmentation with the Ultimate Opening by Reconstruction



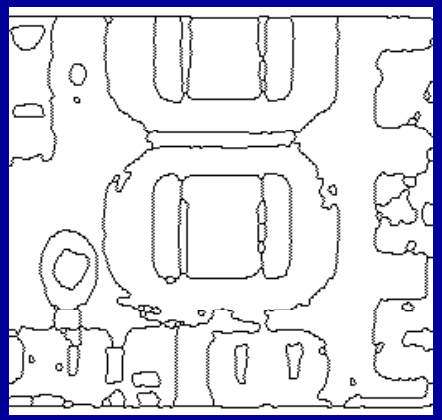
Initial image



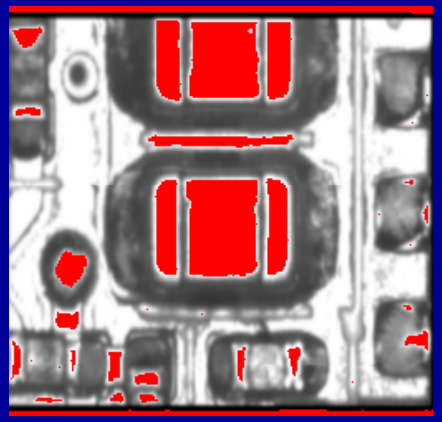
Ultimate opening

Granulometric function

Selection of markers from granulometric function



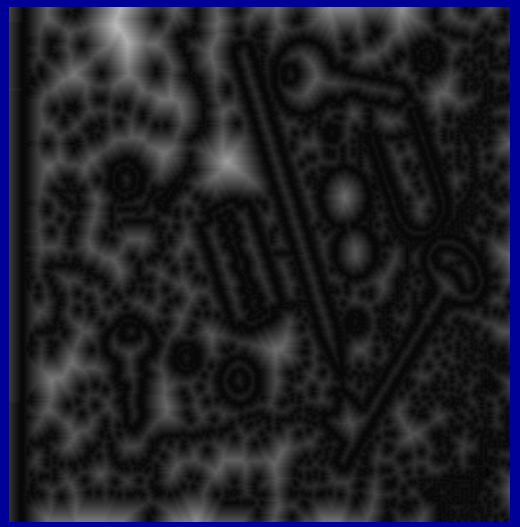
Watershed of the gradient of the ultimate opening



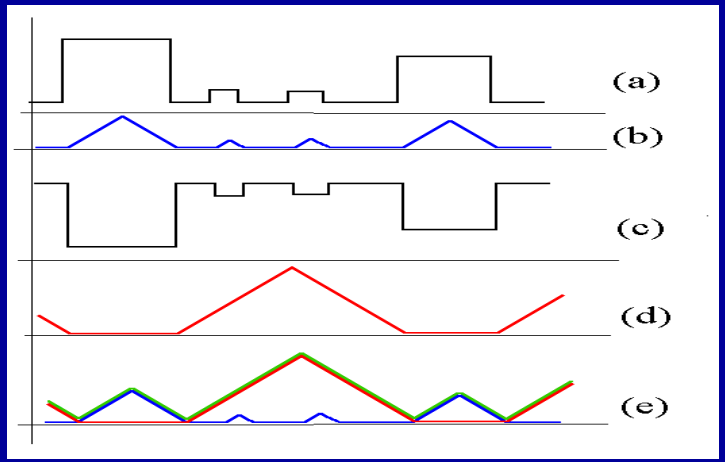
Extraction of salient features

Quasi-Distance and Segmentation

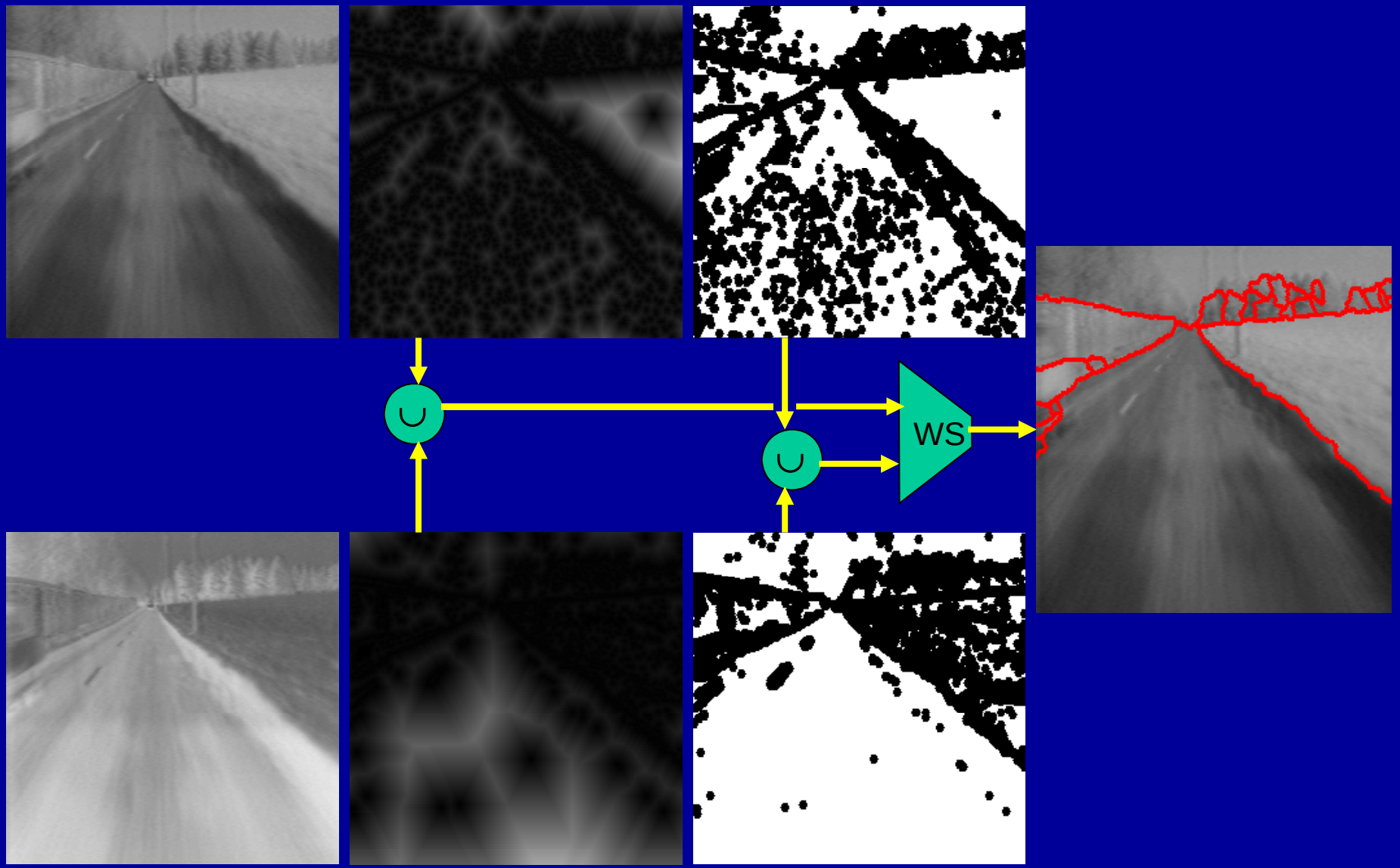
A quasi-distance computed on a greyscale image provides the sizes of the flat (homogeneous) regions → Markers for a segmentation based on size and geometry (convexity).



- **Quasi-distances performed both on the image and the complementary one → d, d'**
- **Sup of the results → h=sup(d,d')**
- **Markers extraction (maxima or threshold)**
- **Watershed of h**

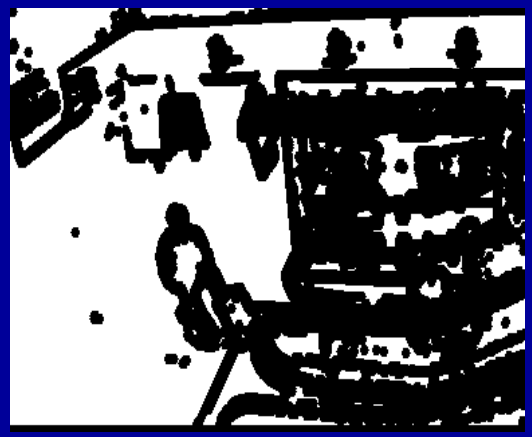


Segmentation With Quasi-Distances

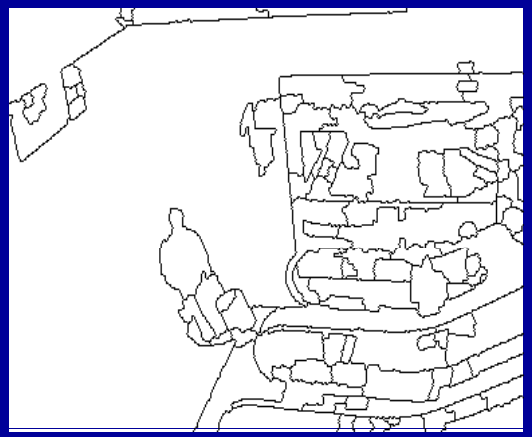


Another Example

Quasi-Distances



Markers

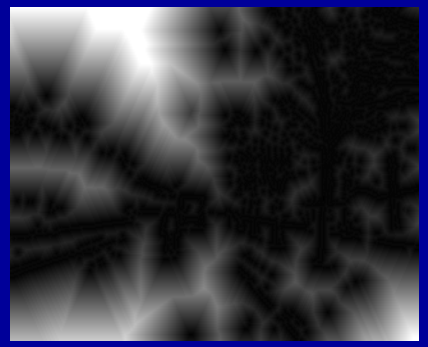


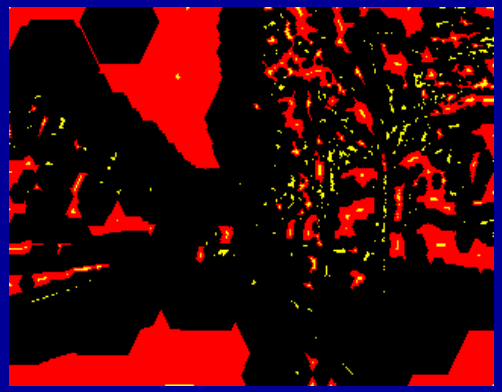
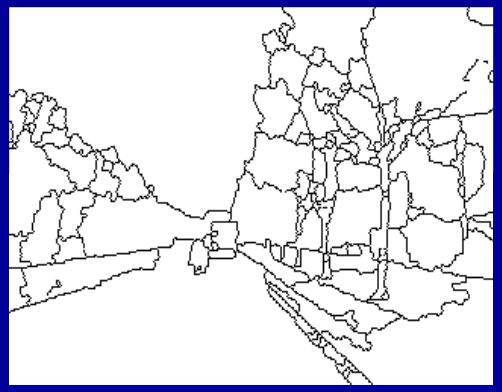
Segmentation

Video surveillance scene

Gradient and Quasi-Distance



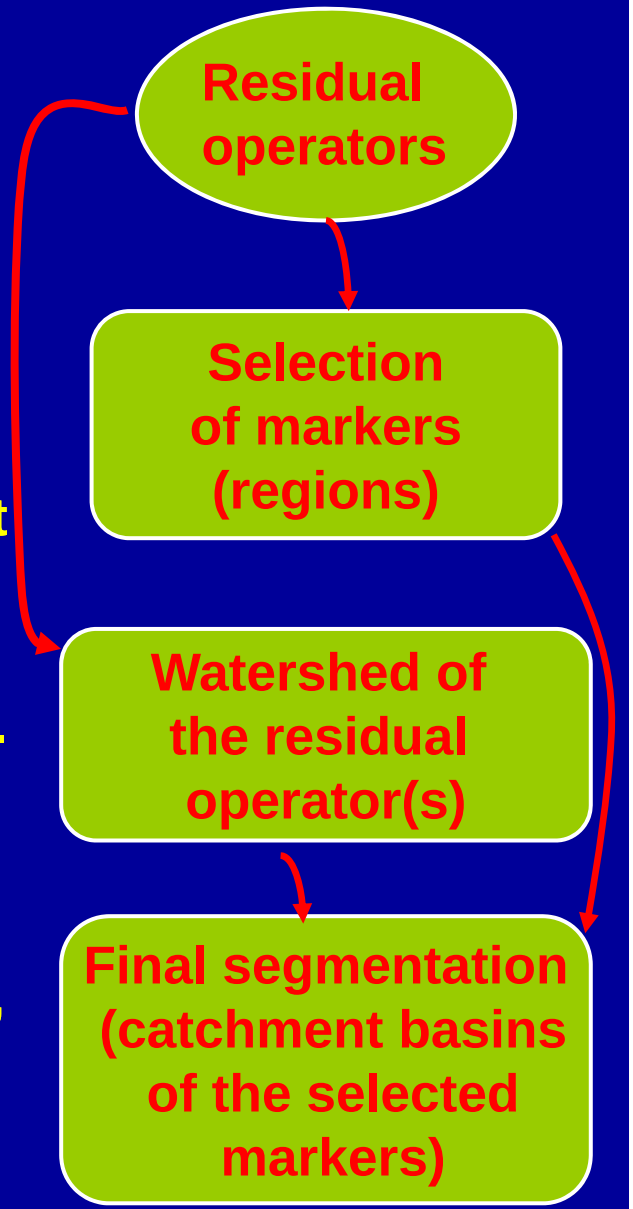



Quasi-distance can be computed on the inverted gradient function

- **Only one quasi-distance is calculated**
- **Hierarchy of regions based on their relative contrast**
- **The shape of regions is taken into account (closure of imperfectly closed regions)**

Towards a New User's Guide

- In the initial user's guide, no clue was given about the operators used for segmentation.
- Criteria functions belong to the residual transforms class and markers are linked to extrema of these functions.
- Residual transformations, not only, emphasize variations of some features (contrast, size, shape, etc.) but also, indicate where the greatest variations occur, what are their amplitudes and which index value produces them.
- New residual transforms have been introduced. They bridge the gap between the numerical and binary images regarding shape and size criteria.
- Other residues are also very efficient: regularised gradients, spatio-temporal gradients, critical balls, pilings (in hierarchical segmentations), etc.



Hierarchical Segmentation, Waterfalls

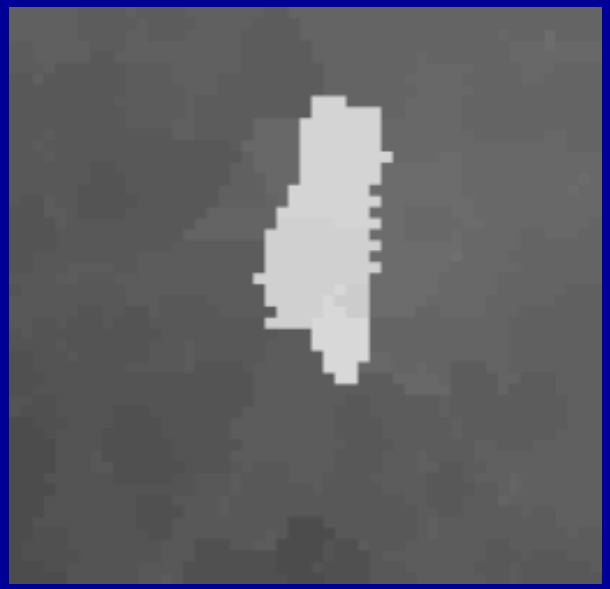
It is not always possible to prevent over-segmentation by marker-controlled watershed because it is not always possible to find good markers and/or segmentation criteria.

Therefore, another approaches of the segmentation which are not based on the a priori selection of markers exist. They aim at defining a hierarchy of segmentations.

The Waterfalls transformation is the other way to solve the over-segmentation problem.

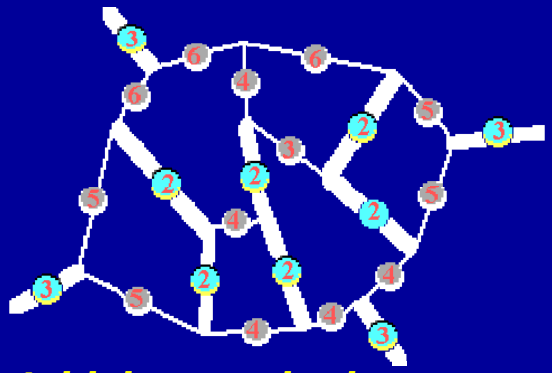
Over-Segmentation and Perception of Images

A simple illustration using a mosaic image



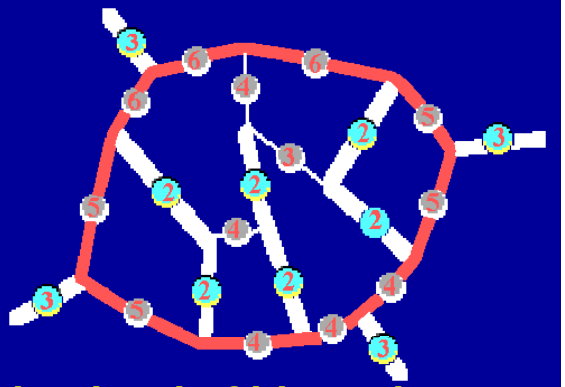
Despite the fact that the image is over-segmented, the white blob can be easily distinguished from the background because, at the same time, the boundaries between the regions inside the blobs and the boundaries inside the background are less contrasted than the boundaries which separate the blob and the background. Both the blob and the background are marked by boundaries with a minimal contrast.

Waterfalls transform: a watershed applied on graphs

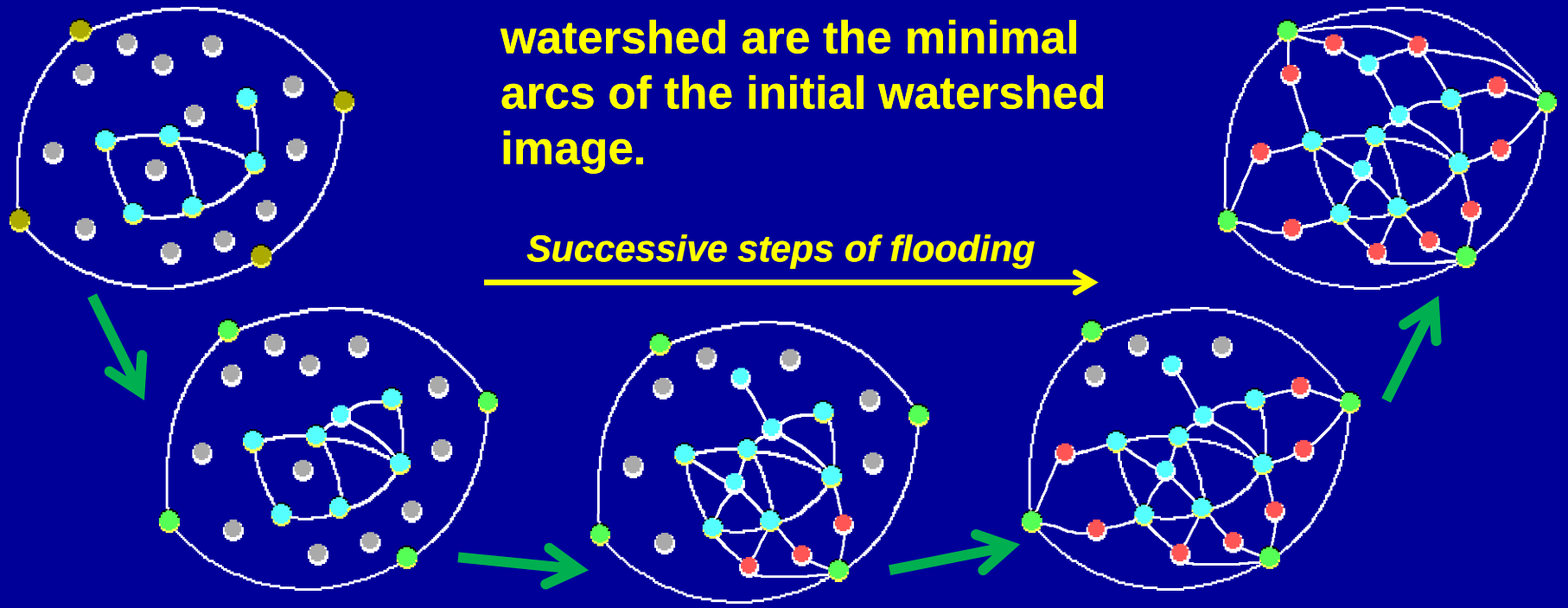


Initial watershed

The waterfalls transform is a watershed transform (propagation) performed on a graph defined from the initial watershed image. The markers of this watershed are the minimal arcs of the initial watershed image.

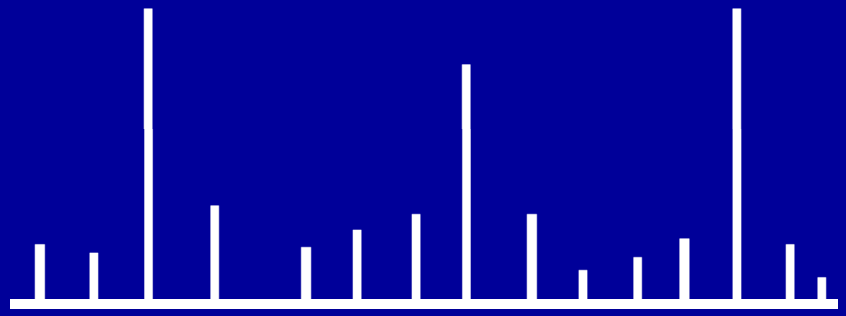


First level of hierarchy

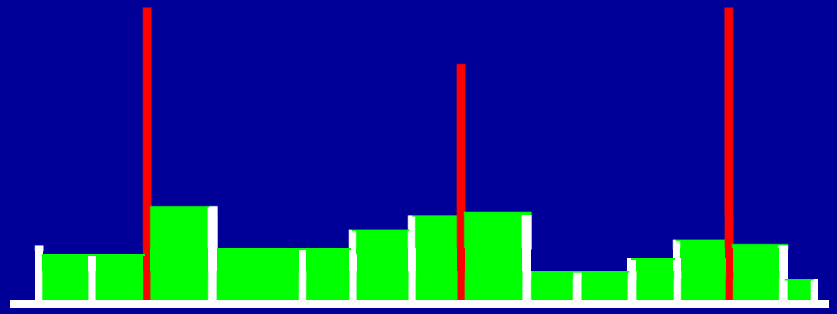


Waterfalls and Hierarchical Images

The waterfalls transformation can also be obtained by performing the watershed transform of a new image, the hierarchical image.



Initial watershed image

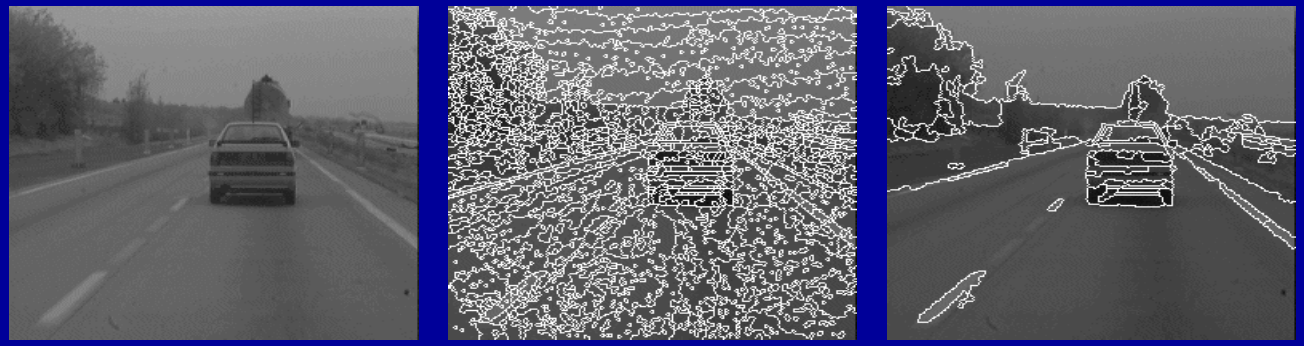


Hierarchical image and waterfalls transformation

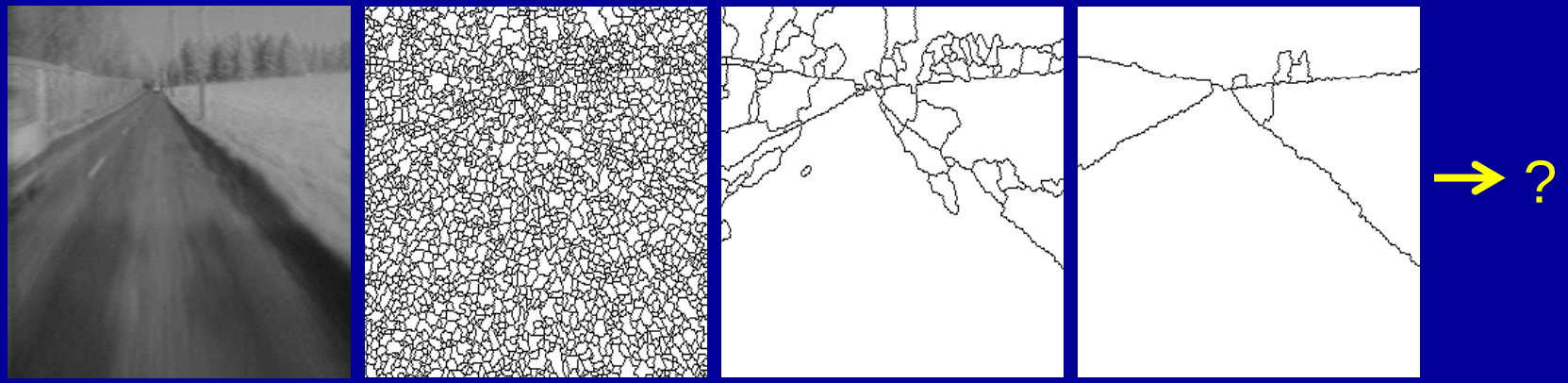
- **Each catchment basin of the initial watershed image is flooded and filled (in green).**
- **This new image is called hierarchical image.**
- **The watershed transform of the hierarchical image is identical to the waterfalls transform (in red).**

Using the Waterfalls Transform

- **Efficient and non parametric approach to reduce over-segmentation.**



- **The process can be iterated.**

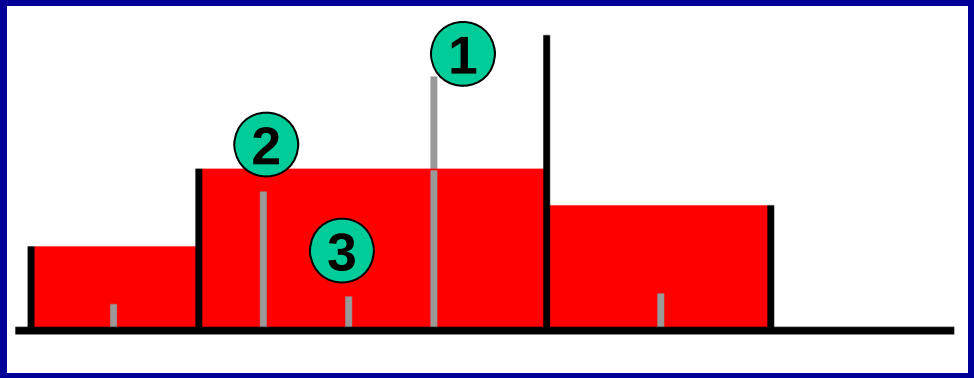


- **But the process ends up with the empty set (no stop criterion).**
- **It is difficult to select a « good » hierarchical level.**
- **Another annoying problem appears…**

Waterfalls Short-sightedness

- The successive hierarchical levels are far from being relevant…

The waterfalls transforms removes too many contours!



In red, hierarchical image h associated with the next level of hierarchy

Three different kinds of removed contours appear:

1. Contours whose altitude is higher or equal to h
2. Contours whose altitude is lower than h but closer to it than to 0
3. Contours whose altitude is close to 0

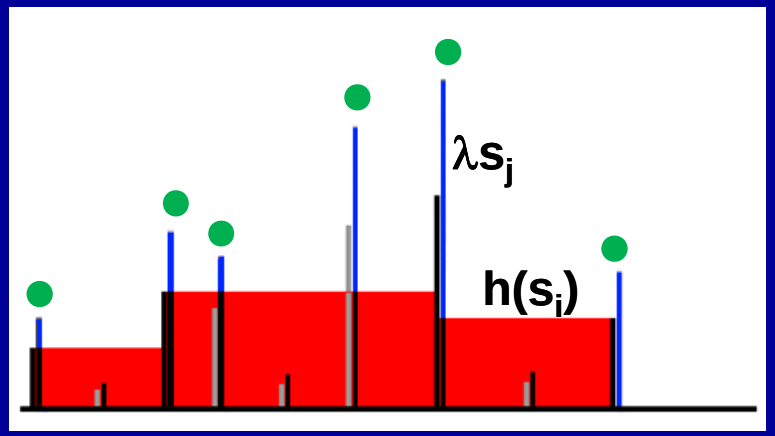
Only the removal of type (3) contours is legitimate!

Towards a General Hierarchical Segmentation algorithm

Note that it is often more efficient to compare the current segmentation s_i with any older one s_j (with I > j) .

Definition of a general algorithm depending on two parameters:

- **Selection of the level of hierarchical segmentation s_j to be compared with the current hierarchical image $h(s_i)$. Sup(i – j, 0) is called the offset.**
- **The heights of the contours belonging to s_j are multiplied by a factor λ and compared to the current hierarchy. Those which are higher define a mask m (green dots):**



$$m = \left\{ x : \lambda\left(s_0 \wedge s_j \right) \geq h\left(s_i \right) \right\}$$

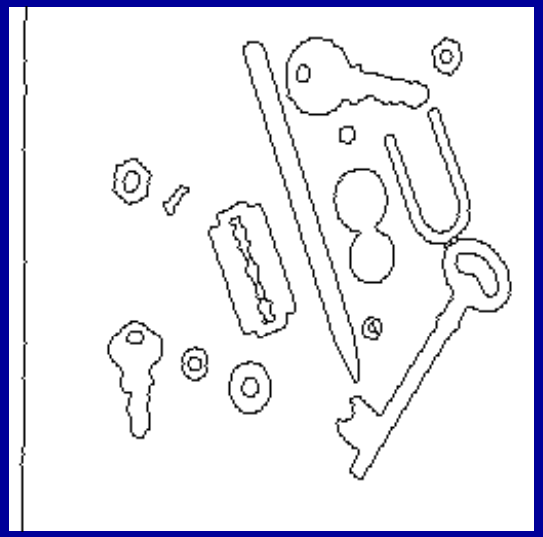
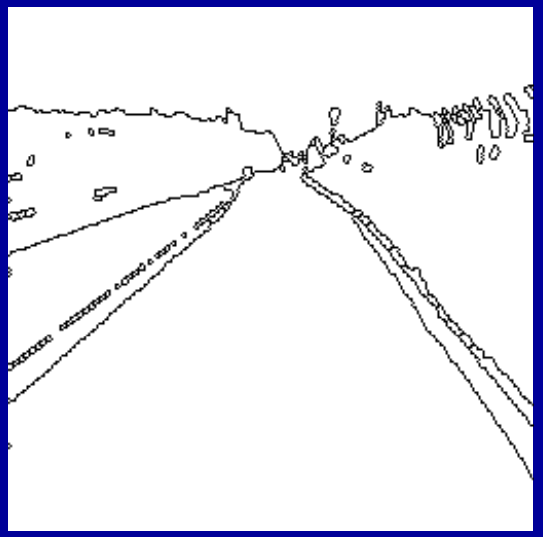
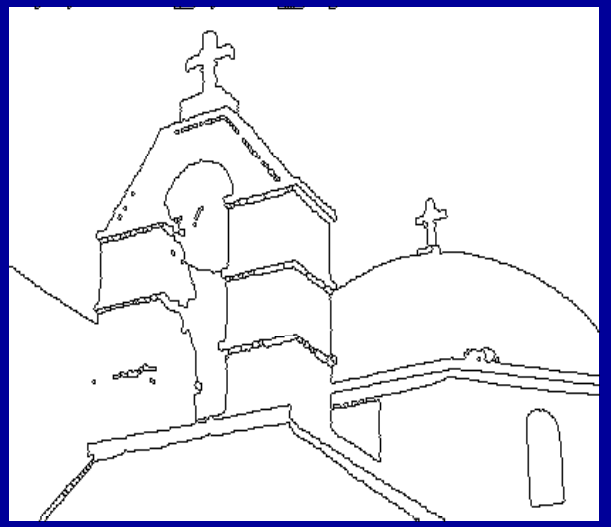
- **The marked contours are reintroduced in the current segmentation s_i:**

$$s'_i = m \wedge \left[h\left(s_i \right) \vee s_0 \right]$$

Offset maximum (the initial segmentation s_0 is always compared to the current hierarchy) and $\lambda = 2$ ⟹ **P algorithm**

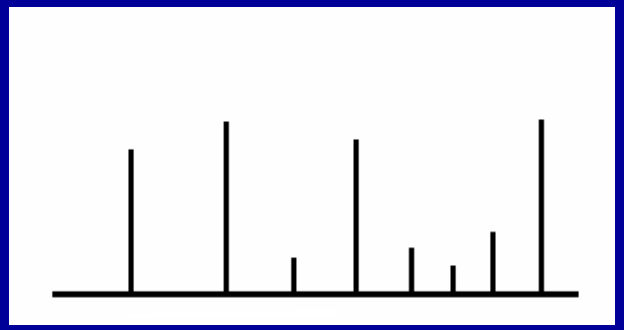
Examples of segmentations with P Algorithm



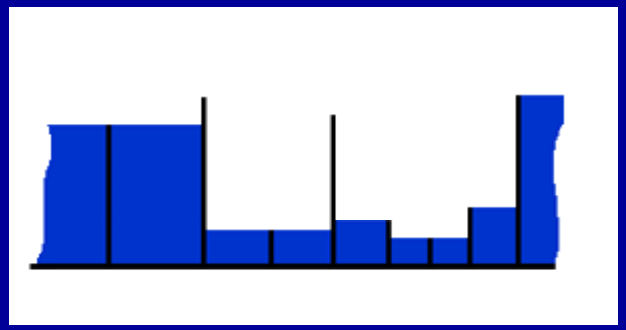





The Return of Residual Transforms: Pilings

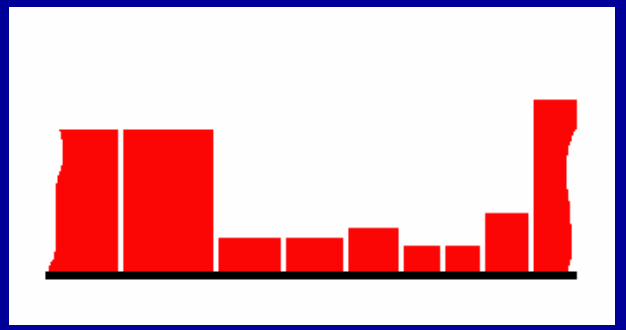
The transformation used to build hierarchical images (catchment basins filling) can also be used to define a new residual operator called pilings.



Initial watershed

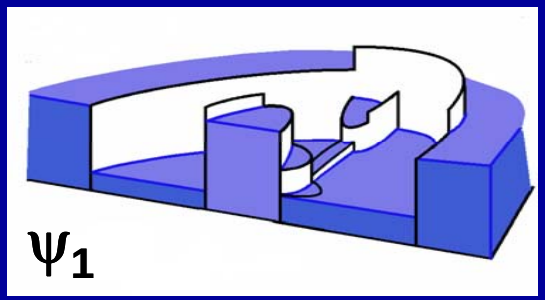


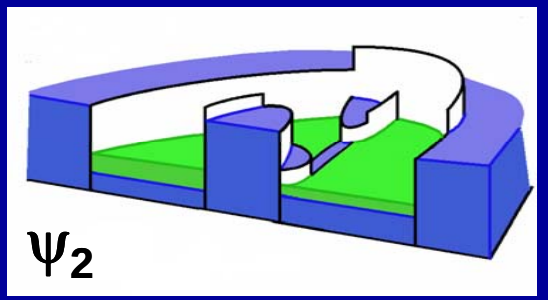
Catchment basins filling

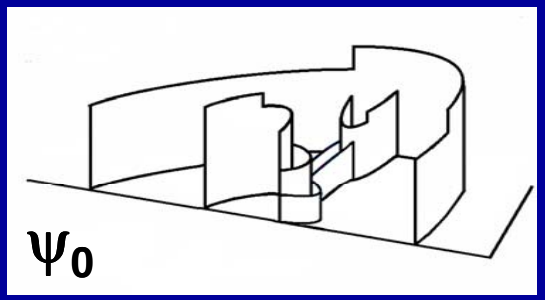


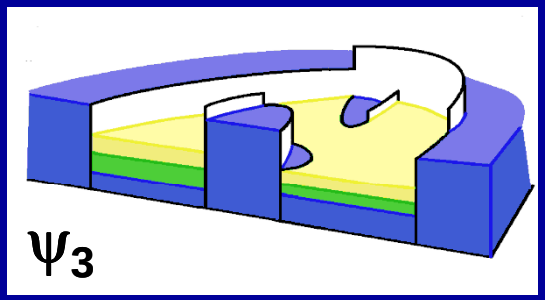
First residue

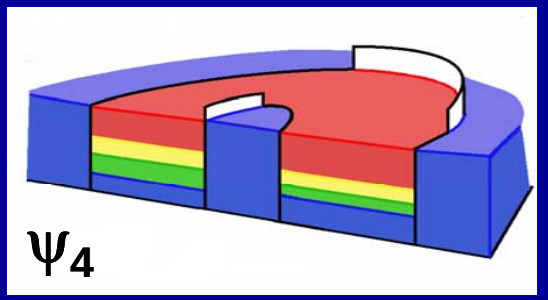
The operation ψ can be iterated. Each step produces a new residue ($\psi_i - \psi_{i-1}$) (in different colours).



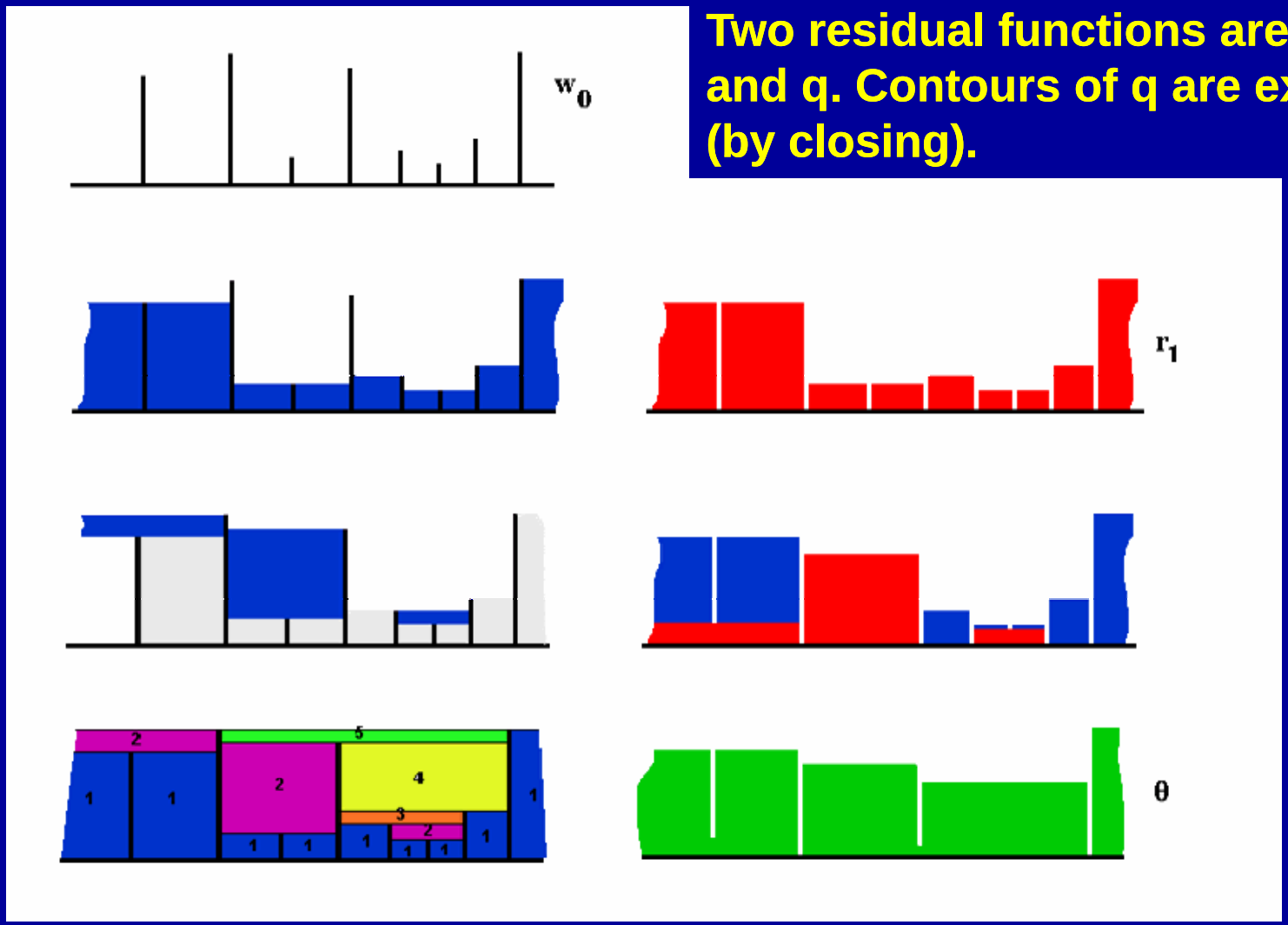






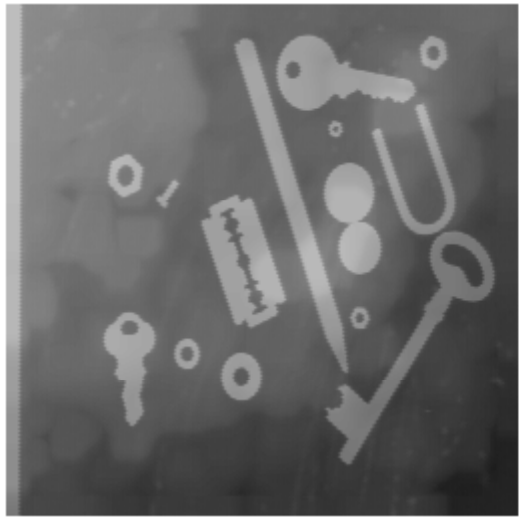


Pilings Residual Transform

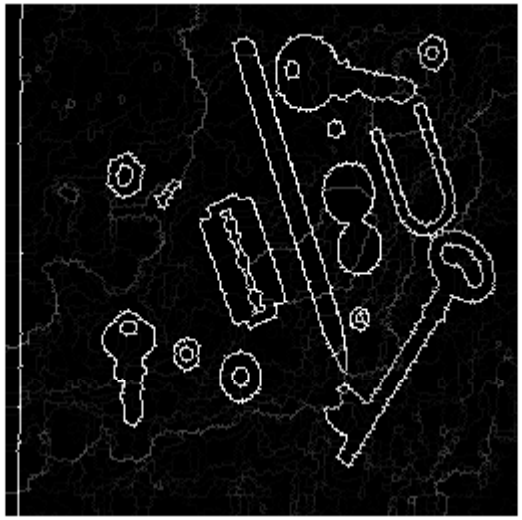


Two residual functions are built, θ and q. Contours of q are extracted (by closing).

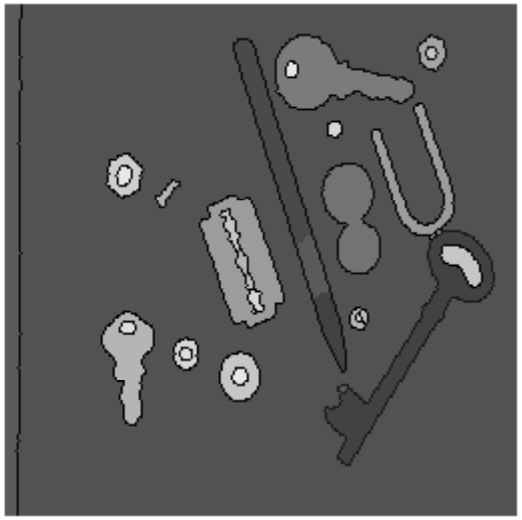
Example of Pilings Residues and Segmentation



Original image

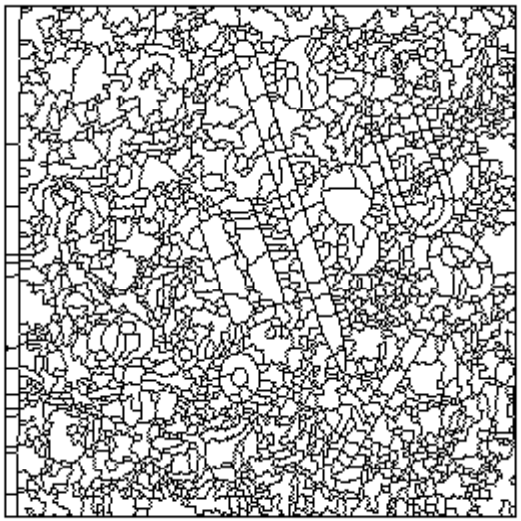


ψ_0

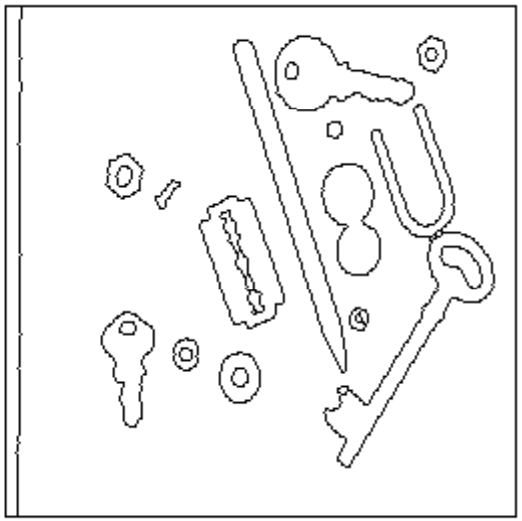


θ

q



Initial contours



contours of θ

A New Impulse for Morphological Image Segmentation

- Almost all the morphological tools used in segmentation belong to the residual transformations class.
- This approach is also applicable to hierarchical segmentation (pilings).
- The residual operators are also very efficient filters.
- Their main advantage lies on their capability to automatically adapt the parameters of the primitive transforms to the local characteristics of the image.
- The results provided by the residual operators are so efficient that the Watershed transform becomes… unnecessary.
- However, some operators are still slow. But new implementations are under study.
- The residual operators open new prospects in morphological image segmentation.